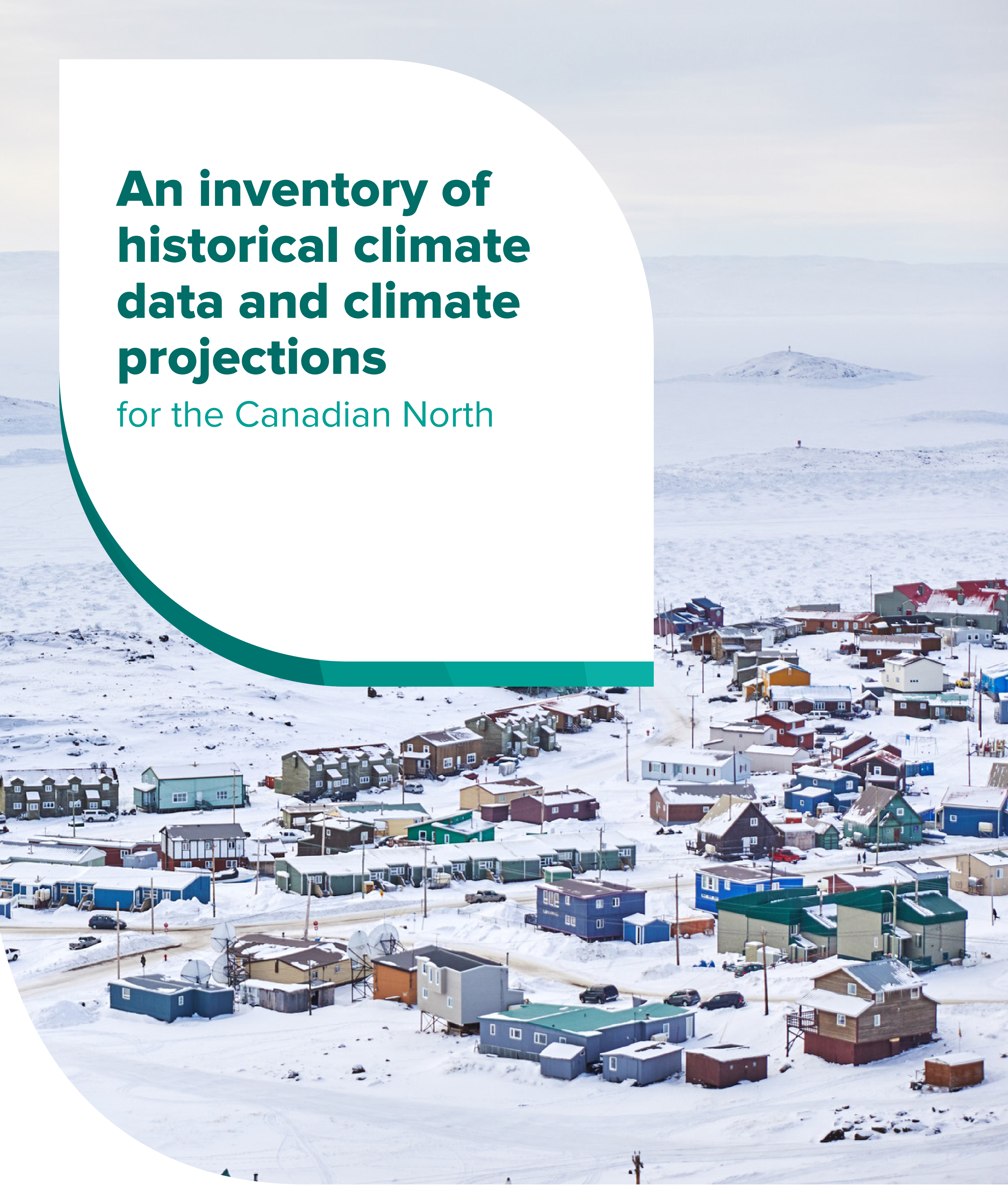
An inventory of historical climate data and climate projections

for the Canadian North



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Edited by:

Emilia Paula Diaconescu (Canadian Centre for Climate Services/Environment and Climate Change Canada), Paul Kushner (University of Toronto), Jennifer Lukovich (University of Manitoba), Alex Crawford (University of Manitoba), Elaine Barrow (Canadian Centre for Climate Services/Environment and Climate Change Canada), Lawrence Mudryk (Climate Research Division/Environment and Climate Change Canada), Marco Braun (Ouranos), Rajesh Shrestha (Watershed Hydrology and Ecology Research Division/Environment and Climate Change Canada), Stephan Gruber (Carleton University), Stephen Déry (University of Northern British Columbia), Stephen Howell (Climate Research Division/Environment and Climate Change Canada), and Lindsay Matthews (Canadian Centre for Climate Services/Environment and Climate Change Canada)

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This report is a product of Northern Cimate Data Working Group, which brings together representatives from government, universities and professional organizations, with working expertise in climate data.

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List of Acronyms

20CRv3: Twentieth Century Reanalysis Project version 3

2D-OI: Two-dimensional optimal interpolation

AgCFSR: Climate Forcing Dataset for Agricultural Modeling based on CFSR data

AgERA5: ECMWF ERA5 data for Agrometeorological indicators

AGCM: Atmospheric General Circulation Model

AgMERRA: Climate Forcing Dataset for Agricultural Modeling based on MERRA data

AHCCD: Adjusted and Homogenized Canadian Climate Dataset

AMSR-E: Advanced Microwave Scanning Radiometer - Earth Observing System sensor

ANUSPLIN: Australian National University Spline

Arctic-rcc: Arctic Regional Climate Center

ASRv2: Arctic System Reanalysis version 2

AWI: Alfred Wegener Institute

BCCA: Bias-correct climate analogues

BCCAQv2: Bias Correction/Constructed Analogues with Quantile mapping reordering version 2

CAA: Canadian Arctic Archipelago

CALM: Circumpolar Active Layer Monitoring

CanESM2: Canadian Earth System Model version 2

CANGRD: Canadian Gridded Temperature and Precipitation Anomalies

CanLEAD: Canadian Large Ensembles Adjusted Dataset

CanSWE: Canadian Historical Snow Water Equivalent dataset

CCCS: Canadian Centre for Climate Services

CCI: Climate Change Initiative

CCIN: Canadian Cryospheric Information Network

CCMEP: Canadian Centre for Meteorological and Environmental Prediction

CDD: Maximum Number of Consecutive Dry Days

CEDA: Centre for Environmental Data Analysis

CEHQ: Centre d’Expertise Hydrique du Québec

CEN: Centre d'études nordiques

CERSAT: Centre ERS d'Archivage et de Traitement

CFS: Canadian Forest Service

CFSv2: The NCEP Climate Forecast System Version 2

CFSR: Climate Forecast System Reanalysis

CHM: Canadian Hydrological Model

CIRA: Cooperative Institute for Research in the Atmosphere

CIRES: Cooperative Institute for Research in Environmental Sciences at the University of Colorado Boulder

CIRNAC: Crown-Indigenous Relations and Northern Affairs Canada

CIS: Canadian Ice Service

CloudSat: CLOUD SATellite

CMAP: CPC Merged Analysis of Precipitation

CMIP: Climate Model Intercomparison Project (phase 5, CMIP5; and phase 6, CMIP6)

CMORPH: CPC MORPHing technique, a high resolution precipitation dataset

CoCoRaHS: Community Collaborative Rain, Hail & Snow Network,

CORDEX: Coordinated Regional Climate Downscaling Experiment

CPC: Climate Prediction Center

CPCU: CPC Unified Gauge-Based Analysis of Global Daily Precipitation

CRBCPI: Climate-Resilient Buildings and Core Public Infrastructure

CRCM5: Canadian regional Climate Model version 5

CRD: Climate Research Division

Crocus-ERA5: Météo-France 1 D snow model using ERA5 data

CryoSat: CRYOgenic SATellite

CRU: Climatic Research Unit

CRU CL: Climatic Research Unit climate data over global land areas

CRUTEM4: Climatic Research Unit Air Temperature Anomalies version 4

CRU TS: Climatic Research Unit Time Series

CSA: Canadian Standards Association

CSV: Comma-separated values

Daymet: Daily Meteorological Surface Data

DIAS: Data Integration and Analysis System

DOE: United States Department of Energy

ECCC: Environment and Climate Change Canada

ECMWF: European Centre for Medium-Range Weather Forecasts

EM: Electromagnetic Induction

ERA5: Fifth major global reanalysis produced by ECMWF

ERA5-Land: ECMWF dataset for land applications based on ERA5

ERA-Interim: ECMWF global atmospheric reanalysis superseded now by the ERA5 reanalysis

ESA: European Space Agency

ESGF: Earth System Grid Federation

ESM: Earth System Model

ESMValTool: Earth System Model Evaluation Tool

ESRI: Environmental Systems Research Institute

ETCCDI: Expert Team on Climate Change Detection and Indices

EUMETSAT: European Organisation for the Exploitation of Meteorological Satellites

FWI: Fire Weather Index

GCM: General Circulation Model

GCOS: Global Climate Observing System

GDDs: Growing Degree Days

GEOSCAN: Geological Survey of Canada

GSCNC: Geological Survey of Canada - Northern Canada

GeoTIFF: Geographic Tagged Image File Format

GHGs: Green House Gases

GISTEMP: Goddard Institue for Space Studies air surface temperature analysis

GLDAS: Global Land Data Assimilation System

GlobSnow: Global Snow Project

GloFAS: Global Flood Awareness System

GloH2O: Portal with global data

GMAO: Global Modeling and Assimilation Office

GMFD: Global Meteorological Forcing Dataset for land surface modeling

GNWT: Government of the Northwest Territories

GPCC: Global Precipitation Climatology Center

GPCP: Global Precipitation Climatology Project

GPI: Geostationary Operational Environmental Sounder Precipitation Index

GPM: Global Precipitation Measurement

GSFC: NASA Goddard Space Flight Center

GTN-P: Global Terrestrial Network for Permafrost

GWF: Global Water Futures

GWFNet: Global Water Futures Net catalogue

HadCRUT3: Hadley Centre Climatic Research Unit Temperature version 3

HadISDH: Met Office Hadley Centre Intergrated Surface Dataset of Humidity

HDDs: Heating Degree Days

HDF: Hierarchical Data Format

HRES: ECMWF's operational high-resolution atmospheric model

HRLDAS: ECMWF's High Resolution Land Data Assimilation system

HVAC: Heating Ventilation Air Conditioning

HTESSEL: land surface scheme in ERA5 (Tiled ECMWF Scheme for Surface Exchanges over Land incorporating land surface Hydrology)

HYDAT: Hydrometric Database

IABP: International Arctic Buoy Programme

IAMs: Integrated Assessment Models (

ICESat: NASA's Ice, Cloud and land Elevation Satellite

IDF: Intensity-Duration-Frequency

IFREMER: French Research Institute for Exploitation of the Sea

IFS: ECMWF Integrated Forecasting System

IMERG: Integrated Multi-satellitE Retrievals for GPM

IMS: Interactive Multisensor Snow and Ice Mapping System

IPA: International Permafrost Association

IPCC: Intergovernmental Panel on Climate Change

ISD: Integrated Surface Database

IT: Information Technology

ITK: Indigenous Traditional Knowledge

IQ: Inuit Qaujimajatuqangit

JMA: Japan Meteorological Agency

JRA-55: Japanese 55-year Reanalysis

LSM: Land-surface model

LST: Land Surface Temperature

LTCE: Long Term Climate Extremes

MBCn: Multivariate bias correction with the N-dimensional probability density function transform

MERRA: Modern Era Retrospective-Analysis for Research and Applications

MERRA-2: Modern Era Retrospective-Analysis for Research and Applications version 2

MERRA-Land: A land-only ("off-line") replay of the MERRA land model component

MESH: Modelisation Environmentale Communautaire – Surface and Hydrology

Met1km: 1-km Resolution Daily Meteorological Dataset

MODIS: Moderate Resolution Imaging Spectro-Radiometer

Mosaic: One of the four land surface models used at GLDAS at NASA

MSC: Meteorological Service of Canada

MSU: Microwave Sounding Unit

MSWEP: Multi-Source Weighted-Ensemble Precipitation

NARR: North American Regional Reanalysis

NASA: National Aeronautics and Space Administration

NCAR: National Center for Atmospheric Research

NCDC: National Climatic Data Center

NCEI: NOAA National Centers for Environmental Information

NCEP: National Centers for Environmental Prediction

NESDIS: National Environmental Satellite, Data, and Information Service

NLDAS: North American Land Data Assimilation System,

NOAA: National Oceanic and Atmospheric Administration

Noah: One of the four land surface models used at GLDAS at NASA

NRCan: Natural Resources Canada

NRCS: Natural Resources Conservation Service

NSIDC: National Snow & Ice Data Center

N.W.T.: Northwest Territories

OGCM: Ocean General Circulation Model

OPI: Outgoing longwave radiation Precipitation Index

OSI SAF: Satellite Application Facility on Ocean and Sea Ice

Ouranos: Consortium sur la climatologie régionale et l'adaptation aux changements climatiques

PAVICS: Analytics and Visualization for Climate Science

PCIC: Pacific Climate Impacts Consortium.

PCMDI: Program for Climate Model Diagnosis & Intercomparison

PDC: Polar Data Catalogue

PERSIANN: Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks

PIN: Permafrost Information Network

PIOMAS: Pan-Arctic Ice Ocean Modeling and Assimilation System

PMW: Passive Microwave

PNWNAMET: Pacific Northwest North America meteorological dataset

PRCPTOT: Total precipitation

PRISM: Parameter-elevation Regressions on Independent Slopes Model

PWRF: Polar Weather Research and Forecasting Model

q: absolute and specific humidity

QDM: Quantile Delta Mapping

R-ARCTICNET: Regional, Arctic Hydrometeorological data Network

RDA: NCAR Research Data Archive

RADARSAT: Radar Satellite

RCM: Regional Climate Model

RCP: Representative Concentration Pathway

RDRSv2: Regional Deterministic Reforecast System version 2

REDCAPP: Reanalysis Downscaling Cold Air Pooling Parameterization

RH: Relative humidity

RHBN: Reference Hydrometric Basin Network

RMSE: Root-mean-square error

RPN: format of standard files used at ECCC

RTS: Retrogressive Thaw Slumps

RX1day: Maximum 1-Day Total Precipitation

RX5days: Maximum 5-Day Precipitation

S14FD: S14 retrospecitive meteorological forcing dataset

SCD: Snow Cover Duration

SCDNA: Station-based serially complete dataset for North America

SCE: Snow Cover Extent

SDII: Simple precipitation intensity index

SIKU: Indigenous Knowledge Social Network

SLP: Sea-Level Pressure

SMAP: Soil Moisture Active Passive

SmartICE: Sea-ice Monitoring and Real-Time Information for Coastal Environments

SMOS: Soil Moisture and Ocean Salinity

SMMR: Scanning Multichannel Microwave Radiometer

Snow CCI: Snow Climate Change Initiative

SSM/I: Special Sensor Microwave/Imager

SSMIS: Special Sensor Microwave Imager/Sounder

SSP: Shared Socioeconomic Pathway

SWAT: Soil and Water Assessment Tool

SWE: Snow Water equivalent

SWOT: Surface Water and Ocean Topography

T_{dw}: Dew point temperature

Tmax: Daily maximum temperature

Tmean: Daily mean temperature

Tmin: Daily minimum temperature

TRMM: Tropical Rainfall Measuring Mission

UCAR: University Corporation for Atmospheric Research.

UDEL: University of Delaware

ULS: Upward-Looking Sonars

UNEP: United Nations Environment Programme

USDA: United States Department of Agriculture

UQAM: Université du Quebec à Montreal

WCRP: World Climate Research Programme

WHERD: Watershed Hydrology and Ecology Research Division

WMO: World Meteorological Organization

WMS: Web Map Service

WorldClim2: Version 2 of World Conservation Monitoring Centre high spatial resolution global weather and climate data

WSC: Water Survey of Canada

WWIC: Weather, Water, Ice, and Climate services

XML: Extensible Markup Language

1 Introduction

Lead authors: Emilia Diaconescu (CCCS/ECCC), Lindsay Matthews (CCCS/ECCC)

Contributors: Ryan Hennessey (CCCS/ECCC) and Paul Kushner (University of Toronto)

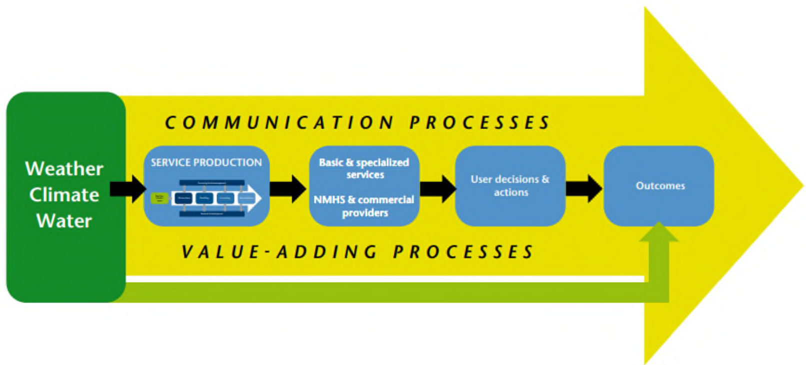
1.1 Background

Warming due to anthropogenic climate change is amplified at northern latitudes with profound implications for Northern communities, ecosystems, and socio-economic development. This points to an acute need to improve resilience to climate change in the Canadian North[1], particularly in light of factors such as remoteness and the dependence on cold-climate-based infrastructure and cold-climate cultural traditions. There is an increased demand at national and provincial levels for putting in place structures for weather, water, ice, and climate (WWIC) *services* that aims at supporting stakeholders in building their resilience and adaptive capacity to address climate change risks.

Climate services are often described as the bridge between climate data developers, whose work focuses on advancing science and knowledge of the climate system, and climate data users. The starting point of this bridge is constituted by a proper understanding of the availability of data and its quality. On the other side, the demand for data from users is important for informing for which purpose and in which form the data should be provided. Therefore, the conceptualization of WWIC *services* is premised on the idea of 'user needs' (WMO, 2011) and effectively addressing WWIC user needs requires multidisciplinary communication through the entire chain of development and delivery of services (Figure 1.1 a; Anderson *et al.*, 2015). WWIC users include all people, regardless of their sectoral, academic, or professional affiliation, who have interacted with climate information, ranging from using broad information to applying detailed climate variables data into their work (Skelton *et al*., 2019). The starting point in the WWIC value chain is the service production process, which is part of the broader and larger communication process. Service production (Figure 1.1 b; Anderson *et al*., 2015) starts with understanding which data exist and how they can be reliably transformed into a product that responds to user needs. Communication with researchers at this early stage is very important to properly select the best data and method.

[1] For the purposes of this project, "the North" or "northern" is used in the context of where the terrain is caracterised by extended periods of freezing temperatures and associated environmental conditions. Administratively, northern Canada, or "the North," consists of the three territories – Yukon, Northwest Territories, and Nunavut as well as Nunavik and Nunatsiavut. In this project, however, a broader context for "the North" will be inclusive of transboundary datasets that may encompass northern areas of the other provinces that are not traditionally included as "the North".

a) WWIC service value chain



b) WWIC Service production

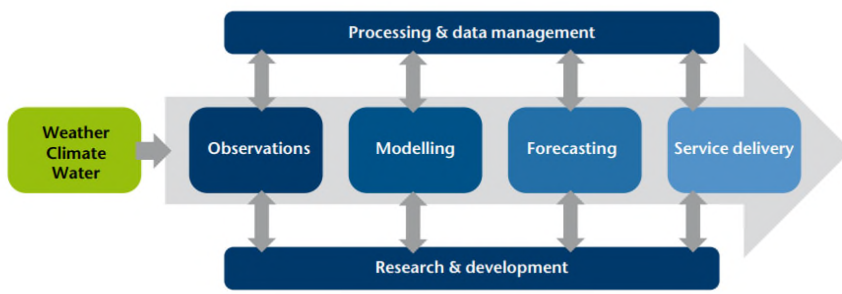


Figure 1.1 Components of a) the WWIC service value-adding chain and b) the WWIC service production and delivery system [Source: Anderson *et al.*, 2015]

In Canada, the Canadian Centre for Climate Services (CCCS) of Environment and Climate Change Canada (ECCC) is working in collaboration with regional climate organizations to provide climate services for the entire country. The project that has led to this report constitutes <u>the first step in a series of steps</u> towards developing climate services for the Canadian North. The focus of this work is on understanding which data exist and their quality and limitations for future development of products for climate risk and climate-change adaptation decision-making and planning in the Canadian North.

Developing climate services for stakeholders in the Canadian North is a challenging task. Stakeholders include environmental regulators, local governments, Indigenous organizations, and economic development organizations. The needs of these stakeholders vary broadly and reflect interests in both the terrestrial and marine environments. Users may originate from sectors such as transportation (ice roads, airports, ports, shipping), community planning, fisheries, tourism, building infrastructure, health, or primary resource extraction (mining, oil, gas, and forestry). All these stakeholders have different data needs that span a variety of timescales from immediate (minutes to hours), to daily, sub-seasonal, seasonal, decadal and beyond. This diversity of applications over a vast geographic area with historically limited environmental monitoring contributes to the challenge of delivering user-driven WWIC service in the region. Previous user needs assessment in the North (e.g., Northern Climate Exchange, 2017; Savanta, 2019; Jeuring *et al*., 2020; Wanger *et al*., 2020; Simonee *et al*., 2021) have identified numerous challenges related to using both historic and projected WWIC information:

- access to data
- location of data in common or centralized repositories
- knowledge of how to use climate projections arising from climate modelling and how to incorporate this information into adaptation strategies
- developing in-house capacity or local resources to apply WWIC information,
- information technology (IT) infrastructure (e.g., lack of computing/software resources or high-speed Internet)
- obtaining community-specific or site-specific information
- integration of Inuit Qaujimajatuqangit or Indigenous Traditional Knowledge.

Many of these challenges stem from complex geographical, social, political, and economic constraints. The first two data challenges stem in part from limited long-term, quality-controlled, and scientifically assessed historical climate data relevant to northern communities and the large variety of scales that define the demand for climate data. There are also limited climate-change scientific analyses tailored for the particular context of the Canadian North, which also presents a challenge in addressing some of the other needs listed above (e.g., knowledge on how to use climate projections).

Therefore, understanding which climate data (historical and climate projections) exist in Canadian North, climate data limitations and in what context climate data can be used represents an important first step in the complex task of developing climate services for the Canadian North.

1.2 Objective of report and target audience

The objective of this report is to identify, inventory, and characterize existing datasets for future development of products for various regional and local applications related to climate-change adaptation decision-making in the Canadian North. Therefore, the report is not addressed directly to decision makers and communities. The primary audience of this report is constituted by climate services organizations, academics, consultants and any other producers of value-added WWIC products.

Although the scope includes both observation-based historical climate data and modelled historical and future climate projections, given available time and resources, the primary focus of the report is on historical climate data, for which a more in-depth assessment is presented. Climate research activities, production of new datasets, the dissemination of data and consideration of Indigenous Traditional Knowledge are outside the mandate of this work at this time. Recommendations on future undertakings are provided as part of this project.

The characteristics of datasets retained for analysis are tabulated with links to documents and websites, many of which are included as appendices. These describe the metadata using a standard format, contain links to download the data, and include additional details on the methodology used to develop the dataset.

1.3 Methods and approach

1.3.1 Establishing the Northern Climate Data Working Group

A 'Northern Climate Data Working Group' was first brought together to advise and help CCCS on how to identify, evaluate, and select climate datasets for various regional and local applications in the Canadian North to support climate change adaptation decision-making. On December 31, 2021, the Working Group counted 15 members representing a wide range of organizations, including Carleton University, Environment and Climate Change Canada, Government of Northwest Territories, Ouranos, University of Calgary, University of Manitoba, University of Northern British Columbia, University of Toronto, University of Victoria, University of Waterloo, and the Yukon University Research Centre. Sixteen (16) contributors helped the Working Group by developing some of the base material for the report. All members and contributors are listed in Section 6 of the report. The Canadian Standards Association operating as CSA Group was contracted to provide the Secretariat for the project. Apart from the Secretariat, all support for the project extramural to CCCS was provided in-kind.

1.3.2 Organization and Meetings

The Working Group met virtually monthly from December 2020 to April 2021 and the meeting frequency increased from April 2021 to December 2021. Terms of reference for the group were finalized in March 2021, reflecting the need to clarify the scope and the working plan. To help coordinate the work and align with the expertise and experience of individual members, in April 2021 the Working Group was divided into four different topic-area focused subgroups:

- Meteorology subgroup
- Snow and hydrology subgroup
- Sea ice subgroup
- Permafrost subgroup

Leaders of each subgroup were encouraged to bring in additional experts to contribute their assistance. The primary focus of these subgroups was on historical climate data rather than climate model output, and this is reflected in the space devoted to each component in the report. The Working Group placed more weight on the assessment of observational-based data sets before undertaking climate-model based analysis because observational analysis is a required input to analysis of climate models, and because climate model output is generally more standardized (and easier to describe) than observational databases.

1.3.3 Selection of priority variables for assessment

Each subgroup was tasked to identify the key variables to be analyzed in this current project and the variables suggested for future work. This selection sought to balance potential user needs with practical availability of data.

Table 1.1 List of climate variables analyzed

Subgroup	Variables analyzed in this report	Variables suggested for future work
Meteorology	• Air surface temperature, • Total precipitation, • Surface humidity, • Surface wind speed and direction	• Surface radiation (shortwave and longwave) • Freezing rain and ice accretion • Snowfall, • Cloudiness
Snow & hydrology	• Snow depth, • Snow water equivalent, • Snow cover, • River discharge	• Rain on snow, • Glaciers, soil moisture, • Lake temperature, • River and lake water level, • Lake ice duration.
Sea ice	• Sea ice concentration, • Sea ice thickness, • Sea ice drift	• Sea level, • Sea surface temperature, • Salinity, • Wave height, • Storm surge
Permafrost	• Ground temperature, • Subsurface ice content, • Permafrost extent • Subsidence and active-layer thickness, • Landform inventories	

1.4 Report structure

The report is structured as follows. Chapter 2 provides general information on the principal data sources for historical observational data (Section 2.1) and for modelled data (Section 2.2). Chapter 3 provides the inventory of the historical observational climate data, and it is divided in sections focusing on the four topic areas (Meteorological data in Section 3.1; Snow and hydrology data in Section 3.2; Sea-ice data in Section 3.3; and Permafrost data in Section 3.4). In each section, dataset general information is summarized in tables, many of them presenting links to documents or/and websites with detailed descriptions. Each section also provides guidance on the selection of datasets for different applications and summarizes their limitations. Chapter 4 provides the inventory of existing ensembles of climate simulations with details regarding the four topic areas presented separately in subsections. Chapter 5 summarizes the key recommendations, and Chapter 6 provides the list of Working Group members and contributors. The report ends with a large number of annexes, which describe the metadata for many of the datasets analyzed in the project using a standard format. The standard format was decided by members during initial meetings. It was also decided that it is of interest to develop distinct descriptions for each type of variable and each dataset, instead of describing only the dataset. For example, for NARR data, there are five (5) annexes available for 5 types of variables (e.g., temperature, precipitation, humidity, wind and snow). Accordingly, the annexes are grouped by type of variable and the tables presented in the report include links to the appropriate annex.

<u>References - Introduction</u>

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2 General description of data sources

2.1 Measurements and model-observational blended products for the Canadian North

Lead authors: Emilia Diaconescu (CCCS/ECCC) and Paul Kushner (University of Toronto)

This report principally considers the following data sources for the Canadian North: station data (overview in Section 2.1.1), gridded observations (Section 2.1.2), reanalyses (Section 2.1.3), and remote sensing datasets. These sources represent the distinctive ways in which climate data is provided, as either point-specific (e.g., station data, site measurements) or gridded (e.g., reanalyses, regridded observations, remote sensing gridded datasets). Point data convey information specific to an identified location where measurements are taken, while gridded data provide information representative of the average or typical values within the area or volume covered by a set of grid cells. To repeat, **variables in a gridded product should generally be interpreted as average values of the grid cell and not as point measurements.** To more precisely relate grid values to local measurements requires the use of downscaling methods that will be mentioned in connection with specific applications.

2.1.1 Station data

Weather stations and field sites provide the most reliable and accurate measurements of several of the variables considered in this report, such as temperature, precipitation, humidity, wind, snow depth, snow water equivalent, river discharge, etc.. However, station infrastructure and maintenance are costly and require deep technical expertise to maintain, or, in the case of field sites, provide project-specific coverage. This limits the number and distribution of measurement stations in the Canadian North compared to the Canadian South. For example, weather stations in the Canadian North are located on the coast or in valleys, and there is a limited number of stations in interior land regions (see Figure 2.1 that shows the location of weather stations across Canada as of September 2016, and Section 3.1). When using multiple-decade weather-station data, climate analysis must account for missing values, and records that cover different periods. Changes in instrumentation, location, and sampling must be taken into account to avoid the occurrence of spurious non-climate related variations. For example, in 1961 there was a change in the observing time at principal stations which affected daily minimum temperature records.

The adjusted and homogenized Canadian climate dataset (AHCCD, Mekis and Hogg, 1999; Mekis and Vincent, 2011; Vincent *et al*., 2012, 2020) of ECCC resolves some of these issues for several climate variables of focus in this report. In this product, daily or monthly observations from nearby sites are often merged into a single record to create a longer time series, and records were tested for artificial shifts (that could be caused by changes in the location of the stations) and homogenized (i.e. adjusted to account for artificial shifts). **Presently, this group recommends that AHCCD be used as the best dataset to analyze local climate evolution over a long period of time in Canada.** This reflects current best practice, since AHCCD is often used to validate other gridded datasets and models. Detailed descriptions of records from AHCCD are provided in Annexes (i.e. annexes for temperature, precipitation, and wind). Note that the number of locations with available AHCCD data is in general small in the Canadian North (even fewer locations than for the Meteorological Service of Canada (MSC) stations as a whole).

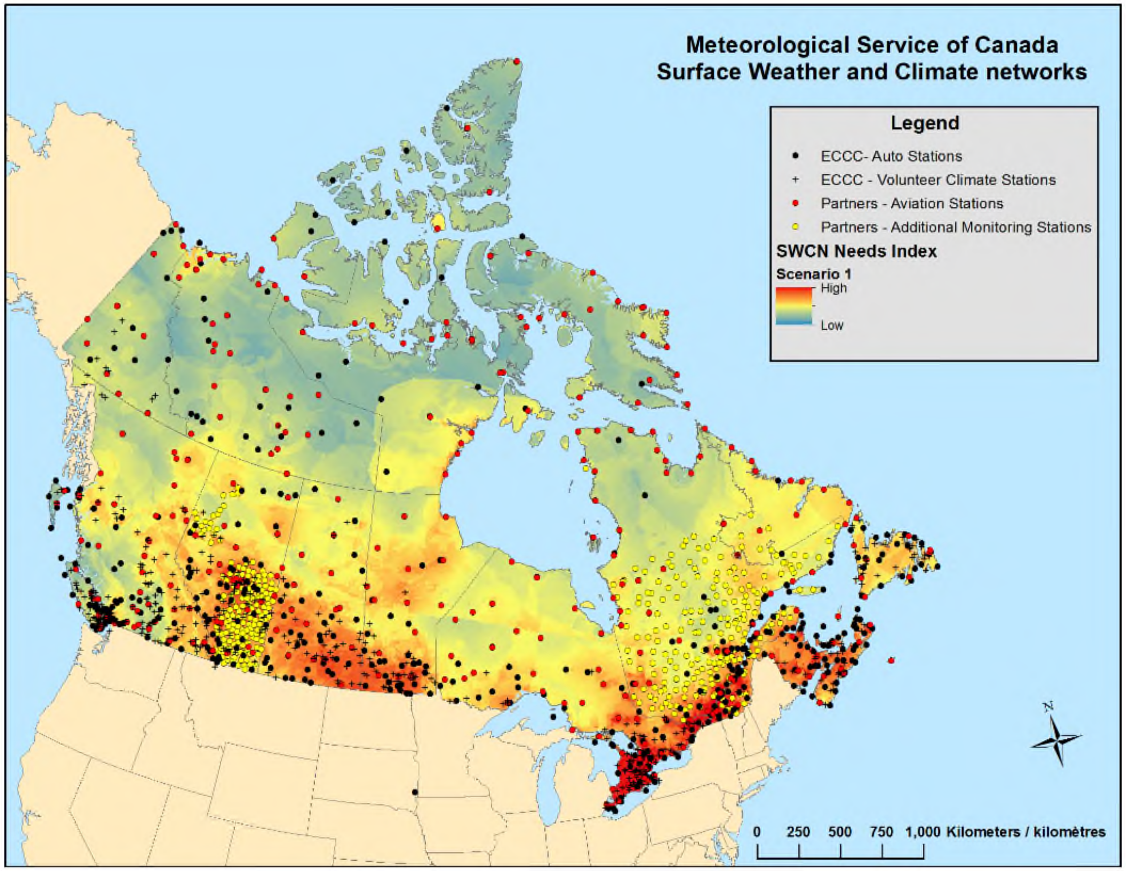

Figure 2.1. Surface weather stations across Canada, as of September 2016, with a Needs Index map in the background. For further details on station network evolution see Mekis et al. 2018. [Source: Mekis *et al*., 2018].

2.1.2 Gridded station-based data

Point data from stations can be transformed to gridded products using a range of mathematical and statistical interpolation methods. These methods range from simpler, such as inverse distance weighting, trend surface analysis, splines (used in ANUSPLIN, and WorldClim2), Thiessen polygons, to more complex, such as krieging or regression models (used in PNWNAMET). While provided with nominal spatial resolution as fine as

1 km (e.g., Daymet, WorldClim2), the suitability of these datasets in the Canadian North has generally not been well analyzed. The primary factor that influences the skill of interpolation methods is the density of the station network, with topographic complexity, and how this is taken into account in the model, being a second important factor (Hofstra *et al*., 2008). Only some of the gridded datasets account for elevation effects (e.g., ANUSPLIN, PNWNAMET, WorldClim2, Daymet). As the mean distance between the stations that are gridded becomes larger than 100 km, the effectiveness of all interpolation methods degrades. Such effects are pronounced in the analysis of temperature and precipitation extremes, as has been demonstrated for European station data (Hofstra *et al*., 2010), for which interpolated daily values are systematically reduced relative to the 'true' average of the area. This strongly affects the climate variables with a relatively high spatial variance, such as precipitation relative to temperature, but can also affect variables such as surface temperature in mountainous regions of strong topographic variability. Large parts of the Canadian North, with prominent topography in Western Canada and sparse inland station distribution, are in this situation (Figure 2.1). Spatial and time variability is greater in high topographic regions and at daily time steps, but this effect decreases for monthly and annual means.

Therefore, despite their past use, the use of datasets obtained with gridding methods for regions of the Canadian North that feature a sparse network of stations should be approached cautiously. Local conditions should be considered when selecting the dataset obtained with a gridding method. For example, applications with a good coverage of stations over a small watershed could consider the use of a gridded dataset. If the region has important topographic variations, a method that incorporates elevation information should be used (see Section 3.1 for further discussion on these points related to temperature). For regions with a small number of stations, hybrid products that make use of assimilation of observations and model output (e.g., RDRSv2) could be a good alternative to gridded observations.

Because of the demand for higher-resolution products in many applications, this report generally focuses on recent versions of datasets that are provided at a nominal spatial resolution finer than about 60 km/0.5°, covering the Canadian North or parts of the Canadian North. With our interest in using this data for climate applications, we retained only datasets with a duration spanning a decade or more. Nevertheless, the concerns above regarding use of interplated data from sparse networks should be borne in mind.

2.1.3 Reanalyses and reanalysis-based datasets

Reanalyses represent a valuable complement to gridded station data based solely on infilling between stations. Reanalyses are produced by assimilating observational data (e.g., radiance information from available satellites, in situ observations, including land stations and marine observations, aircraft, rawinsonde, and profiler data) into numerical weather prediction models over long historical periods (see Cullather *et al*., 2016 for a comprehensive review). Reanalyses offer a large number of meteorological and land-surface variables that preserve the physical relationships between them and cover a long period and spatial scales from regional to global in a uniform and self-consistent manner. Available at increasingly fine resolution, they represent a valuable source of data for impact models and climate models that require the input of several variables with physical self-consistency. Practitioners should pay careful attention to the horizontal resolution of each reanalysis product (e.g., 0.25 degree to 1 degree) and recognize the limitations of its temporal sampling (e.g., 1h, 3h, 6h, daily).

The quality of observations, of the assimilation process, and the underlying numerical model determine the accuracy of the reanalysis product. Where observations are relatively sparse, reanalyses output is more strongly influenced by the forecast model. As previously noted, the Canadian North has a limited number of in-situ observations. Additionally, satellite sensors have difficulty in profiling the lower atmosphere over snow- and ice-covered surfaces, and geostationary satellites do not cover the high latitudes (Cullather *et al.*, 2016). Consequently, the observations provide less of a constraint on reanalyses over the Canadian North compared to the Canadian South. It should also be noted that if at a certain moment a new type of observation is introduced into the data assimilation scheme (e.g., new satellite data) the output will subsequently be more constrained by observations than in the previous period. This may produce artificial trends or variability in the estimated variables.

Accounting for their known limitations, reanalyses, especially those accompanied by quantification of uncertainty of state estimates, remain the best and most consistent continuous estimates of the state of the atmosphere, and in some cases, the only estimates that are available (Cullather *et al*., 2016). For example, seasonal forecasts over the Arctic are presently verified by comparing model estimates with reanalyses data for many variables, including 2 m temperature (see presentations on [Arctic Regional Climate Centre (arctic-rcc.org)]). In this report, our discussion on reanalysis products focuses on four important centers that produce global atmospheric reanalyses: the European Centre for Medium-Range Weather Forecasts (ECMWF), the National Aeronautics and Space Administration (NASA), the National Centers for Environmental Prediction (NCEP) and the Japan Meteorological Agency (JMA). We will frequently refer to ECMWF's ERA5, NASA's MERRA and MERRA-2, NCEP's CFSR, and JMA's JRA-55 reanalysis products (see *List of Acronyms* for acronym definitions).

The need to refine the spatial resolution of reanalyses and optimize performance in specific regions has prompted the introduction of regional reanalyses and re-forecasting using fine resolution limited-area numerical prediction models (e.g., NCEP's NARR, ASRv2 developed by Byrd Polar Research Center, ECCC's RDRSv2). Those approaches simulate the atmosphere and/or land state at a finer resolution than the global reanalyses, and continuous assimilation of observations will limit the model tendency to drift and thereby limit errors relative to dynamical downscaling approaches. From the three regional products that cover the Canadian North, NARR has coarser spatial resolution than global reanalysis ERA5 (32 km comparative to approximately 28 km), while ASRv2 (15 km) and RDRSv2 (10 km) are new products that cover just the recent period.

In addition, global atmospheric reanalyses can be used to force advanced land surface models at a finer resolution (e.g., MERRA-Land, ERA-Land). Observations in land surface models have an indirect influence through the atmospheric forcing used to run the land model; this indirect influence can bring about some drift of the model state. On the other hand, self-consistency of physical laws and finer resolution, providing accurate incorporation of terrain influences, are strengths of this approach. ERA5-Land, for example, provides 2 m temperature at 10 km spatial resolution, while the corresponding driving variable from ERA5 is at approximately 28 km.

Other approaches to obtain high-resolution data consists in downscaling of global atmospheric reanalyses with, or without, bias correction (e.g., AgMERRA, AgCFSR, AgERA, GMFD, CRU JRA, S14FD). AgMERRA (approximately 28 km; based on MERRA reanalysis), AgCFSR (approximately 28 km; based on CFSR reanalysis) and AgERA (10 km; based on ERA reanalysis) were developed to be used as input for agriculture and agro-ecological studies. Therefore, sub-hourly data for several surface meteorological data were aggregated at a daily time step (for air temperature, the daily data is provided for the mean, minimum and maximum daily temperature). GMFD (approximately 28 km; based on NCEP/NCAR reanalysis), CRU JRA (approximately 56 km; based on JRA-55) and S14FD (approximately 56 km; based on JRA-55) were developed to serve as forcing datasets for different impact models. All those products use as a downscaling approach interpolation methods to obtain the increase in nominal resolution. Information about specific variables available from all those reanalyses is provided in Chapter 3.

Practitioners should be aware of which data is assimilated in a given reanalysis; while this is documented in the products compiled here, identifying data sources used in assimilation remains a challenge for new and even experienced users. One general point is that even if reanalyses assimilate many observations, the greatest number of observations are from satellite data, which began to be collected in earnest in the early 1970’s and became a regular part of operational assimilation from the start of the ‘satellite era’, 1979. More specifically, MERRA, CFSR, and NCEP do not assimilate surface temperature and precipitation measurements at stations. It should also be noted that, ERA5, NARR, and RDRSv2 assimilate in some ways surface temperature from stations. JRA-55 assimilates indirectly some surface temperature measurements, as well as passive microwave for snow cover, but not precipitation (Kobayashi *et al*., 2015). AgMERRA, AgCFSR, GMFD, CRU JRA and S14FD, downscale surface variables from the global atmospheric reanalyses at a higher resolution and/or correct them with surface station data. Such corrections and the downscaling process can affect the relationship between variables for each dataset. Therefore, for the Canadian North, the corrections do not a priori assure a better dataset than those from the “parent” global reanalyses or from regional products with similar or finer spatial resolution (e.g., ERA5, ASRv2, RDRSv2, ERA5-Land), which as stated previously maintain self-consistency corresponding to the resolution of the parent model. AgMERRA, AgCFSR, GMFD datasets were not updated since 2014 and there are no plans to continue them. AgERA5 is a new product based on ERA5. AgERA5 does not correct the ERA5 bias; it just aggregates to daily time steps at the local time zone and corrects the fields towards a finer topography using regression equations trained on ECMWF's operational high-resolution atmospheric model (HRES) at a 0.1° resolution.

In the peer-reviewed literature, comparison of reanalysis products with gridded station products (Section 2.1.2) is commonly carried out but is subject to representation errors (Keller and Wahl, 2021; Cullather *et al.*, 2016), since the area average representation of gridded datasets strongly depends on the density of observations. Comparison of reanalysis with in-situ measurements and stations (Section 2.1.1) is also subject to representation errors, especially in regions with complex topography or surface heterogeneity (Keller and Wahl, 2021). Comparisons of these kinds should be done using independent, validating data (observations that are not integrated or assimilated by the reanalysis), which in some cases it is difficult to find. Validation against data that is assimilated will tend to give good results at those specific locations but does not guarantee good results far from those points.

Overall, practitioners should keep in mind the following key points related to use of reanalyses:

- Caution should be exercised in applying reanalysis to the Canadian North and in particular should ensure a good characterization of how different reanalyses represent variables of interest close to station or field measurement locations, as sparse as they are. It can be expected that reanalyses are closer to station observations at those locations but diverge in regions without stations.
- Care should be taken when using reanalyses to define trends or variability over a long period of time as the changes in the amounts and types of observational data that is assimilated by them may produce artificial trends or variability along the dataset time series.
- The overarching conclusion of Przybylak and Wyszyński (2020) (see also Serreze and Barry, 2014) should also be considered: ʹʹdue to discrepancies in reanalyses, it is necessary to take under consideration the averages from multiple reanalysis' data to properly analyse the mean state of the Arctic climate system.ʹʹ

2.2 Climate model simulations of historical and projected future conditions for the Canadian North

Lead Authors: Paul Kushner (University of Toronto) and Elaine Barrow (CCCS/ECCC)

Output from climate models is a distinctive but critical data source for climate analysis and adaptation decision-making; its use in the Canadian North poses a technical challenge to many applications. Climate model output covers historic and future, or 'projected', conditions (Eyring *et al*., 2016). Historic climate model output can be assessed or compared to historic climate data from stations, reanalysis, and other sources. Such a comparison needs to account for climate model experiment design; generally speaking, climate model output cannot be taken as being precisely equal to past observed conditions, for reasons to be discussed below, but it must represent well the statistics of the past climate. A comparison between climate model output and observed historic data can furnish an assessment of climate-model suitability for a given application. If the climate model output is found to be suitable for an application, the model-observation comparison also furnishes numerical adjustments to better align climate model output with regional or local conditions. In applications, this kind of calibration (downscaling) typically targets point/station-level data or gridded data at a finer resolution than the climate model. Projected climate data can then be combined with these adjustments to yield an analysis of future conditions, for a given application.

Climate models represent past, current, and projected climate variability and change in a physically consistent manner. Over several decades, climate model realism has increased alongside improving knowledge of the climate system and advancing computing technology. Basic physical climate models are called GCMs, which stands for global climate models or general circulation models. GCMs comprise complex computer algorithms and software that are based on the principles of fluid dynamics, thermodynamics, and "radiative transfer", that is, the flow of electromagnetic radiation through the sun-atmosphere-earth system. A GCM represents, on a computer, the mathematical equations of the physical processes of the atmosphere, ocean, cryosphere and land surface, and the interactions and feedbacks between them. The Earth-atmosphere-ocean system is divided into thousands of three-dimensional grid cells, each typically with a horizontal resolution of between 100 and

300 km and containing the mathematical equations describing how energy and materials are transferred through the climate system (Figure 2.2). There are generally between 30 to 40 vertical layers in the atmosphere, three to 10 layers in the soil and between 40 and 50 layers in the ocean.

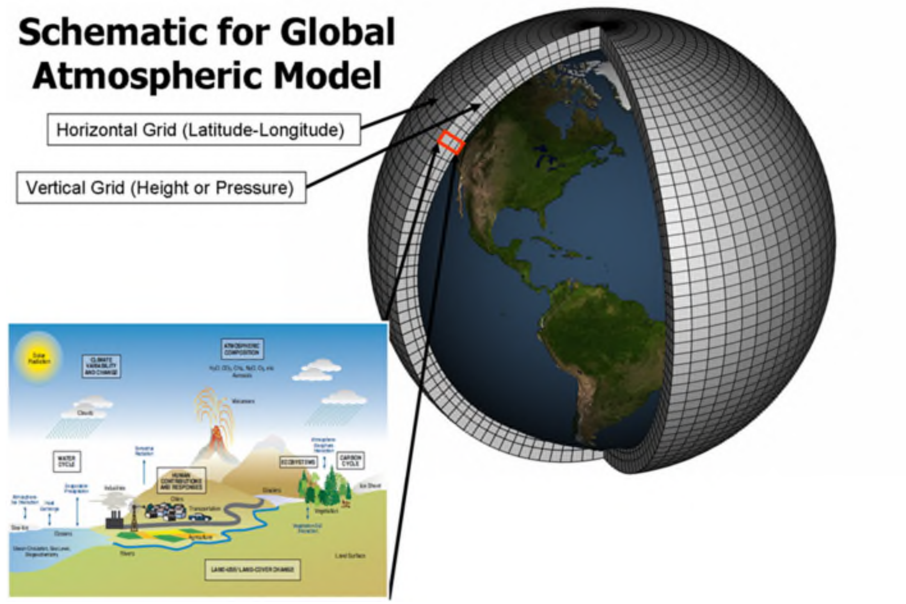

Figure 2.2: Simplified representation of a climate model. The climate processes occurring in each of the many thousands of grid cells are represented by equations based on the fundamental laws of physics, fluid motion and chemistry. [Source: Cannon et al., 2020]

Besides their resolution, GCMs are distinguished by the complexity and completeness of climate system components they represent. Earth System Models (ESMs) represent the most recent generation of climate models. They have all the components of a typical GCM but also include biogeochemical cycles, which describe the transfer of chemicals between living things and their physical and biological environment. ESMs, therefore, can include and explicitly represent the carbon and nitrogen cycles, atmospheric chemistry, ocean ecology and changes in vegetation and land use. Including these biogeochemical cycles means that marine and terrestrial ecosystems (e.g., forests) within the ESM can respond to atmospheric CO_2, temperature and rainfall. This allows us to model the fate of carbon from CO_2 and other greenhouse gases (GHGs) emitted into the atmosphere through fossil-fuel combustion.

Despite the complexity of climate models, the models are not perfect. Although they represent our best understanding of how the Earth-atmosphere-ocean system works, the climate system is highly complex and it remains fundamentally impossible to model all of its processes. The relatively coarse spatial scales of the models limits explicit modelling of processes that occur at finer-than-grid scales, such as cloud processes, convective processes, and turbulence. In these instances, the physical, chemical and biological processes are parameterized, i.e., their effects are represented by approximations whose design varies across different models.

No climate model exists in a vacuum. The international climate modelling community, which consists of many climate modelling groups running dozens of GCMs and ESMs, organizes itself under the auspices of the Coupled Model Intercomparison Project (CMIP), which is part of the World Climate Research Programme (WCRP). While these climate models are all based on the same physical principles, each group parameterizes the same processes in a slightly different manner, and makes different choices about model structure and horizontal and vertical resolution. In addition, modelling groups make design decisions about which processes to include or not in a given model, which provides another source of model diversity. This results in different models responding in a range of ways to the same forcing, such as anthropogenic GHG forcing. At this point, the present approach to deal with this ‘’**uncertainty in model representation of the climate**’’ is the pluralist approach that focuses on using ensembles of many climate models (Meeht *et al.*, 2007), selected by various means according to the application [e.g., Massonnet *et al*., 2012; Evans *et al*., 2013; Cannon, 2015; Cook *et al.*, 2017; Herger *et al*., 2018; Docquier and Koenigk, 2021]. However, there are limitations to this approach and alternative approaches have been suggested, as for example the unified approach which focuses more resources on fewer models with finer resolution and improved overall representation of all processes (Hurrell *et al*., 2009, Palmer, 2012).

As for any mathematical model, climate models need initial conditions as input to initialize the computations and boundary conditions that represent external parameters and variables. Because it is impossible to know the exact state of the climate at one moment in time and because the climate system is a chaotic system (a small difference in initial conditions will result in a new solution – e.g., the timing of oscillations in atmospheric and ocean circulation, like El Niño-Southern Oscillation or the Arctic Oscillation, will differ for each model run with slightly different initial conditions), it is not possible to simulate the time evolution of the climate system in a deterministic way even if the climate model were able to perfectly capture the system. The approach to deal with what is named ‘’ **internal climate variability**’’ is to run multiple simulations from each model. While an individual simulation or ‘realization’ from one model cannot predict exactly the timing of various phenomena in the climate system, their statistical characteristics can be potentially well characterized by a sufficiently large ensemble of realizations. Consequently, each climate center has submitted to CMIP a multiple number of realizations with the same model. **Thus, because of internal climate variability, a model that is run over the historic period is inherently incapable of precisely representing historical day-to-day weather conditions.** However, a GCM can be considered to be realistic to the extent that its climate statistics are consistent with observed climate statistics.

Presently, ensembles with multiple realizations of different GCMs and ESMs are used to simulate the pre-industrial climate and the historical evolution of the climate, as well as for creating future climate projections. Given the current complexity of ESMs, an enormous range of climate- and environment-related variables can be output for each ESM grid cell to describe the physical state of the atmosphere, land surface and ocean. Although the actual model simulations are performed typically at time steps of 10-20 minutes, storage considerations mean that data are not archived at such a high time resolution. Instead a tiered approach is employed in which a select few variables are stored on hourly to three hourly timescales and an increasing number of variables are stored on daily and monthly timescales. Model output is in principle available for all the subdomains of interest for this report, including meteorological, snow/hydrology, sea ice and, to a limited extent, permafrost-related variables. However, all model output needs to be evaluated for suitability of the process and spatio-temporal representation depending on the applications.

Climate model results share the same sampling considerations as reanalyses data (Section 2.1.3). Because, as for reanalysis products, GCM/ESM output is gridded, climate model comparison to observations should account for local factors, observational density, and adjustments for specific sites (such as topography not explicitly represented in GCMs).

The enormous and growing amount of model output available presents both challenges and opportunities for applications to the Canadian North. Observational data limitations described in Section 2.1 for the Canadian North suggest that assessment of the realism of GCMs and ESMs remains a serious challenge in this region. Although examples of such applications exist at least on large scales (e.g., Guo and Wang, 2016, Bush and Lemmen, 2019; Mudryk *et al*., 2021), there are fewer examples of downscaling ESM data for applications of interest to northern communities (e.g., Teufel and Sushama, 2019; Barrette *et al*., 2020). Finally, finding the best method of selecting among ESMs for suitability of purpose remains a complex issue for the Arctic (e.g., Massonnet *et al*., 2012). But on balance, given the increased attention to representation of cold climate processes in polar regions, there are now improved opportunities to exploit several generations of ESMs to gauge consistency and robustness of climate projections in the Canadian North.

We provide the following overall guidance that practitioners should keep in mind related to use of climate model output:

- Prior to using climate model outputs in applications for future projections in the Canadian North, a good understanding of how processes are represented in the climate models and a comparison to observed historical climate data should be undertaken. By design, the results of climate models covering the historical period should not be equal to the observations at each instant. Instead, the statistics of climate model outputs should be compared to observed statistics, using multiple realizations of a given climate model, as available.
- Because GCMs and recent ESMs differ in resolution, process representation, etc., it is recommended to use multiple GCMs/ESMs in any given analysis. GCM/ESM selection depends on application.
- Care should be taken when using climate model output to define trends or variability over a long period of time as the effects of internal variability can be significant [Deser *et al.*, 2016], especially at high latitudes; trend analysis requires an assessment over a large ensemble of realizations.

Details about climate model forcing, other aspects of experimental design, the ensembles available for download, discussion of limitations, and consideration of present best practice in applications for the Canadian North are presented in Chapter 4.

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3 Assessment of northern historical climate data

3.1 Meteorological data

Lead Authors: Emilia Diaconescu (CCCS/ECCC), Marco Braun (Ouranos) and Paul Kushner (University of Toronto)

Contributors: Aleksandra Elias Chereque (University of Toronto), Jennifer Lukovich (University of Manitoba), Michael Allchin (University of Calgary), Carrington Pomeroy (CCCS/ECCC), Kenneth Chow (CCCS/ECCC), Housseyni Sankare (CCCS/ECCC).

3.1.1 Introduction

This chapter presents the list of available datasets for the meteorological variables that are the most important for climate change adaptation studies in the Canadian North.

Human activities are highly impacted by the changes and variations in the physical properties of the layer of air situated near the surface of the Earth. Those changes are of interest at daily, seasonal and climate scales. Table 3.1 describes the seven Essential Climate Variables identified by the Global Climate Observing System (GCOS) for worldwide monitoring, in the category of Surface Air Variables.

Table 3.1 Essential Climate Variables identified by GCOS for worldwide monitoring, in the category of Surface Air Variables (Source: https://www.climate.gov/maps-data/primer/air-atmospheric-climate-variables)

No.	Name	Definition and description of basic measurements at meteorological and climate stations
1	Near-surface temperature	Near surface air temperature is the temperature of the air around us, generally measured at a height of around two metres above the surface (also named **2 m temperature**), reported in degrees Celsius (°C). Measurements are made using thermometers, shielded from direct solar energy. The most common type of thermometer is the liquid-in-glass thermometer. More precise thermometers measure air temperature by checking how much electricity can pass through a sample of pure metal.
2	Total precipitation	**Total precipitation** is water in liquid or solid form that falls to Earth's surface from clouds. It can be in the form of drizzle, snow, ice, freezing rain, or hail. Rain gauges are the most common instrument used to measure rainfall (liquid precipitation). A rain gauge is an open-at-the-top container that is calibrated to measure the depth of liquid caught, which is reported in depth units (volume/unit area) of millimetres (mm), metres (m) or inches (in).
3	Surface wind speed and direction	Wind is air in motion relative to the Earth's surface. It is a vector quantity, meaning it is described in terms of both speed and direction of motion. Anemometers are used to measure wind speed, which is reported in metres per second (ms^{-1}). Wind vanes and windsocks measure wind direction. Wind directions refer to where the wind is coming from; for example, a north wind is coming from the north and blowing towards the south. Winds are most commonly

No.	Name	Definition and description of basic measurements at meteorological and climate stations
		described using **the eastward and the northward components** (the horizontal component of wind moving towards the east and towards north).
4	Water vapour	Water vapour is water in the atmosphere in its vapour (gaseous) form. Half of the water vapour in the atmosphere is found within two kilometres of the Earth's surface. **Absolute humidity** reported in grams of water vapour per kilogram of air (g kg^{-1}) or **specific humidity,** in grams of water vapour per kilogram of dry air (g kg^{-1}), represent common measures of the amount of water vapour in air. **Relative humidity** reported as percent (%) of water vapour pressure compared to a saturated (condensed) vapour pressure, tells how much water vapour is in the air relative to the amount it has the potential to hold at a given temperature. The instrument used to measure water vapour content in the air is called a hygrometer. The simplest type of hygrometer is made from human hair, which swells and lengthens as it absorbs water vapour from the air.
5	Atmospheric pressure	Atmospheric pressure is the weight-per-unit area of the column of air above it. As gas molecules are always moving in every direction, air pressure is the same in all directions. Barometers measure air pressure. The most common type of barometer is a sealed flexible container of air. When the air pressure outside the container changes, the container responds by contracting or expanding. This change is registered by a needle or digital readout. These values are expressed in millibars (mb), which is a unit of pressure commonly used in aviation and meteorology that is equal to 1 hectoPascal (hPa) or 100 Pascal (Pa), where one Pa is one newton per square metre (Nm^{-2}). Standard sea level pressure is 1013.25 mb, or a nominal value of about thousand millibars. Changes in atmospheric pressure can indicate a change in weather.
6	Surface longwave radiation	Surface longwave radiation is defined as the flux density of radiation emitted by the gases, aerosols and clouds of the atmosphere to the Earth's surface and it is measured in watts per square meter (W/m^2). The long wavelength radiation (or the infrared-range radiation) returned to the surface is mainly measured by a pyrgeometer.
7	Surface shortwave radiation	Surface shortwave radiation is defined as the flux density of the solar radiation at the Earth's surface. The unit of measurement for radiation is that of irradiance, watts per metre squared (Wm^{-2}). On the ground, an instrument called a solar pyranometer measures the amount of incoming solar radiation that reaches Earth.

Although all variables in the table are essential for climate analysis, the four first variables in the table (2 m temperature, total precipitation, surface wind speed and direction, and surface water vapour) are considered as essential for climate change adaptation studies at local scales

in northern Canada, and constitute the focus of this chapter. For each of the four variables we will present first the historical datasets estimated from observations. Descriptions of the modelled datasets (historical and future projections) are presented in Chapter 4.

The previous table also presents the classical instruments used in the measurement of those variables at meteorological and climate stations. As mentioned in Section 2.1, those historical records are local, the period that they cover varies with the location and may include missing values over the period of record. Station measurements are unevenly distributed over the land and their total number has changed over time with an important decline in the number of manual stations after 1990 (Mekis *et al*., 2018). For the Canadian North, most of the meteorological and climate records started in 1950's, the number of stations is much smaller than in the southern Canada and unevenly distributed (see Figure 2.1 that shows the locations of stations from several surface networks in Canada, as of September 2016).

Characteristics of station data, gridded observational data, and reanalysis data were discussed in Section 2.1. In addition, for meteorological variables, estimates from satellites have recently become available for some of the meteorological variables over the recent past. Some hybrid datasets, combining station measurements with reanalyses or satellite data, also exist. Consequently, the historical observation-based sections for meteorological variables will present the following type of datasets:

a) Station data (presented in blue)
b) Gridded observations (presented in yellow)
c) Reanalysis (presented in green)
d) Re-gridded reanalysis with or without bias corrections (presented in orange)
e) Satellite data (presented in pink)
f) Hybrid data (presented in violet)

Historical meteorological variables are necessary as a first step in Climate Change Vulnerability and Risk Assessments to define the baseline conditions that describe the climate over the historical period. Historical data is also used to evaluate climate models skill over the historical period, to bias correct climate projections. Some of the meteorological variables are also used as input for local permafrost models and regional land surface models.

The following explains some considerations that were taken into account when selecting and documenting the existing meteorological datasets for the historical period.

1) Only datasets covering the Canadian North in whole or in part are considered.
2) A 30-year period of record is indicated to meet international best practice for climate analyses in order to allow for a sufficient period to identify important, human-caused changes and trends, and for comparison and validation of climate model simulations. To the datasets that comply with this criterion, we have added some datasets of strategic importance. For example, some new datasets were developed

recently, and while presently there are not 30 years of data available for that specific dataset, there are plans to extend the data to a longer period, or for stations, they are considered as important because no other records are available for that specific region and they are valuable in the development of gridded products.

3) Regarding the use of gridded datasets, the climatological and monthly means of various variables have generally large-scale patterns but are strongly controlled by local effects. This is especially seen for precipitation field and wind, and in a shorter measure for humidity and temperature. However, the local effects for all variables are stronger on fields with smaller time steps, as the daily means and hourly values. Some of the factors that produce local effects are the proximity to large water bodies and the topography. Consequently, the gridded datasets should have a good spatial resolution in order to capture the local characteristics. For this reason, in this report only those gridded datasets with a nominal spatial resolution finer than about 0.6°, covering northern Canada or parts of northern Canada are considered. Some of the reanalyses or gridded datasets have evolved in time and several versions are available for public use. Only the most recent versions are presented here as those are considered to use the most advance models and technic, therefore are susceptible to provide the best results.

Each of the four variables are presented separately. The section is ending with supplementary datasets from stations that are not integrated into the Meteorological Service of Canada (MSC) network and can be of interest for local applications.

3.1.2 Near surface air temperature

Near-surface air surface temperature named 2 m temperature because "surface" air temperature observations are taken at 2 m above ground is one of the most commonly recorded climate variables. Information about this variable is important for many socio-economic sectors of activity (e.g., health, agriculture, energy demand, transportation) because of its impact on humans as well as on natural systems. Temperature data (including mean, daily range, degree hours, and seasonal percentages within ranges of values) are standard data incorporated into “weather files” used for designing, planning, and sizing building energy systems and equipment. There is a large variety of indices based on this variable that are defined according to context-specific applications: from mean climatological values to extremes and threshold-based indices. Some of those indices are computed using 2 m daily-mean temperature (Tmean), other using 2 m daily-minimum temperature (Tmin) or 2 m daily-maximum temperature (Tmax). Table 3.2 provide the definition of some of the most commonly used temperature climate indices that are important for the Canadian North.

Table 3.2 Examples of temperature climate indices important for the Canadian North (Source: Climdex project and ClimateData.ca).

Index	Temperature variable needed for computation	Definition	Sample applications
Winter temperature (mean and variation)	Tmean	The average and standard deviation of Tmean over the winter season	Seasonal winter trail conditions and safety
5°C Growing Degree Days (GDDs)	Tmean	The number of degree days accumulated above a threshold temperature of 5°C in the selected time period.	5°C GDDs is a measure of whether climate conditions are warm enough to support plant and insect growth. When the daily average temperature is warmer than the threshold temperature, growing degree days are accumulated. For forage crops, a threshold temperature of 5°C is generally used.
Heating Degree Days (HDDs)	Tmean	The number of degree days accumulated below 17°C or 18°C in the selected time period. (threshold values may vary, but 17°C or 18°C are commonly used in Canada).	HDDs give an indication of the amount of space heating (e.g., from a gas boiler/furnace, baseboard electric heating or fireplace) that may be required to maintain comfortable conditions inside a building during cooler months. When the daily average temperature is colder than the threshold temperature, HDDs are accumulated. Larger HDD values indicate a greater need for space heating.
Hottest temperature of the year	Tmax	Maximum annual value of Tmax.	High temperatures have an impact on human and ecosystem health, define the design of buildings and vehicles, and shape the transportation and energy use.
Ice days	Tmax	Annual count of days when Tmax < 0 °C. Let $Tmax_{ij}$ be daily maximum temperature on day i in year j. Count the number of days where $Tmax_{ij} < 0$ °C.	This index indicates the number of days when temperatures have remained below freezing for the entire 24-hour period. This index is an indicator of the length and severity of the winter season, and is important for winter roads season and to evaluate the health of foragers.
Coldest temperature of the year	Tmin	Minimum annual value of Tmin	Cold weather is an important aspect of life in northern Canada. Cold temperatures affect human health and safety, determine what plants and animals can live in the area, limit or enable outdoor activities, define the design of buildings and vehicles, and shape the transportation and energy use.

Index	Temperature variable needed for computation	Definition	Sample applications
Last Spring Frost	Tmin	The spring date after which there are no Tmin less than 0°C during the growing season.	The Last Spring Frost marks the approximate beginning of the growing season for frost-sensitive crops and plants.
First Fall Frost	Tmin	The first date in the fall (or late summer) on which Tmin is less than 0°C.	The First Fall Frost marks the approximate end of the growing season for frost-sensitive crops and plants.

Consequently, the following table (Table 3.3) provides information about existing datasets with sub-daily 2 m temperature data (which can be used to estimate the daily mean, minimum or maximum temperature), daily mean temperature as well as existing datasets that provides daily minimum and daily maximum temperatures.

For each dataset, a link to summaries describing the metadata is provided.

Table 3.3 Summary of observation-based historical datasets with 2 m temperature available

Name	Source	Type	Spatial domain	Spatial resolution	Temporal coverage	Time step	Format	Comments	Link to metadata description and reference paper
MSC Observations	MSC/ECCC	Station data	Canada	Point data	Variable (1940-present)	Hourly; Daily; Monthly	CSV; GeoJSON	In-situ measurements at the automatic and manual stations of ECCC that include daily climate stations, which produce one or two observations per day of temperature and precipitation, and hourly stations, which typically measure more meteorological variables. Provides values for 2 m temperature, Tmean, Tmax and Tmin.	Description of data: Annex 7.1.1
MSC Climate Normals	MSC/ECCC	Station data	Canada	Point data	1941-1970; 1951-1980; 1961-1990; 1971-2000; 1981-2010.	Climatological means	CSV; GeoJSON	Provides Climate Normals at MSC stations, and they are based on Canadian climate stations with at least 15 years of data in a given 30-year period.	Description of data: Annex 7.1.2
MSC Daily Climate Records	MSC/ECCC	Station data	Canada	Point data	Variable	Records for each day of the year	CSV; GeoJSON	"Virtual" climate stations have been developed by joining climate data for an urban location, from nearby stations to make long-term records. For	Description of data: Annex 7.1.3

Name	Source	Type	Spatial domain	Spatial resolution	Temporal coverage	Time step	Format	Comments	Link to metadata description and reference paper
(LTCE, Long Term Climate Extremes)								each long-term record, the extremes (record values) of Tmax, Tmin, total precipitation and snowfall for each day of the year were identified. Provides the highest Tmax, the highest Tmin, the lowest Tmax and the lowest Tmin and the year when the record was reached.	
AHCCD	CRD/ECCC	Station data	Canada	Point data	Variable (1950 to present)	Daily; Monthly; Seasonal; Annual	ASCII; CSV; GeoJSON	In-situ data with adjustments (derived from statistical procedures) to the original record to account for discontinuities from non-climatic factors, such as instrument changes or station relocation. Daily observations from nearby sites were often merged into a single record to create a long-time series. AHCCD was developed for use in climate research, including climate change studies. It provides values for Tmean, Tmin and Tmax. Tmean was computed from Tmax and Tmin.	Description of data: Annex 7.1.5 Reference: Vincent *et al.* (2020)
Hydro-Québec Station data	Hydro-Québec	Station data	Northern Québec at hydroelectric stations	Point Data	Variable (1990 to present)	Variable (sub-daily to daily)	n.a.	Hydro-Québec collects data at stations situated near their hydroelectric installations. The stations are mostly located south of the 55˚ parallel and vary in temporal coverage and resolution.	Description of data: Annex 7.2.5 Data: https://www.hydroquebec.com/documents-data/act-respecting-access/access-information-request.html
White Pass Railway & River Divisions dataset, Yukon	Yukon Research Centre	Station data from archives	The upper Yukon River basin	Point data	1902-1957	Daily	Excel files	Dataset digitalized from Yukon Archives containing a total of at least 77,966 observations at 30 locations along the railway line and along the waterways between Atlin, British Columbia and Dawson City, Yukon. Some of the data was quality controlled. This dataset helps to fill spatial and temporal gaps in the ECCC record for the upper Yukon River basin.	Description of data: http://yukonresearch.yukoncollege.yk.ca/wpyr/
SCDNA	University of Saskatchewan	Station data and reanalyses blend	North America	Point data	1979-2018	Daily	NetCDF	In-situ station data, with missing values replaces by reanalysis data. Provides values for Tmin and Tmax.	Description of data: GWFNet

Name	Source	Type	Spatial domain	Spatial resolution	Temporal coverage	Time step	Format	Comments	Link to metadata description and reference paper
									Reference: Tang *et al.* (2020)
CANGRD	CRD/ECCC	Gridded observations	Canada	50 km x 50 km	1948-2017 (anomalies)	Monthly; Seasonal; Annual	CSV; GeoJSON	It is derived by the interpolation of monthly climate anomalies from the AHCCD data. Tmean was computed from Tmax and Tmin. Provides anomalies of Tmin, Tmax and Tmean.	Description of data: Annex 7.1.6 Reference: Vincent *et al.* (2020)
ANUSPLIN	CFS/NRCan	Gridded observations	Canada and North America	(10 km x 10 km) and (2 km x 2 km)	1950-2017	Daily; Pentad; Monthly; Climatological means	ASCII; NetCDF	The dataset is obtained by interpolation of station data. Provides values for Tmin, Tmax. Tmean can be computed from Tmax and Tmin.	Description of data: Annex 7.1.15 Reference: MacDonald *et al.* (2020)
CRU TS Version 4	CRU/University of East Anglia	Gridded observations	Global (land only)	0.5° x 0.5°	1901–2018	Monthly	NetCDF	It is derived by the interpolation of monthly climate anomalies from weather station observations, using angular-distance weighting. It is using the 1961–1990 period as reference for the anomalies. The resulting gridded anomalies are converted to actual values. Provides values for Tmean and diurnal temperature range. Tmin, Tmax are provided as derived products. CRU TS4.00 is a full release, differing in methodology from the v3.24.01. release.	Description of data: CRU TS v4.00 (uea.ac.uk) Reference: Harris *et al.* (2020)
WorldClim2	World Conservation Monitoring Centre/UNEP	Gridded observations	Global (land only)	10 arc minutes (~340 km); 5 arc minutes; 2.5 arc minutes; 30 arc seconds (1 km)	1970-2000	Monthly	GeoTIFF	Interpolated using station data and satellite derived covariates. Provides values for Tmin, Tmax and Tmean.	Description of data: UNEP/GRID-Geneva Reference: Fick and Hijmans (2017)
Daymet Version 4	Environmental Sciences Division/Oak	Gridded observations	North America (land only)	1 km x 1 km	1980-2019	Daily	NetCDF	Interpolated using station data. Provides values for Tmin, and Tmax. Tmean can be computed from Tmax and Tmin.	Description of data: ORNL DAAC

Name	Source	Type	Spatial domain	Spatial resolution	Temporal coverage	Time step	Format	Comments	Link to metadata description and reference paper
	Ridge National Laboratory								Reference: Thornton *et al.* (2020).
PNWNAMET	PCIC	Gridded observations	North-western North America	3.75 arc minutes (~6 km)	1945-2012	Daily	ASCII; NetCDF	Interpolated based on AHCCD data. Provides values for Tmin, Tmax and Tmean. Spatial coverage is limited to western provinces/territories, expanding west from ~100˚W and south of ~75˚N. Expands into US for full cross-boundary watershed coverage.	Description of data: PCIC Reference: Werner *et al.* (2019)
Met1km	NRCan	Blend of gridded products	Canada	1 km x 1 km	1901–2017	Daily	n.a.	It is a blend of several gridded products (CRU JRA, GMFD, ANUSPLIN, and PNWAMET). The data is constructed by adding interpolated anomalies (with respect to long-term climatology) from the coarse resolution gridded daily datasets overtop the high-resolution monthly 1 km climatology from WorldClim2. There can be issues with discontinuities at month boundaries using this approach unless the monthly climatology is properly smoothed to day-of-year climatology. Another concern is related to the temporal non-stationarity due to the stitching together of different gridded daily datasets in different parts of the period, and also potential loss of coherence between variables stemming from drawing different variables from different datasets.	Description of data and reference: Zhang *et al.* (2020)
ERA5	ECMWF	Global atmospheric reanalysis	Global	0.25° x 0.25°	1950 to present	Hourly; Daily; Monthly	GRIB; NetCDF	5th generation reanalysis. Assimilates surface temperature from stations separately from the atmospheric analysis component using a univariate 2-dimensional optimal interpolation (2D-OI). In ERA5, hourly 2 m temperature is an instantaneous parameter provided at hourly time step from the analysis. Monthly data is pre-calculated as monthly-mean averages from hourly data. Minimum and maximum temperature at 2 metres since previous post-processing are available from the forecasts only. However, ERA5 forecast model has a cold bias in the lower regions of the troposphere over most parts over the globe, which is partially corrected by the analysis system. It is therefore recommended to use the instantaneous	Description of data: Annex 7.1.4 Reference: Hersbach *et al.* (2020)

Name	Source	Type	Spatial domain	Spatial resolution	Temporal coverage	Time step	Format	Comments	Link to metadata description and reference paper
								hourly (analyzed) 2 m temperature to construct the minimum and maximum over longer periods, such as Tmin and Tmax.	
CFSR	NCEP	Global atmospheric reanalysis	Global	0.5° x 0.5°	1979-2017	Sub-daily; Monthly	GRIB	2nd generation reanalysis. Does not assimilate surface temperature from stations. CFSR ends March 2011; CFSV2 begins April 2011.	Description of data: Annex 7.1.7 Reference: Saha *et al.* (2014)
MERRA-2	NASA	Global atmospheric reanalysis	Global	½° latitude x ⅝° longitude	1980 to present	Hourly; Daily; Monthly	NetCDF	2nd generation reanalysis. Does not assimilate surface temperature from stations.	Description of data: Annex 7.1.8 Reference: Gelaro *et al.* (2017)
JRA-55	JMA	Global atmospheric reanalysis	Global	0.6258° x 0.6258°	1957-2021	3h; 6h; Daily; Monthly	NetCDF	2nd generation reanalysis. Assimilates surface temperature from stations separately from the atmospheric analysis component using a univariate 2-dimensional optimal interpolation (2D-OI). Temperature from islands are not used because they are not representative at the grid scale of JRA-55. Determining whether an observation is from an island is based on the 0.25-degree resolution land cover data; consequently, observations from the coast are also excluded.	Description of data: Annex 7.1.9 Reference: Kobayashi *et al.* (2015)
ASRv2	Byrd Polar Research Center/The Ohio State University; UCAR/NCAR	Regional reanalysis	Arctic	15 km x 15 km	2000-2016	3h; Monthly	NetCDF	Is using the Polar Weather Research and Forecasting Model (PWRF) and High Resolution Land Data Assimilation system (HRLDAS). Is initialized and driven by ERA-Interim. Assimilates surface temperature from stations. Does not assimilate satellite temperatures retrievals but includes satellite radiances. 2 m temperature is available from the 2D surface analysis.	Description of data: Annex 7.1.10 Reference: Bromwich *et al.* (2010)
NARR	NCEP	Regional reanalysis	North America	32 km x 32 km	1979-2021	Sub-daily; Monthly	GRIB	It is initialized and driven by NCEP/NCAR Global Reanalysis 2. Does not assimilate surface temperature from stations. Does not assimilate satellite temperatures retrievals but includes satellite radiances.	Description of data: Annex 7.1.11

Name	Source	Type	Spatial domain	Spatial resolution	Temporal coverage	Time step	Format	Comments	Link to metadata description and reference paper
									Reference: Mesinger *et al.* (2006)
RDRSv2	CCMEP/ECCC	Regional reanalysis	North America	10 km x 10 km	2000-2017 (1980-1999 pending)	Hourly	RPN	Assimilates surface temperature from stations. It is initialized and driven by ERA-Interim reanalysis and relies only on surface observations and no remote sensing observations, such as satellite. Temperature data is available as instantaneous predicted values at hourly time steps. Tmax and Tmin are not available from the forecast. They can be computed by users using the hourly near-surface air temperature.	Description of data: Annex 7.1.12 Reference: Gasset *et al.* (2021)
20CRv3	CIRES; NOAA; DOE	Global atmospheric reanalysis	Global	T254 (approximately 75 km at the equator)	20CRv3.SI is available for years 1836-1980 and 20CRv3.MO is available for years 1981-2015	3h; Daily; Monthly	NetCDF	Assimilates only surface observations of synoptic pressure. Boundary conditions of pentad sea surface temperature and monthly sea ice concentration and time-varying solar, volcanic, and carbon dioxide radiative forcings are prescribed.	Description of data: ANNEX 7.1.13 Reference: Compo *et al.* (2011)
ERA5-Land	ECMWF	Land surface reanalysis/model	Global (land only)	0.1° x 0.1° (9 km)	1950 to present	Hourly; Monthly	GRIB; NetCDF	Off-line land model driven by ERA5 using a finer spatial resolution and including a series of improvements making it more accurate for all types of land applications. Does not include direct assimilation of data: it is indirectly influenced through the ERA5 atmospheric forcings. The output is interpolated to 0.10 deg lon/lat from the native model grid of 9 km.	Description of data: Annex 7.1.14 Reference: Muñoz-Sabater *et al.* (2021)
AgERA	ECMWF	Re-gridded reanalysis	Global (land only)	0.1° x 0.1°	1979 to present	Daily	NetCDF	Downscales ERA5 using regression equations trained on ECMWF's operational high-resolution atmospheric model (HRES) at a 0.1° resolution. Provides values for Tmin, Tmax and Tmean.	Description of data: Copernicus
AgCFSR	NASA	Re-gridded reanalysis with corrections	Global (land only)	0.25° × 0.25°	1980-2010	Daily	NetCDF	This data is an end product (will not be updated). Provides values for Tmin, Tmax and Tmean. Combines CFSR reanalysis with observation-based datasets (CFSR Tmax and Tmin values are corrected for each month in each year with average monthly temperature from CRU and WM on a 0.5-degree grid; Diurnal temperature range is	Description of data: NASA Reference: Ruane *et al.* (2015)

Name	Source	Type	Spatial domain	Spatial resolution	Temporal coverage	Time step	Format	Comments	Link to metadata description and reference paper
								adjusted to be equivalent to CRU diurnal temperature range and ensure that Tmax > Tmin.)	
AgMERRA	NASA	Re-gridded reanalysis with corrections	Global (land only)	0.25° × 0.25°	1980-2010	Daily	NetCDF	This data is an end product (will not be updated). Provides values for Tmin, Tmax and Tmean. Combines MERRA reanalysis with observation-based datasets (MERRA daily Tmax and Tmin values shifted by average monthly temperature correction from CRU and WM for each month in each year on 0.5° grid. DTR: Adjusted to be 0.75 of the way between MERRA and CRU DTRs. Ensure that Tmax > Tmin.)	Description of data: NASA Reference: Ruane *et al.* (2015)
GMFD	Princeton University	Re-gridded reanalysis with corrections	Global (land only)	0.25° × 0.25°	1948-2016	3h; Daily; Monthly	NetCDF	This data is an end product (will not be updated). Combines NCEP reanalysis with observation-based datasets (e.g. monthly values of CRU TS3.24.01 gridded at 0.5° spatial resolution). Provides values for Tmin, Tmax and Tmean.	Description of data: RDA Princeton Reference: Sheffield *et al.* (2006)
CRU JRA	CRU/University of East Anglia	Re-gridded reanalysis with corrections	Global (land only)	0.5° × 0.5°	1901-2018	6h	NetCDF	Combines JRA-55 reanalysis with CRU gridded-observation dataset. Provides values for 2 m temperature at each 6h.	Description of data: CEDA Archive
S14FD	DIAS	Re-gridded reanalysis with corrections	Global	0.5° x 0.5°	1958-2013	Daily	NetCDF	This data is an end product (will not be updated). Combines JRA-55 reanalysis with gridded-observation datasets. Provides values for Tmin, Tmax and Tmean.	Description of data: DIAS Reference: Iizumi *et al.* (2017)

The following summarizes the points that should be considered when a dataset is selected for historical climate analyses of 2 m temperature or climate indices computation in the Canadian North:

a) **The best solution in describing 2 m air temperature local climate, trends and evolution over a long period of time in the Canadian North, is to use good quality homogenized data series from stations as provided in AHCCD:** In-situ measurements, as those from MSC stations, represent the most reliable datasets. The AHCCD dataset (Vincent *et al.*, 2020) was developed by ECCC to resolve some of issues with data inhomegeneity at stations. A detailed description of air temperature records from AHCCD is provided in Annex 7.1.5 and Vincent et al. 2020. AHCCD is also often used to validate the skill of gridded datasets, reanalyses and models in simulating local characteristics. A good practice in the evaluation of reanalyses and gridded products is to verify that the target dataset is independent of the evaluated product (the target stations are not incorporated into the product that is evaluated). Table 3.3 provides information on which datasets are assimilating or use MSC or AHCCD stations. Evaluation against a dataset with stations that were incorporated into the products does not assure that the evaluated product has the same skill outside those station locations.

b) **AHCCD can be used for local statistical downscaling of models in locations where the dataset has a good temporal coverage (e.g., 20 years of data).** Unfortunately, the AHCCD does not present data for all locations in the Canadian North, and different locations have different periods with data.

c) **Despite their past use, the use of datasets obtained with gridding methods for regions of the Canadian North that feature a sparse network of stations should be approached cautiously. Only regional applications in areas with a good coverage of stations (e.g., a small watershed) and without large topographic variations could consider the use of a gridded-observation datasets.** Several gridded-observation datasets are provided in Table 3.3 that could be used to fill the gap from stations. As mentioned in Section 2.1, the primary factors that influences the gridded products are the density of the stations incorporated in the product, and the topographic complexity of the region. For temperature, in the Canadian North special attention should be given to regions with important topography, as those regions are subject to important «semi-permanent» inversions, where temperature increases with height (e.g., the deep valleys of Yukon). This makes simple scaling by altitude (e.g., using a standard lapse rate or an adiabatic lapse rate) inappropriate. Figure 3.1 (Rapaić *et al*., 2015) shows the average spread between six gridded observations datasets (CANGRD, CRUTEM4, CRU-TS3.1, GISTEMP, HadCRUT3, and UDEL) for anomalies of winter mean temperature on a grid of approximately 50 km spatial resolution. The six datasets diverge largely over the mountain regions where the density of stations is reduced but are similar for the other regions. This result suggests that in regions with important topographic variations, a dataset produced using a method that incorporates elevation information and accounts for temperature inversions should be used. Table 3.3 includes three datasets obtained with different gridding methods that include elevation information in their methodologies: ANUSPLIN, PNWNAMET, and WorldClim2. It should be noted that ANUSPLIN's thin-plate smoothing splines, which uses latitude, longitude and elevation as smoothing coordinates, does not represent discontinuities from cliffs and fault lines, which can affect extreme values, and does not account for temperature inversions. PNWNAMET is using the PRISM model, which takes into account temperature inversions from stations, but it is dependent on existence of stations at different elevations.

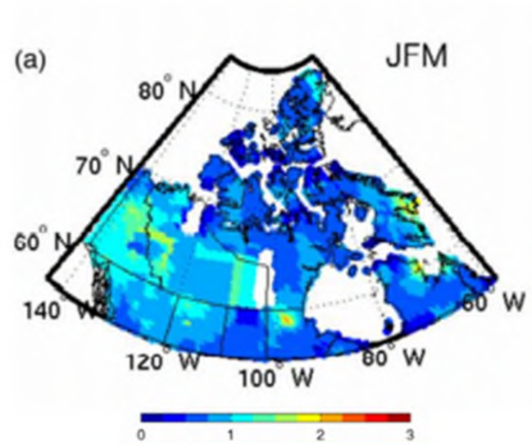

Figure 3.1 Average spread between six gridded observations datasets (CANGRD, CRUTEM4, CRU-TS3.1, GISTEMP, HadCRUT3, and UDEL) for anomalies of winter seasonal mean temperature on a grid of approximately 50 km spatial resolution. [Source: Rapaić et al., 2015]

d) **Reforecasts and reanalyses represent a valuable alternative to gridded-observation datasets for applications that require 2 m air temperature data over large regions without good station records, for impact models, and for statistical downscaling and bias correction of climate models over large regions in the Canadian North. However, a rigorous evaluation focused only on Candian North is recommended first.** Table 3.3 provide information about the last generation of global and regional reanalyses, most of them very recent versions. The statistical downscaling and bias correction of climate models is usually done against one dataset that is considered to represent the best the historical period at the spatial scale of interest. Presently, it is difficult to recommend one particular reanalysis for those applications over the Canadian North as many of the new datasets are not yet evaluated in a rigorous manner over this region. Some scientific papers focused on 2 m temperature over limited parts of the Canadian North (Cao *et al*., 2019; Diaconescu *et al*., 2018; Sheridan *et al.*, 2020), the entire North America (Keller and Wahl, 2021; Tarek *et al*., 2020) or over the Arctic (Avila-Diaz *et al*., 2021; Lindsay *et al*., 2014; Przybylak and Wyszyński, 2020). As discussed in Section 2.1.3, the observations provide less of a constraint on reanalyses over the Canadian North compared to the Canadian South and the results of continental-scale evaluations could be biases by the much larger number of stations in regions outside the Canadian North. Broadly, however, 2 m temperature is one of the variables for which reanalyses have in general a good skill, especially over regions without important topographic features. For example, Avila-Diaz *et al.* (2021) compare ASRv2, NARR, ERA5, MERRA-2 and GMFD, over North American land north of 42-degree parallel, against the gridded data product Daymet and focuses on 9 temperature-based annual indices from Expert Team on Climate Change Detection and Indices (ETCCDI) over a 17-year period (2000–16). The paper shows that ASRv2, ERA5 and MERRA-2 are closer to Daymet, while NARR and GMFD have smaller scores for the northern regions (Arctic seaboard, Yukon River, Mackenzie River and Hudson Bay Seaboard – see Figure 4 from the paper). It should be noted that there is a limited number of station data that is used in the Daymet interpolation over the Arctic, that the analysis is focusing just on annual indices, and that ERA5 and NARR are assimilating 2 m temperature that partially could also be integrated in the Daymet product, which constitutes the validation data. As mentioned in Section 2.1.3, averaging multiple reanalyses could provide a better estimate of climate characteristics over the Canadian North than using a single one.

e) **For local impact models, in regions without station data, the use of two or three reanalyses is also recommended. Those should be downscaled to the level of the location of interest.** Local impact models need data at the local level. For example, permafrost occurrence and properties exhibit strong lateral variation over ranges of only a few metres to a few kilometres, due to the effects of topography, vegetation cover, ground material, water bodies and flow or snow distribution (Gruber, 2012). The local downscaling of reanalyses can be done using methods that take into account the elevation even for regions without stations. Cao *et al*., (2017) compared several downscaling methods that rely on physically based empirical–statistical relationships and do not require local station data. For regions with important temperature inversions, they recommend the use of REDCAPP method. The model uses as proxy of surface effects the difference between near-surface air temperature and pressure-level temperature from reanalyses. The method was validated over the Swiss Alps and the Qilian Mountains. It must be noted that a full simulation of the atmospheric physics and land surface at high resolution will likely outperform this parameterization used in the REDCAPP. However they are not freely available for use at any location. The REDCAPP method is written in Python, and it is available via GitHub (https://github.com/geocryology/REDCAPP).

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3.1.3 Total Precipitation

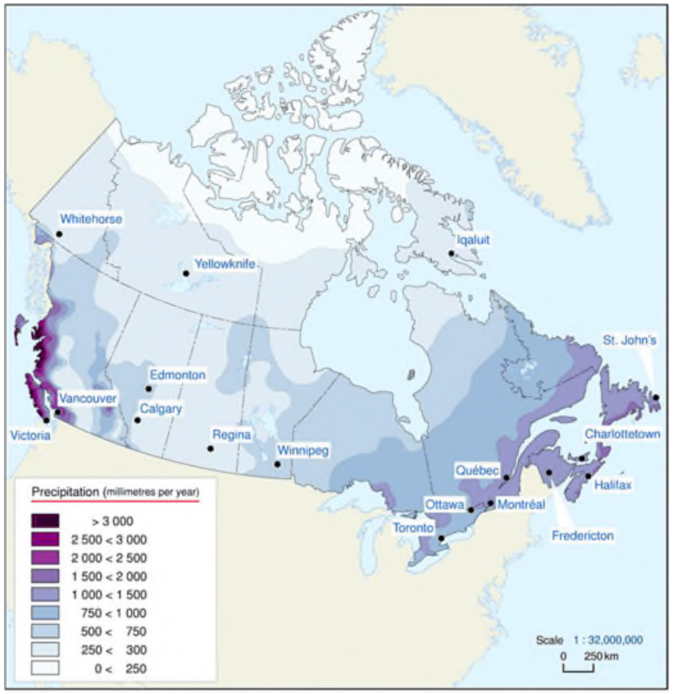
Precipitation can be defined as all liquid or frozen water that condenses from atmospheric moisture and falls back to Earth. It can take different forms like drizzle, rain, sleet, ice or snow, and varies in intensity. Together with evapotranspiration and condensation, precipitation is a key process in the global water cycle. Precipitation develops when droplets form in the atmosphere at below dewpoint temperatures and accumulate to be too heavy to remain suspended in mid-air.

Along with temperature, precipitation is one of the most commonly recorded meteorological quantities, with records dating back several centuries. The longest continuous observational record of precipitation in Canada dates back to 1840 when the Toronto Meteorological Observatory started operating a station at Fort York.

Precipitation is physically described as linear depth, usually recorded in millimetres (volume/area), kg m^{-2} (mass/area) (WMO, https://library.wmo.int/doc_num.php? explnum_id=3152). However, to address precipitation intensity, the linear depth is put in relation to time units to describe the flux, usually in millimetres per hour or per day (mm h^{-1}, mm d^{-1}, kg m^{-2} s^{-1}). An equivalent amount of precipitation can be denoted in litres per square metre (l m^{-2}). Snow depth is commonly measured in centimetres and can be translated to its Snow Water Equivalent (SWE) with the same units as liquid precipitation.

Precipitation develops in three main types: convective, stratiform and orographic rainfall, each involving a vertical upward motion of air. This uplift invokes cooling of the air, leading to condensation forming clouds and eventually droplets falling from the cloud. While convective and orographic rainfall can be spatially rather confined, stratiform precipitation may cover very large areas extending over hundreds of kilometres. The duration of precipitation events varies from minutes to days, where convective events may be short in duration and high in intensity, while stratiform and orographic events tend to last longer, with usually lower intensities. Orography usually plays a major role in the seasonal and spatial distribution of precipitation with upwind slope locations receiving abundant precipitation and lee sides remaining substantially dryer. The large variation of precipitation in time and space as well as the specifics of measuring it contributes to much larger uncertainties and errors in precipitation estimates when compared to temperature or other climate variables.

Climatological annual mean precipitation over Canada is shown in Figure 3.2. Coastal regions, in particular along the western cordillera in the West receive consistently larger amounts of precipitation than the central plains and the Great Lakes water bodies bring somewhat higher precipitation amounts to their Eastern surroundings. In the Canadian North, however, the precipitation along coasts is much less pronounced and a northward gradient towards much dryer conditions prevails, with less than 250 mm per year over the Canadian Arctic Archipelago. Generally, the winter season in Canada tends to provide lower amounts of precipitation than the summer season, to varying degrees and annual amplitudes of different magnitudes across the continent.



Note(s): The data for this map were estimated using a two-pass inverse distance-weighted interpolation of the 1971 to 2000 normal precipitation data from the Meteorological Service of Canada, using the Albers Equal Area Conic projection (Statistics Canada, Environment Accounts and Statistics Division).

Source(s): Environment Canada, Meteorological Service of Canada. Statistics Canada, Environment Accounts and Statistics Division.

Figure 3.2 Climatological annual mean precipitation (1971-2000) over Canada. [Source: https://www150.statcan.gc.ca/n1/pub/16-201-x/2006000/4177438-eng.htm]

The delivery of water through precipitation plays an important role for fauna and flora and the ecosystems that sustain them. Humans depend on precipitation for growing crops and livestock and exploit the water bodies fed by rainfall and snow melt for drinking water, industry, transport, and recreational activities. Water management is a crucial part of human activity and precipitation as its key driver is closely monitored. Both too much precipitation leading to floods as well as persistent periods without precipitation can cause critical conditions and even lead to catastrophic impacts, with flooding and droughts being some of the costliest natural disasters. Same of the most used precipitation climate indices are presented in Table 3.4.

Table 3.4 Some of the most used precipitation climate indices (Source: Climdex project and ClimateData.ca)..

Index	Precipitation variable needed for computation	Definition	Applications
Annual, seasonal and monthly averages and variations of precipitation	Daily precipitation	The average and standard deviation of annual, seasonal or monthly mean precipitation.	General description of a location's or region's climate and its variation across seasons and the annual cycle.
Total precipitation (PRCPTOT)	Daily precipitation	The PRCPTOT index is defined by the total amount of precipitation (rain and snow combined) that falls within the selected time period.	Precipitation significantly impacts water availability, agricultural practices, electricity generation and wildfire suppression. This indicator provides information about overall water availability.
Maximum 1-Day Total Precipitation (RX1day)	Daily precipitation	The RX1day index describes the largest amount of precipitation (rain and snow combined) that falls within a single 24-hour day for the selected time period. This index is commonly referred to as the wettest day of the year.	Very high 1-day precipitation totals could be the result of intense, but short-lived precipitation events such as thunderstorms, or may be due to precipitation occurring steadily over the course of the day. Short duration, high intensity precipitation events may lead to flash flooding, particularly in urban areas where storm drains may be overwhelmed. Heavy snowfall events can cause damage to buildings and disrupt transportation services.
Maximum 5-Day Precipitation (RX5days)	Daily precipitation	The RX5days index describes the largest amount of precipitation (rain and snow combined) to fall over 5 consecutive days for the selected time period.	High precipitation totals can cause flooding in urban areas, damage to crops and roads, and erode top soil. Heavy snowfall events can cause damage to buildings and disrupt transportation services.

Index	Precipitation variable needed for computation	Definition	Applications
Wet Days > NN mm	Daily precipitation	Wet Days > NN mm index describes the number of days where more than NN mm of precipitation (rain and snow combined) falls in a given time period (annual, seasonal). Common thresholds for NN mm are 1 mm, 10 mm and 20 mm, but other values may be used.	Adequate precipitation is crucial to water availability, agriculture, electricity generation and wildfire suppression.
Amount of daily precipitation above the 95th or 99th percentile	Daily precipitation	The amount of daily precipitation above the 95th (99th) percentile is the annual total precipitation falling during the 5% (1%) heaviest precipitation events.	These indicators describe strong and extreme precipitation events that may involve flooding, strong erosion and can affect and damage infrastructure.
Simple precipitation intensity index (SDII)	Daily precipitation	The SDII index is defined as the ratio of annual or seasonal total precipitation to the number of days during the year or season when precipitation occurred. Precipitation days are days where precipitation ≥ 1 mm.	This indicator provides information about the average intensity of precipitation events.
Maximum Number of Consecutive Dry Days (CDD)	Daily precipitation	The CDD index describes the longest spell of days where less than 1 mm of precipitation falls daily.	Periods of dry weather can impact agriculture, energy demands and water availability. Drought conditions may result when dry periods are long-lasting.

Table 3.5 presents high-level information on the retained observation-based historical datasets, for total precipitation. For each dataset, a link to summaries describing the metadata is provided.

Table 3.5 Summary of observation-based historical datasets with total precipitation available.

Name	Source	Type	Spatial domain	Spatial resolution	Temporal coverage	Time step	Format	Comments	Link to metadata description and reference paper
MSC Observations	MSC/ECCC	Station data	Canada	Point data	Variable (1940 to present)	Hourly; Daily; Monthly	CSV; GeoJSON	In-situ measurements at the automatic and manual stations of ECCC that include daily climate stations, which produce one or two observations per day of temperature and precipitation, and hourly stations, which typically measure more meteorological variables. It provides values for total precipitation, rain, snowfall as well as for the number of days when those variables are higher than specific thresholds (0.2 mm, 5 mm, 10 mm, 25 mm).	Description of data: Annex 7.2.1
MSC Climate Normals	MSC/ECCC	Station data	Canada	Point data	1941-1970; 1951-1980; 1961-1990; 1971-2000; 1981-2010.	Climatological means	CSV; GeoJSON	Provides Climate Normals at MSC stations, and they are based on Canadian climate stations with at least 15 years of data in a given 30-year period. It provides values for total precipitation, rain, snowfall as well as for their maximum daily values and the number of days when they are higher than specific thresholds (0.2 mm, 5 mm, 10 mm, 25 mm).	Description of data: Annex 7.2.2
MSC Daily Climate Records (LTCE, Long Term Climate Extremes)	MSC/ECCC	Station data	Canada	Point data	Variable	Records for each day of the year	CSV; GeoJSON	“Virtual” climate stations have been developed by joining climate data for an urban location, from nearby stations to make long-term records. For each long-term record, the extremes (record values) of Tmax, Tmin, total precipitation and snowfall for each day of the year were identified. It provides values for the greatest precipitation and the year when the record was reached.	Description of data: Annex 7.2.3

Name	Source	Type	Spatial domain	Spatial resolution	Temporal coverage	Time step	Format	Comments	Link to metadata description and reference paper
AHCCD	CRD/ECCC	Station data	Canada	Point data	Variable (1950 to present)	Daily; Monthly; Seasonal; Annual	ASCII; CSV; GeoJSON	In-situ data with adjustments (derived from statistical procedures) to the original record for total precipitation, rain and snowfall. The data accounts for a number of known errors in precipitation measurements, specific to different types of rain gauges. Daily precipitation amounts below a minimum measurable amount were set to a value of zero in the past. However, the accumulated impact of these trace amounts can become significant, especially in areas like the Arctic where precipitation amounts are low. Adjustments were applied to account for this underestimation by assigning a value to these days: 0.1 mm was applied for rain, whereas for snow the adjustment factor ranged from 0.03 to 0.07 mm depending on the station location. Nearby observations were sometimes joined and adjustments were applied based on a simple ratio computed using available periods of overlapping data.	Description and data: Annex 7.2.4 Reference: Mekis and Vincent (2011)
Hydro-Québec Station data	Hydro-Québec	Station data	Northern Québec at hydroelectric stations	Point Data	Variable (1990 to present)	Variable (sub-daily to daily)	n.a.	Hydro-Québec collects data at stations situated near their hydroelectric installations. The stations are mostly located south of the 55˚ parallel and vary in temporal coverage and resolution. It provides values for total precipitation, rain and snowfall.	Description of data: Annex 7.2.5 Data: https://www.hydroquebec.com/documents-data/act-respecting-access/access-information-request.html
SCDNA	University of Saskatchewan	Station data and reanalyses blend	North America	Point data	1979-2018	Daily	NetCDF	In-situ station data, with missing values replaced by reanalysis data. It provides values for total precipitation.	Description of data: GWFNet Reference: Tang *et al.* (2020

Name	Source	Type	Spatial domain	Spatial resolution	Temporal coverage	Time step	Format	Comments	Link to metadata description and reference paper
CANGRD	CRD/ECCC	Gridded observations	Canada	50 km x 50 km	1948 - 2017 (anomalies)	Monthly; Seasonal; Annual	CSV; GeoJSON	It is derived by the interpolation of monthly climate anomalies from the AHCCD data. Precipitation anomalies are normalized by dividing by the mean reference period and expressed as percentage change (%). It provides values for total precipitation.	Description of data: Annex 7.2.6 Reference: Vincent *et al.* (2020)
ANUSPLIN	CFS/NRCan	Gridded observations	Canada and North America	(10 km x 10 km) and (2 km x 2 km)	1950 - 2017	Daily; Pentad; Monthly; Climatological means	ASCII; NetCDF	The dataset is obtained by interpolation of station data with ANUSPLIN method. It provides daily, pentad, monthly and climatological mean values for total precipitation.	Description of data: Annex 7.2.16 Reference: MacDonald *et al.* (2020)
WorldClim2	World Conservation Monitoring Centre/UNEP	Gridded observations	Global (land only)	10 arc minutes (~340 km); 5 arc minutes; 2.5 arc minutes; 30 arc seconds (1 km)	1970-2000	Monthly	GeoTIFF	Interpolated using climate station data and satellite derived covariates. It provides values for total precipitation.	Description of data: Annex 7.2.17 UNEP/GRID-Geneva Reference: Fick and Hijmans, (2017)
PNWNAMET	PCIC	Gridded observations	North-western North America	3.75 arc minutes (~6 km)	1945-2012	Daily	ASCII; NetCDF	Interpolated based on AHCCD data. Spatial coverage is limited to western provinces/territories, expanding west from ~100˚W and south of ~75˚N and expands into US for full cross-boundary watershed coverage. It provides values for total precipitation.	Description of data: Annex 7.2.18 Pacific Climate Impacts Consortium Reference: Werner *et al.* (2019)

Name	Source	Type	Spatial domain	Spatial resolution	Temporal coverage	Time step	Format	Comments	Link to metadata description and reference paper
Met1km	NRCan	Blend of gridded products	Canada	1 km x 1 km	1901–2017	Daily	n.a.	It is a blend of several gridded products (CRU JRA, GMFD, ANUSPLIN, and PNWAMET). The data is constructed by adding interpolated anomalies (with respect to long-term climatology) from the coarse resolution gridded daily datasets overtop the high-resolution monthly 1 km climatology from WorldClim2. There can be issues with discontinuities at month boundaries using this approach unless the monthly climatology is properly smoothed to day-of-year climatology. Another concern is related to the temporal non-stationarity due to the stitching together of different gridded daily datasets in different parts of the period, and also potential loss of coherence between variables stemming from drawing different variables from different datasets. It provides values for total precipitation.	Description of data: Annex 7.2.19 Reference: Zhang *et al.* (2020)
GPCC	WMO	Gridded observations	Global	0.5° x 0.5°; 1° x 1°; 2.5° x2.5°	1891-2016	Daily; Monthly; Climatological means	Binary; NetCDF	Products provided by the GPCC are not bias corrected for systematic gauge measuring errors. It provides values and anomalies for total precipitation.	Description of data: Annex 7.2.20 http://gpcc.dwd.de/ Reference : Schneider *et al.* (2021)

Name	Source	Type	Spatial domain	Spatial resolution	Temporal coverage	Time step	Format	Comments	Link to metadata description and reference paper
CRU TS Version 4	CRU/University of East Anglia	Gridded observations	Global	0.5 x 0.5	1901-2015	Monthly	ASCII; NetCDF	It is derived by the interpolation of monthly climate anomalies from weather station observations, using angular-distance weighting. It is using the 1961–1990 period as reference for the anomalies. The resulting gridded anomalies are converted to actual values. CRU TS4.00 is a full release, differing in methodology from the v3.24.01. release. It provides values and anomalies for total precipitation.	Description of data: Annex 7.2.21 Reference: Harris *et al.* (2020)
ERA5	ECMWF	Global atmospheric reanalysis	Global	0.25° x 0.25°	1950 to present	Hourly; Daily; Monthly	GRIB; NetCDF	5th generation reanalysis. ERA5 combines vast amounts of historical observations into global estimates using advanced modelling and data assimilation systems. Total precipitation is the accumulated liquid and frozen water, comprising rain and snow that falls to the Earth's surface. It is the sum of large-scale precipitation and convective precipitation. Large-scale precipitation is generated by the cloud scheme in the ECMWF Integrated Forecasting System (IFS). Convective precipitation is generated by the convection scheme in the IFS, which represents convection at spatial scales smaller than the grid box. This parameter does not include fog, dew or the precipitation that evaporates in the atmosphere before it lands at the surface of the Earth. Beside total precipitation, it also provides values for convective and large scale precipitation, rain, snowfall, snowfall rate water equivalent, Instantaneous large-scale surface precipitation fraction, maximum total precipitation rate since previous post-processing, total column rain water, total column snow water, precipitation type and others.	Description of data: Annex 7.2.7 Reference: Hersbach *et al.* (2020)

Name	Source	Type	Spatial domain	Spatial resolution	Temporal coverage	Time step	Format	Comments	Link to metadata description and reference paper
CFSR	NCEP	Global atmospheric reanalysis	Global	0.5° x 0.5°	1979-2017	Sub-daily; Monthly	GRIB	2nd generation reanalysis. CFSR ends March 2011; CFSV2 begins April 2011. Beside total precipitation, it also provides values for convective precipitation and total precipitation rate.	Description of data: Annex 7.2.8 Reference: Saha *et al.* (2014)
MERRA-2	NASA	Global atmospheric reanalysis	Global	½° latitude x ⅝° longitude	1980 to present	Hourly; Daily; Monthly	NetCDF	2nd generation reanalysis. MERRA-2 provides observations-corrected precipitation fields based on a merged satellite–gauge precipitation product (CPCU; Chen et al. 2008) with a full correction for latitudes below 42.5°, a linear tapering between CPCU and the MERRA-2 model precipitation between 42.5° and 62.5°, and no correction for latitudes at 62.5° and higher. Beside the bias corrected total precipitation, it also provides values for maximum precipitation rate during one day, anvil precipitation, convective precipitation, nonanvil large scale precipitation, total precipitation from atm model physics, bias corrected snowfall, bias corrected liquid water convective precipitation, bias corrected liquid water large scale precipitation, and others.	Description of data: Annex 7.2.9 Reference: Gelaro *et al.* (2017)
JRA-55	JMA	Global atmospheric reanalysis	Global	0.6258° x 0.6258°	1957-2021	3h; 6h; Daily; Monthly	NetCDF	2nd generation reanalysis. It provides values for convective precipitation, large scale precipitation, snowfall rate and water equivalent.	Description of data: Annex 7.2.10 Reference: Kobayashi *et al.* (2015)

Name	Source	Type	Spatial domain	Spatial resolution	Temporal coverage	Time step	Format	Comments	Link to metadata description and reference paper
ASRv2	Byrd Polar Research Center/The Ohio State University; UCAR/NCAR	Regional reanalysis	Arctic	15 km x 15 km	2000-2016	3h; Monthly	NetCDF	Is using the Polar Weather Research and Forecasting Model (PWRF), the High Resolution Land Data Assimilation (HRLDAS) system and it is initialized and driven by ERA-Interim. It provides forecast values for convective and grid scale precipitation, grid scale snowfall, grid scale graupel, and the fraction of frozen precipitation.	Description of data: Annex 7.2.11 Reference: Bromwich *et al.* (2018)
NARR	NCEP	Regional reanalysis	North America	32 km x 32 km	1979-2021	Sub-daily; Monthly	GRIB	It is initialized and driven by NCEP/NCAR Global Reanalysis 2. It provides forecast values for convective and total precipitation, and the type of precipitation (snow, ice pellets, freezing rain, or rain).	Description of data: Annex 7.2.12 Reference: Mesinger *et al.* (2006)
RDRSv2	CCMEP/ECCC	Regional reanalysis	North America	10 km x 10 km	2000-2017 (1980-1999 pending)	Hourly	RPN	Assimilate precipitation measurements from stations. It is initialized and driven by ERA-Interim reanalysis and rely only on surface observations and no remote sensing observations, such as satellite or radar data. It provides forecast and analyzed values for total precipitation.	Description of data: Annex 7.2.13 Reference: Gasset *et al.* (2021)
20CRv3	CIRES; NOAA; DOE	Global atmospheric reanalysis	Global	T254 (approximately 75 km at the equator)	20CRv3.SI is available for years 1836-1980 and 20CRv3.MO is available for years 1981-2015	3h; Daily; Monthly	NetCDF	Assimilates only surface observations of synoptic pressure. Boundary conditions of pentad sea surface temperature and monthly sea ice concentration and time-varying solar, volcanic, and carbon dioxide radiative forcings are prescribed. It provides values for convective and total precipitation, and the type of precipitation (snow, ice pellets, freezing rain, or rain).	Description of data: ANNEX 7.2.14 Reference: Compo *et al.* (2011)

Name	Source	Type	Spatial domain	Spatial resolution	Temporal coverage	Time step	Format	Comments	Link to metadata description and reference paper
ERA5-Land	ECMWF	Land surface reanalysis/model	Global (land only)	0.1° x 0.1° (9 km)	1981 to present	Hourly; Monthly	GRIB; NetCDF	Off-line land model driven by ERA5 using a finer spatial resolution and including a series of improvements making it more accurate for all types of land applications. Does not include direct assimilation of data: it is indirectly influenced through the ERA5 atmospheric forcings. It provides values for total precipitation and snowfall. The output is interpolated to 0.10 deg lon/lat from the native model grid of 9 km.	Description of data: Annex 7.2.15 Reference: Muñoz-Sabater *et al.* (2021)
AgERA5	ECMWF	Re-gridded reanalysis	Global (land only)	0.1° x 0.1°	1979 to present	Daily	NetCDF	Downscales ERA5 using regression equations trained on ECMWF's operational high-resolution atmospheric model (HRES) at a 0.1° resolution. It provides values for liquid and solide precipitation duration fractions and precipitation flux.	Description of data: Copernicus
AgCFSR	NASA	Re-gridded reanalysis with corrections	Global (land only)	0.25° × 0.25°	1980-2010	Daily	NetCDF	This data is an end product (will not be updated). Combines CFSR reanalysis with observation-based datasets. Wet days: Average of CRU wet days for each month in each year. Mean: CFSR daily values multiplied by correction factor imposing mean of CRU, GPCC, and UDEM for each month and each year at 0.5 resolution. 0.25° details imposed from average monthly spatial pattern drawn from ensemble of TRMM, CMORPH, and PERSIANN.	Description of data: NASA Reference: Ruane *et al.* (2015)
AgMERRA	NASA	Re-gridded reanalysis with corrections	Global (land only)	0.25° × 0.25°	1980-2010	Daily	NetCDF	This data is an end product (will not be updated). Combines MERRA reanalysis with observation-based datasets. Wet days: MERRA-Land and CRU wet days for each month in each year. Mean: MERRA-Land daily values multiplied by correction factor imposing mean of CRU, GPCC, and UDEM for each month and each year at 0.5 resolution. 0.25° details imposed from average monthly spatial pattern drawn from ensemble of TRMM, CMORPH, and PERSIANN.	Description of data: NASA Reference: Ruane *et al.* (2015)

Name	Source	Type	Spatial domain	Spatial resolution	Temporal coverage	Time step	Format	Comments	Link to metadata description and reference paper
GMFD	Princeton University	Re-gridded reanalysis with corrections	Global (land only)	0.25° × 0.25°	1948-2016	3h; Daily; Monthly	NetCDF	This data is an end product (will not be updated). Combines NCEP reanalysis with observation-based datasets (namely the monthly CRU TS3.24.01 gridded at 0.5 horizontal spatial resolution). It provides values for total precipitation.	Description of data: RDA Princeton Reference: Sheffield *et al.* (2006)
CRU JRA	CRU/University of East Anglia	Re-gridded reanalysis with corrections	Global (land only)	0.5° × 0.5°	1901-2020	6h	NetCDF	Combines JRA-55 reanalysis with CRU gridded-observation dataset. It provides values for total precipitation.	Description of data: CEDA Archive
S14FD	DIAS	Re-gridded reanalysis with corrections	Global	0.5° x 0.5°	1958-2013	Daily	NetCDF	This data is an end product (will not be updated). Combines JRA-55 reanalysis with gridded-observation datasets. It provides values for daily total precipitation.	Description of data: DIAS Reference: Iizumi *et al.* (2017)
CloudSat	CIRA/Colorado State University	Satellite data	Between 80 N-S due to orbit - along track - product disseminated as tiles; retrieval not performed over land	Nominally 2 km along track and 1 km across track. The radar has a native vertical resolution of 480 m.	2006-2011, 2011-2020 (daytime only operations, interrupted record)	Monthly	Binary; HDF	Remotely sensed using W-band radar profiling. Sensitive to low intensity rain and snowfall events. Good high latitude coverage. Only reports rainfall rate over ocean, but reports snowfall rate and precipitation occurrence everywhere (land and ocean).	Description of data: Annex 7.2.22 Reference: Haynes *et al.* (2009)
GPCP V2.3	GSFC/NASA	Gridded hybrid data: observations, satellite	Global	2.5° x 2.5°	1979 to present	Monthly; Climatological means	Binary; NetCDF	It is a hybrid product that uses remote sensing, rain gauge stations, and sounding observations. Current version (V2.3) product has been used to assess global precipitation, as a reference dataset	Description of data: Annex 7.2.23 Reference:

Name	Source	Type	Spatial domain	Spatial resolution	Temporal coverage	Time step	Format	Comments	Link to metadata description and reference paper
								for Arctic precipitation, and to study decadal variability of Arctic precipitation. Considered to be a Climate Data Record. Improvements to some limitations applicable to the North coming in V3.X (see below).	Adler *et al.* (2018)
GPCP V3.1	GSFC/NASA	Gridded hybrid data: observations, satellite	Global	0.5° x 0.5°	1983 to present	Monthly	Binary; NetCDF	It is a hybrid product that uses remote sensing, rain gauge stations, and sounding observations. CloudSat, TRMM, and GPM combined climatology are used to adjust precipitation values, with CloudSat dominating at high latitudes (65 N-82 N). This may be an improvement of the representation of precipitation in the Canadian North, but there are some inhomogeneities in the record. This is not considered a Climate Data Record like V2.3. Use with some caution.	Description of data: Annex 7.2.23 https://docserver.gesdisc.eosdis.nasa.gov/public/project/MEaSUREs/GPCP/GPCP_ATBD_V3.1.pdf
GPCP Daily	GSFC/NASA	Gridded hybrid data: observations, satellite	Global	1° x 1°	1996-2015	Daily	Binary; NetCDF	It is a hybrid product that uses remote sensing, rain gauge stations, and sounding observations. Daily precipitation product at higher resolution than its companion GPCP Monthly product. Considered to be a Climate Data Record. May have some limitations in the North due to use of various datasets. Product is adjusted using GPCP Monthly product to agree climatologically.	Description of data: Annex 7.2.24 Reference: Huffman *et al.* (2001)
CMAP/O - CPC	CPC/NOAA	Gridded hybrid data: observations, satellite	88.75 N-S	2.5° x 2.5°	1979-2020	Pentad; Monthly; Climatological means	ASCII; NetCDF	It is a hybrid product that uses remote sensing and rain gauge stations. Offers monthly averaged precipitation rate values (mm/day) obtained from 5 kinds of satellite estimates (GPI, OPI, SSM/I scattering, SSM/I emission, and MSU) along with gauge data. Gaps over high latitudes may exist due to poor coverage. It reports rainfall	Description of data: Annex 7.2.25 Reference: Xie *et al.* (2007)

Name	Source	Type	Spatial domain	Spatial resolution	Temporal coverage	Time step	Format	Comments	Link to metadata description and reference paper
								and snowfall rate and precipitation occurrence. Climate normals (monthly, 1981-2010) are also available.	
CMAP/A - CPC	CPC/NOAA	Gridded hybrid data: observations, satellite, reanalyses	88.75 N-S	2.5° x 2.5°	1979-2020	Pentad; Monthly; Climatological means	ASCII; NetCDF	It is a hybrid product that uses remote sensing, rain gauge stations and NCEP/NCAR reanalysis. Considered an "enhanced" version of CMAP/O, this dataset includes blended NCEP/NCAR reanalysis precipitation values with the satellite estimates and gauge data. The reanalysis precipitation values are used to fill gaps, so may be dominant in the Canadian North. Climate normals (monthly, 1981-2010) are also available.	Description of data: Annex 7.2.26 Reference: Xie *et al.* (2007)
IMERG v6	NASA	Gridded hybrid data: observations, satellite	Global	0.1° x 0.1°	2000 to present	30 min.; Daily; Monthly	Binary; HDF	It is a hybrid product that uses TRMM estimates (2000-2014) + Global Precipitation Measurement estimates (GPM 2014 - present). This merged product gives an estimate of precipitation rate using the GPM (Global Precipitation Measurement) constellation of passive microwave satellites. Latest version (V6) fuses early estimates collected during the operation of the TRMM satellite (2000-2015) with more recent satellite estimates of precipitation during the operation of GPM (2014 - present). **Note: the zone outside 60 N-S is only populated with gauge data and satellite estimates in areas without snowy/icy surfaces, so data coverage is incomplete.** Some validation has been done against Candian station data. Probability of liquid precipitation is also available.	Description of data: Annex 7.2.27 Reference: Tan *et al.* (2019)

Name	Source	Type	Spatial domain	Spatial resolution	Temporal coverage	Time step	Format	Comments	Link to metadata description and reference paper
MSWEP version 2	GloH2O	Gridded hybrid data: observations, satellite, reanalyses	Global	0.1° x 0.1°	1979 to present	3h	NetCDF	MSWEP is a global precipitation product that merges gauge, satellite, and reanalysis data to obtain the highest quality precipitation estimates at every location.	Description of data: http://www.gloh2o.org/mswep/ Reference: Beck *et al.* (2019)

The following are notes about the different types of datasets and points that should be considered when selecting a historical precipitation dataset for application in the Canadian North.

a) Station data: Measurement of rainfall and snowfall is essential for water resources planning, agriculture, power generation, irrigation, flood control and forecasting. Compared to temperature, measuring precipitation precisely is a much more difficult effort. Rain gauges are containers of a defined size that will capture the falling rain or snow. The gauge is emptied and the water amount is measured at regular intervals. However, various factors affect the amount of precipitation recorded, with wind being the main source of errors in observations. Small amounts of the captured water are unrecorded as they wet the surface of the instrument. Some of the fallen rain will evaporate before it is recorded and heavy rain may lead to splashing of the droplets, also resulting in a measurement that is lower than the actual precipitation. Low intensity and short duration precipitation events may also be under-sampled with rain gauges. On the other hand, condensation inside the gauge may increase the observed amount of water. Overall, errors in precipitation measurements can amount to 4-6% depending on wind speed and rainfall intensity (Devine and Mekis, 2008). Snow measurement is even more difficult and errors in strong winds can exceed 20% (Goodison *et al*., 1998). The ECCC AHCCD (see Annex 7.2.4 and Mekis and Vincent, 2011) undergoes a separate adjustment of rain and snow in order to compensate for these errors, using spatially variable correction factors for snow due to regionally different snow densities. As the map of stations in Figure 1.1 shows, station density in northern regions of Canada is low, with tens to hundreds of kilometres between stations. Given the small spatial extent of precipitation from convective cells, precipitation station data may be misleading for nearby areas (while temperatures will vary little in adjacent areas of the station, the precipitation recorded may have only affected the station but other amounts or no precipitation may have occurred in nearby areas).

b) Gridded data: Climatological data are often required in spatially distributed form rather than in the point format of stations. As mentioned in Section 2.1, to describe the coverage of large areas such as watersheds or provinces, point data are often interpolated to establish a gridded dataset, i.e. 2D value fields, with the quality and utility of such a grid depending largely on the quality and the distribution of the input data. As mentioned above, precipitation is highly variable in time and space and, unlike temperature, is not continuous in time and space. This poses difficulties for the interpolation of station data onto a grid. Ideally, each cell of the grid would contain one or more stations so that the grid-cell information would be backed by actual observed values. This may be the case in areas of high station density and for grids of a few tens of kilometre grid sizes. However, northern Canada's station network is very sparse so that, as a function of the grid's resolution, many grid cells will not be backed by actual station data. Particularly higher temporal resolution data must therefore be used with caution as the interpolation may create misleading precipitation information. At longer temporal aggregations the spatial field of actual precipitation becomes much smother, as over a month's or a season's time the statistics of precipitation distribution will be smoothed (with the exception of orographic precipitation which is highly governed by the terrain). Therefore, interpolated lower temporal resolution data like monthly values are more likely to reproduce a real representation of precipitation of an area.

c) Precipitation in reanalysis and reanalysis-based products: In areas with sparse station coverage such as the Canadian North, reforecasts and reanalysis datasets provide a valuable alternative to station data and gridded datasets derived therefrom (for a comprehensive overview of reanalysis products see Section 2.1.3). While the completeness of reanalysis datasets is a clear advantage, they need to be used with caution. Their validation shows different levels of reliability in both their intercomparison and within a given dataset. For example, Rapaić *et al*. (2015) report particularly important spatial, seasonal, and temporal variability for precipitation over the Canadian Arctic, most pronounced in mountain regions, coastal areas and over the Canadian Arctic Archipelago. The biases vary in time and space and some reanalyses have larger wet biases (CFSR, 20CR, Rapaić, *et al*., 2015). The results of the evaluation appear to change with application. For example, NARR precipitation validated favourably for the Canadian North (Rapaić *et al*., 2015, Keller and Wahl, 2021) is recommended to be taken with care for water cycle analysis over parts of Québec by Sabarly *et al*. (2016). Generally, the difference between the precipitation of the reanalyses (and other gridded data) increases after around 2003 due to a stark decrease in available stations and a change in the type and collections of data assimilated in the reanalysis (Rapaic *et al*., 2015). Authors recommend a multi-dataset approach to compensate for the differences found in the various reanalysis data.

d) Precipitation data derived from satellites: Satellite derived precipitation data are usually a combination of one or several precipitation data with estimates derived from satellite imagery. The temporal and spatial resolution depends on the instrument used in their production. Except for geostationary satellites, most satellites give near-global coverage on some repeat cycle. For example, some satellites may sample at least once per 100 km grid cell every sixteen days (CloudSat). Depending on the orbit, they will have more frequent sampling at some latitudes than others. Here we consider only datasets that have coverage up to at least 60˚N. However, a single satellite does not fly over a region more than twice per day, and the gaps between overpasses may miss short-lived precipitation events. This is why merged or "hybrid" precipitation datasets are useful, as they can combine the observations from multiple satellite platforms to fill in some of the gaps. Typically, passive microwave or infrared instruments are used to estimate precipitation. Infrared sensors estimate cloud top temperatures, and an algorithm is used to relate the measured temperature to a precipitation estimate. Microwave-based algorithms derive precipitation from both scattering and emission from hydrometeors and cloud droplets. Note that emission cannot be used to estimate precipitation over land due to the heterogeneity of the surface emissivity. Low intensity and short duration precipitation events tend to be under-sampled. Currently, there are no studies that evaluate those datasets over the Canadian North.

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3.1.4 Surface Humidity

How much water vapour is suspended in the air can be expressed in multiple ways. Table 3.6 summarizes the meteorological variables related to water vapour.

Table 3.6: Humidity variables and their properties (from Willett K. M., 2007)

Variable	What does it measure?	Units	Uses	How is it measured?
RH (relative humidity)	Closeness of the air to saturation	%	- Measure of human comfort - Parameter in climate models	- Directly by hygrometers or electronic RH sensors -Derived from vapour pressure and saturated vapour pressure
q (absolute and specific humidity)	Absolute humidity is the ratio of the mass of water vapour to the total mass of moist air , while specific humidity is the ratio of the mass of water vapour to the mass of dry air	g kg^{-1}	- Climate studies (necessary for calculating evaporation) - Parameter in climate models	-Derived from vapour pressure and pressure

Variable	What does it measure?	Units	Uses	How is it measured?
T_{dw} (dew point temperature)	The atmospheric temperature lowered to the point of saturation	° C	- Climate studies - Synoptic analyses	- Directly from Dewcel sensors and dew point hygrometers - Derived from psychrometric tables or combinations of other variables
T_w (wet-bulb temperature)	The temperature at which the measured air is saturated by evaporating water into it from the wet bulb	° C	- Synoptic analyses	- Directly from wet-bulb thermometers -Derived from psychrometric tables or combinations of other variables

Some of these variables are directly measured at meteorological and climate stations, some are just output from forecast and climate models without a direct measurement at stations. However all of them are widely used in meteorological and climate fields. Water vapour plays a key role in determining the dynamical and radiative properties of the climate system and its transport around the atmosphere is a fundamental component of the hydrological cycle. Among the variables presented in Table 3.6, specific humidity is considered as very important in climate model evaluation and in the research field, and dew point temperature is of interest for assessing atmospheric soundings and the development of clouds and convection in models.

Relative humidity, dew point temperature and wet-bulb temperature provide important inputs to building envelope and heating/ventilation/air conditioning design as well as building energy modelling. Such data is frequently incorporated into "weather files" and ''design days'' that serve as inputs in these applications. Such data could be potentially useful for northern users in assessment and design of current and future community housing, industrial and office sites as well as design of building retrofits for improved human comfort and energy efficiency.

Extreme values of relative humidity have significant impacts on human comfort conditions in terms of thermal stress as well as on the strength and frequency of forest fires. In high temperature conditions, high humidity inhibits evaporation, making cooling by perspiration less effective and can create heat stress and many health problems for people and animals. Fortunately, those conditions are rarely met in the Canadian North. Nevertheless, wildfires are experienced in a large part of Yukon and Northwest Territories (https://cwfis.cfs.nrcan.gc.ca/ha/nfdb).

This section presents an inventory of historical datasets covering the Canadian North that have available specific and/or relative humidity. The information is summarized in Table 3.7. Surface relative humidity can also be estimated from 2 m air temperature and dew point temperature (e.g., https://www.weather.gov/media/epz/wxcalc/vaporPressure.pdf). Table 3.7 mentions if a dataset does not have available relative humidity but provides dew point temperature instead.

Table 3.7 Summary of observation-based historical datasets with specific and/or relative humidity available

Name	Source	Type	Spatial domain	Spatial resolution	Temporal coverage	Time step	Format	Comments	Link to metadata description and reference paper
MSC Observations	MSC/ECCC	Station data	Canada	Point data	Variable (1940 to present)	Hourly; Daily; Monthly	CSV; GeoJSON	In-situ surface measurements at the automatic and manual stations of ECCC stations. Measurements for relative humidity and/or dew point temperature are available at some stations.	Description of data: Annex 7.3.1
Hydro-Québec Station data	Hydro-Québec	Station data	Northern Québec at hydroelectric stations	Point Data	Variable,1990 to present	Variable (sub-daily to daily)	n.a.	Hydro-Québec collects data at stations situated near their hydroelectric installations. The stations are mostly located south of the 55˚ parallel and vary in temporal coverage and resolution.	Description of data: Annex 7.2.5 Data: https://www.hydroquebec.com/documents-data/act-respecting-access/access-information-request.html
CRU CL v. 2.0	CRU/University of East Anglia	Gridded observations	Global (land surface)	10 arcminutes (0.1666667 degree)	1961-1990	Climatological means	ASCII	Provide relative humidity. The data was interpolated from means at 5950 global stations for the period centred on 1961 to 1990. Available: climatology of 1961-1990 monthly means	Description of data: CRU CL 2.0 Reference : New *et al.* (2002)
HadISDH	Met Office/Hadley Centre	Gridded observations; Station data	Global	5° x 5° for gridded data and point for stations	1973 - 2020	Monthly	ASCII; NetCDF	Monthly means and anomalies (relative to a 1981-2010 base period) are provided for six surface humidity variables (including specific and relative humidity) and temperature alongside uncertainty estimates (observation and grid box sampling). Utilizes simultaneous sub daily temperature and dew point temperature data from >4500 quality controlled and homogenized HadISD stations that have sufficiently long records. All humidity variables are calculated at hourly resolution and monthly means are created and next interpolated on a global grid.	Description of data: HadISDH Reference: Willett *et al.* (2014)

Name	Source	Type	Spatial domain	Spatial resolution	Temporal coverage	Time step	Format	Comments	Link to metadata description and reference paper
ERA5	ECMWF	Global atmospheric reanalysis	Global	0.25° x 0.25°	1950 - present	Hourly; Daily; Monthly	GRIB; NetCDF	5th generation reanalysis. Relative humidity and specific humidity are provided on pressure levels only. Surface relative humidity can be estimated from the values on pressure levels or computed using 2 m air temperature and dew point temperature (information on both temperature variables are provided in Near Surface temperature subsection).	Description of data: COPERNICUS Reference: Hersbach *et al.* (2020)
CFSR	NCEP	Global atmospheric reanalysis	Global	0.5° x 0.5°	1979/01 to 2017/11	Sub-daily; Monthly	GRIB	3rd generation reanalysis. CFSR ends March 2011; CFSV2 begins April 2011. Provides specific humidity and relative humidity. Provides also dew point temperature (information on temperature variables are provided in Near Surface temperature subsection).	Description of data: Annex 7.3.2 Reference: Saha *et al.* (2014)
MERRA-2	NASA	Global atmospheric reanalysis	Global	½° latitude x ⅝° longitude	1980/01 to present	Hourly; Daily; Monthly	NetCDF	2nd generation reanalysis. Provides 2 m and 10 m specific humidity. Provides also 2 m dew point temperature (information on temperature variables are provided in Near Surface temperature subsection).	Description of data: Annex 7.3.4 Reference: Gelaro *et al.* (2017)
JRA-55	JMA	Global atmospheric reanalysis	Global	0.6258° x 0.6258°	1957/12 to 2021/05	3h; 6h; Daily; Monthly	NetCDF	2nd generation reanalysis. Provides 2 m specific humidity and 2 m relative humidity.	Description of data: Annex 7.3.5 Reference: Kobayashi *et al.* (2015)
ASRv2	Byrd Polar Research Center/The Ohio State University; UCAR/NCAR	Regional reanalysis	Arctic	15 km x 15 km	2000/01 to 2016/12	3h; Monthly	NetCDF	Is using the Polar Weather Research and Forecasting Model (PWRF) and High Resolution Land Data Assimilation (HRLDAS) systems and it is initialized and driven by ERA-Interim. Provides 2 m specific humidity and 2 m relative humidity.	Description of data: Annex 7.3.6 Reference: Bromwich *et al.* (2010)
NARR	NCEP	Regional reanalysis	North America	32 km x 32 km	1979/01 to 2021/04	Sub-daily; Monthly	GRIB	It is initialized and driven by NCEP/NCAR Global Reanalysis 2. Provides 2 m specific humidity and 2 m relative humidity. Provides also 2 m dew point temperature	Description of data: Annex 7.3.7

Name	Source	Type	Spatial domain	Spatial resolution	Temporal coverage	Time step	Format	Comments	Link to metadata description and reference paper
								(information on temperature variables are provided in Near Surface temperature subsection).	Reference: Mesinger *et al.* (2006)
RDRSv2	CCMEP/ECCC	Regional reanalysis	North America	10 km x 10 km	2000 -2017, (1980 - 1999 pending)	Hourly	RPN	It is initialized and driven by ERA-Interim reanalysis and rely only on surface observations and no remote sensing observations, such as satellite. Provides 1.5 m specific humidity and 1.5 m relative humidity. Provides also 1.5 m dew point temperature (information on temperature variables are provided in Near Surface temperature subsection).	Description of data: Annex 3.7.8 Reference: Gasset *et al.* (2021)
20CRv3	CIRES; NOAA; DOE	Global atmospheric reanalysis	Global	T254 (approximately 75 km at the equator)	20CRv3.SI is available for years 1836-1980 and 20CRv3.MO is available for years 1981-2015	3h; Daily; Monthly	NetCDF	Assimilates only surface observations of synoptic pressure and boundary conditions of pentad sea surface temperature and monthly sea ice concentration and time-varying solar, volcanic, and carbon dioxide radiative forcings are prescribed. Provides 2 m specific humidity and 2 m relative humidity.	Description of data: ANNEX 7.3.3 Reference: Compo *et al.* (2011)
ERA5-Land	ECMWF	Land surface reanalysis/model	Global (land only)	0.1° x 0.1° (9 km)	1950 - present	Hourly; Monthly	GRIB; NetCDF	Off-line land model driven by ERA5 using a finer spatial resolution and including a series of improvements making it more accurate for all types of land applications. Do not include direct assimilation of data: it is indirectly influenced through the ERA5 atmospheric forcings. Do not provide specific or relative humidity. However, it provides 2 m dew point temperature (information on temperature variables are provided in Near Surface temperature subsection). The output is interpolated to 0.10 deg lon/lat from the native model grid of 9 km.	Description of data and reference: Muñoz-Sabater *et al.* (2021)
AgERA	ECMWF	Re-gridded reanalysis	Global (land only)	0.1° x 0.1°	1979-present	Daily	NetCDF	Downscales ERA5 using regression equations trained on ECMWF's operational high-resolution atmospheric model (HRES) at a 0.1° resolution. Provides values for 2 m relative humidity and 2 m dew point temperature.	Description of data and reference: Copernicus

Name	Source	Type	Spatial domain	Spatial resolution	Temporal coverage	Time step	Format	Comments	Link to metadata description and reference paper
AgCFSR	NASA	Re-gridded reanalysis with corrections	Global (land only)	0.25° × 0.25°	1980-2010	Daily	NetCDF	This data is an end product (will not be updated). Provides values Relative Humidity at Time of Max Temp (%). This was calculated from CFSR specific humidity, maximum temperature, and surface pressure and then linearly interpolated to 0.25-degree grid.	Description of data: NASA Reference: Ruane *et al.* (2015)
AgMERRA	NASA	Re-gridded reanalysis with corrections	Global (land only)	0.25° × 0.25°	1980-2010	Daily	NetCDF	This data is an end product (will not be updated). Provides values Relative Humidity at Time of Max Temp (%). This was calculated from MERRA specific humidity, maximum temperature, and surface pressure and then linearly interpolated to 0.25-degree grid.	Description of data: NASA Reference: Ruane *et al.* (2015)
GMFD	Princeton University	Re-gridded reanalysis with corrections	Global (land only)	0.25° × 0.25°	1948-2016	3h; Daily; Monthly	NetCDF	This data is an end product (will not be updated). Combines NCEP reanalysis with observation-based datasets (namely the monthly CRU TS3.24.01 gridded at 0.5 horizontal spatial resolution). Provides values for specific humidity.	Description of data: RDA Princeton Reference: Sheffield *et al.* (2006)
CRU JRA v2.1	CRU/University of East Anglia	Re-gridded reanalysis with corrections	Global (land only)	0.5° × 0.5°	Jan.1901 - Dec. 2020	6h	NetCDF	Combines JRA-55 reanalysis with CRU gridded-observation dataset. Provides values for specific humidity at each 6h.	Description of data: CEDA Archive
S14FD	DIAS	Re-gridded reanalysis with corrections	Global	0.5° x 0.5°	1958-2013	Daily	NetCDF	This data is an end product (will not be updated). Combines JRA-55 reanalysis with gridded-observation datasets. Provides values for daily mean 2 m relative humidity (rh2m, %) and daily mean 2 m specific humidity (spfh2m, kg kg-1)	Description of data: DIAS Reference: Iizumi *et al.* (2017)

The following summarizes the points that should be considered when a dataset is selected for historical climate analyses of surface humidity or climate indices computation in northern Canada:

a) The Fire Weather Index (FWI) is a numeric rating of fire intensity, and it is used as a general index of fire danger throughout the forested areas of Canada. Its calculation requires daily values of temperature, relative humidity, wind speed, and 24-hour precipitation that were taken at solar noon, when the sun is at its peak directly overhead. Therefore**, historical estimations of FWI will need series of sub-daily data** that allows the estimation of solar noon variables. Just a limited number of stations and reanalyses-based datasets provide relative humidity at sub-daily temporal resolution and there are no comparison studies available on their performance over northern Canada for FWI computation.

b) **The estimation of historical trends for relative humidity and the relative humidity evaluation of reanalyses and models in northern Canada are complicated by issues with the instruments measuring relative humidity in cold climate** (Déry and Steiglitz, 2002). Icing and reservoir freezing were found to be particular problems for automatic stations in Canada if instruments were not checked regularly. It is recommended to use statistical methods to detect and adjust for artificial discontinuities in individual station records (homogenization). Homogenization, while unlikely to remove all non-climatic discontinuities in the data, produces a dataset that is far more robust (Willett, 2007). Wijngaarden and Vincent (2005) and Vincent *et al*., (2007) provide information on a homogenized data set of relative humidity and dew point temperatures for 75 stations in Canada. A significant negative step due to the replacement of the psychrometer by the dewcel instruments was observed for relative humidity at 52 stations, mostly in the Canadian North. For the dewpoint time series, the step for the introduction of the dewcel was observed at nine stations (mostly located in the northeast). Very few significant steps were detected in the specific humidity time series, because in cold temperatures, the specific humidity values are very low and do not vary much (Vincent *et al*., 2007). More information is provided in the Annex 7.3.1 which is describing MSC station measurements for humidity.

c) HadISDH dataset of monthly means of surface humidity was designed as a gridded product for studying **large scale trends and variability**, and assessing the validity of climate models. Stations incorporated in the product were homogenized and quality controlled. The effect of topographic elevation on spatial continuity in humidity is complex and relatively unstudied. In HadISDH, the interpolation is realized into a coarse global grid (5° x 5° spatial resolution). A single coarse-resolution grid box may incorporate a number of stations at different elevations (Willett *et al*., 2014). However, many studies mentioned that for trend analyses, anomalies are preferable to absolute values because they largely remove station specific variability (including variation due to elevation). HadISDH dataset includes anomalies values as well as absolute values.

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3.1.5 Surface Wind Speed and Direction

This section presents an inventory of historical datasets covering northern Canada that have available surface wind speed and/or direction. The information is summarized in Table 3.8.

Table 3.8 Summary of observation-based historical datasets with surface wind speed and/or direction available

Name	Source	Type	Spatial domain	Spatial resolution	Temporal coverage	Time step	Format	Comments	Link to metadata description and reference paper
MSC Observations	MSC/ECCC	Station data	Canada	Point data	Variable (1940 to present)	Hourly; Daily; Monthly	CSV; GeoJSON	In-situ surface measurements at the automatic and manual stations of ECCC stations. Available: direction of Maximum Gust (10s deg) and speed of Maximum Gust (km/h).	Description of data: Annex 7.4.1
MSC Climate Normals	MSC/ECCC	Station data	Canada	Point data	1941-1970, 1951-1980, 1961-1990, 1971-2000 and 1981-2010	Climatological means	CSV; GeoJSON	Provides Climate Normals at MSC stations, and they are based on Canadian climate stations with at least 15 years of data in the 30-year period.	Description of data: Annex 7.4.2
AHCCD	CRD/ECCC	Station data	Canada	Point data	Variable (1950 to 2014)	Monthly	ASCII; CSV; GeoJSON	In-situ wind data with adjustments (derived from statistical procedures) to the original record to account for discontinuities from non-climatic factors, such as instrument changes or station relocation.	Description of data: Annex 7.4.3 Reference: Wan *et al.* (2010)
Hydro-Québec Station data	Hydro-Québec	Station data	Northern Québec at hydroelectric stations	Point Data	Variable,1990 to present	Variable (sub-daily to daily)	n.a.	Hydro-Québec collects data at stations situated near their hydroelectric installations. The stations are mostly located south of the 55˚ parallel and vary in temporal coverage and resolution.	Description of data: Annex 7.2.5 Data: https://www.hydroquebec.com/documents-data/act-respecting-access/access-information-request.html
MISU	Bolin Centre for Climate Research Stockholm University	Ship-based data	Oden cruise trajectory	Point data	August, September, 2018	1-minute and 30-minute averages	Matlab; NetCDF; CSV	Measurements taken onboard the Icebreaker Oden during 2018 cruise from weather station including anemometer and Vaisala PTU pressure sensor, combined with computational fluid dynamics model to correct for wind direction.	Description of data: Bolin Centre for Climate Research

								Caution should be exercised for winds exceeding 60 ° from bow on.	Reference: Prytherch (2021) Vullers et al. (2021)
WorldClim2	World Conservation Monitoring Centre/UNEP	Gridded observations	Global (land only)	30 arc s (1 km)	1970-2000	Monthly	GeoTIFF	Interpolated using climate station data and satellite derived covariates. Provides values for wind speed.	Description of data: UNEP/GRID-Geneva Reference: Fick and Hijmans (2017)
PNWNAMET	PCIC	Gridded observations	North-western North America	3.75 arc minutes (~6 km)	1945-2012	Daily	ASCII; NetCDF	Wind data is derived by re-gridding 10 m wind speed from the 20th Century Reanalysis V2 (20CR2). The wind data have not been adjusted to take wind field deformation by small-scale topographic features into account.	Description of data: PCIC Reference: Werner *et al.* (2019)
Met1km	NRCan	Blend of gridded products	Canada	1 km x 1 km	1901–2100	Daily	n.a.	It is a blend of several other gridded products (CRU JRA, Princeton, NRCANmet, and PNWAmet). The data is constructed by adding interpolated anomalies (with respect to long-term climatology) from the coarse resolution gridded daily datasets overtop the high-resolution monthly 1 km climatology from WorldClim2. There can be issues with discontinuities at month boundaries using this approach unless the monthly climatology is properly smoothed to day-of-year climatology. Another concern is related to the temporal non-stationarity due to the stitching together of different gridded daily datasets in different parts of the 1901- period, and also potential loss of coherence between variables stemming from drawing different variables from different	Reference: Zhang *et al.* (2020)

								datasets within given blocks of time.	
Canadian Wind Atlas	ECCC	Numerical simulations	Canada	2 km	2008 – 2010	10 min	CSV	This product provides data for a limited number of years (2008 – 2010) that have not been recently updated. Its global counterpart, available for a longer timeframe (2008 – 2017), is the Global Wind Atlas.	Benoit et al., (2002) Modelled historical data Canada Wind Atlas
ERA5	ECMWF	Global atmospheric reanalysis	Global	0.25° x 0.25°	1950 - present	Hourly; Daily; Monthly	GRIB; NetCDF	5th generation reanalysis. Provides: Instantaneous 10m wind gust, 10m v and u component of wind, 10m v and u component of neutral wind, and 100m v and u component of wind.	Description of data: Annex 7.4.4 Reference: Hersbach *et al.* (2020)
CFSR	NCEP	Global atmospheric reanalysis	Global	0.5° x 0.5°	1979/01 to 2017/11	Sub-daily; Monthly	GRIB	3th generation reanalysis. CFSR ends March 2011; CFSV2 begins April 2011. Provides instantaneous 10m v and u component of wind.	Description of data: Annex 7.4.5 Reference: Saha *et al.* (2014)
MERRA-2	NASA	Global atmospheric reanalysis	Global	½° latitude x ⅝° longitude	1980/01 to present	Hourly; Daily; Monthly	NetCDF	2th generation reanalysis. Provides 2 m, 10 m and 50 m eastward and northward wind, surface wind speed and Maximum surface wind speed.	Description of data: Annex 7.4.6 Reference: Gelaro *et al.* (2017)
JRA-55	JMA	Global atmospheric reanalysis	Global	0.6258° x 0.6258°	1957/12 to 2021/05	3h; 6h; Daily; Monthly	NetCDF	2th generation reanalysis. Provides 10m v and u component of wind and 10m Maximum wind speed.	Description of data: Annex 7.4.7 Reference:

									Kobayashi *et al.* (2015)
ASRv2	Byrd Polar Research Center/The Ohio State University; UCAR/NCAR	Regional reanalysis	Arctic	15 km x 15 km	2000/01 to 2016/12	3h; Monthly	NetCDF	Is using the Polar Weather Research and Forecasting Model (PWRF) and High Resolution Land Data Assimilation (HRLDAS) systems and it is initialized and driven by ERA-Interim. Provides 10m v and u component of wind (grid relative as well as Earth relative components)	Description of data: Annex 7.4.8 Reference: Bromwich *et al.* (2010)
NARR	NCEP	Regional reanalysis	North America	32 km x 32 km	1979/01 to 2021/04	Sub-daily; Monthly	GRIB	It is initialized and driven by NCEP/NCAR Global Reanalysis 2. Provides u and v components of the wind at 10 m and 30 m.	Description of data: Annex 7.4.9 Reference: Mesinger *et al.* (2006)
RDRSv2	CCMEP/ECCC	Regional reanalysis	North America	10 km	2000 - 2017, (1980 - 1999 pending)	Hourly	RPN	It is initialized and driven by ERA-Interim reanalysis and rely only on surface observations and no remote sensing observations, such as satellite. Provides v and u component of wind (grid relative as well as Earth relative components), wind speed and meteorological wind direction at 10 m and 40 m.	Description of data: Annex 7.4.10 Reference: Gasset *et al.* (2021)
20CRv3	CIRES; NOAA; DOE	Global atmospheric reanalysis	Global	T254 (approximately 75 km at the equator)	20CRv3.SI is available for years 1836-1980 and 20CRv3.MO is available for years 1981-2015	3h; Daily; Monthly	NetCDF	Assimilates only surface observations of synoptic pressure and boundary conditions of pentad sea surface temperature and monthly sea ice concentration and time-varying solar, volcanic, and carbon dioxide radiative forcings are prescribed. Provides V and u component of wind at 10 m above the surface.	Description of data: ANNEX 7.4.11 Reference: Compo *et al.* (2011)
ERA5-Land	ECMWF	Land surface reanalysis/model	Global (land only)	0.1° x 0.1° (9 km)	1950 to present	Hourly; Monthly	GRIB; NetCDF	Off-line land model driven by ERA5 using a finer spatial resolution and including a series of improvements making it more accurate for all types of land applications. Do not include direct assimilation of data: it is indirectly influenced through the ERA5 atmospheric forcings.	Description of data: Annex 7.4.12 Reference: Muñoz-Sabater *et al.* (2021)

								Provides V and u component of wind at 10 m above the surface. The output is interpolated to 0.10 deg lon/lat from the native model grid of 9 km.	
ECOA	ECMWF	Operational analysis	global	7 km	2016-present	6-hourly	NetCDF4		NCAR link Moore, 2021
AgERA	ECMWF	Re-gridded reanalysis	Global (land only)	0.1° x 0.1°	1979-present	Daily	NetCDF	Downscales ERA5 using regression equations trained on ECMWF's operational high-resolution atmospheric model (HRES) at a 0.1° resolution. Provides values for 10m wind speed.	Description of data: Copernicus
AgCFSR	NASA	Re-gridded reanalysis with corrections	Global (land only)	0.25° × 0.25°	1980-2010	Daily	NetCDF	This data is an end product (will not be updated). Provides wind speed obtained by adjusted CFSR 10 m wind speeds to 2 m velocities and then linearly interpolating it to 0.25-degree grid.	Description of data: NASA Reference: Ruane *et al.* (2015)
AgMERRA	NASA	Re-gridded reanalysis with corrections	Global (land only)	0.25° × 0.25°	1980-2010	Daily	NetCDF	This data is an end product (will not be updated). MERRA wind speeds are linearly interpolated to 0.25-degree grid.	Description of data: NASA Reference: Ruane *et al.* (2015)
GMFD	Princeton University	Re-gridded reanalysis with corrections	Global (land only)	0.25° × 0.25°	1948-2016	3h; Daily; Monthly	NetCDF	This data is an end product (will not be updated). Combines NCEP reanalysis with observation-based datasets (namely the monthly CRU TS3.24.01 gridded at 0.5 horizontal spatial resolution). Provides surface wind speed.	Description of data: RDA Princeton Reference: Sheffield *et al.* (2006)
CRU JRA v2.1	CRU/University of East Anglia	Re-gridded reanalysis with corrections	Global (land only)	0.5° × 0.5°	Jan.1901 - Dec. 2020	6h	NetCDF	Combines JRA-55 reanalysis with CRU gridded-observation dataset. Provides zonal and meridional components of wind speed.	Description of data: CEDA Archive
S14FD	DIAS	Re-gridded reanalysis with corrections	Global	0.5° x 0.5°	1958-2013	Daily	NetCDF	This data is an end product (will not be updated). Combines JRA-55 reanalysis with	Description of data: DIAS Reference:

								gridded-observation datasets. Provides values for daily 10m wind speed.	Iizumi *et al.* (2017)

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3.1.6 Supplementary meteorological station data

The following table is presenting some station data that are not included in MSC network of stations and could be of interest for local applications.

Table 3.9 Supplementary meteorological station data

Name	Source	Data type	Spatial domain	Spatial Resolution	Temporal Coverage	Time Step	Format	Comments	Link to metadata description and reference paper
Bennett Townsite, Yukon	Parks Canada	Station data	1 station in Yukon	Point data	Since 2015	Hourly	n.a.	Less than 10 years of data. Available variables: rainfall 1h, 2m temperature, relative humidity, wind direction, wind gust, wind Speed Details at: http://rwis.gov.yk.ca/stations/PCB/	Description of data: Annex 7.5.1
Yukon Avalanche Association Weather Network	Yukon Avalanche Association	Station data	1 to 7 stations (depending on variable) in Yukon	Point data	Variable (some starts in 1970, other in 2018)	Variabl e (sub-daily to daily)	n.a.	It is not yet clear if data is stored and may be available for public. Available variables: precipitation, 2m temperature, relative humidity, wind direction, wind gust, wind speed Details at: http://www.yukonavalanche.ca/wx	Description of data: Annex 7.5.2
Kluane Lake Research Station	Arctic Institute of North America/University of Calgary	Station data	Single weather station in Yukon	Point data	Depends on variable; most of them are from June 2017 to present.	Sub-daily	CSV; Excel files; NetCDF	Data currently available on request: intention is to link station to Arctic Sensor Web database. Data available through Global Cryosphere Watch (currently from sporadic multi-month manual downloads) Temporary URL: https://sulzfluh.slf.ch/kluane.nc.html Available variables: precipitation, 2m temperature, relative humidity, wind direction, wind gust, wind speed	Description of data: Annex 7.5.3
Scotty Creek Research Site, Northwest Territories	Bill Quinton/Wilfred Laurier University	Station data	3 stations in Northwest Territories	Point data	Depends on station (staring in 2001, 2004, and 2007)	30 min.	n.a.	Details at: https://ccrnetwork.ca/science-programme/wecc-observatories/scotty-creek.php http://giws.usask.ca/meta/Metadata_ScottyCreek.html http://www.scottycreek.com Available variables: precipitation, 2m temperature, relative humidity, wind direction, wind ppeed	Description of data: Annex 7.5.4

Trail Valley Creek Research Site, Northwest Territories.	Dr. Phil Marsh/Wilfred Laurier University	Station data	3 stations in Northwest Territories	Point data	1991-2013	30 min.	n.a.	Available variables: precipitation, 2m temperature, relative humidity, wind direction, wind Speed	Description of data: Annex 7.5.5
Havikpak Creek Research Site, Northwest Territories	Dr. Phil Marsh/Wilfred Laurier University	Station data	1 station in Northwest Territories	Point data	1991-2013	30 min.	n.a.	Details at: https://ccrnetwork.ca/science-programme/wecc-observatories/havikpak-creek.php http://giws.usask.ca/meta/Metadata_HavikpakCreek.html Available variables: precipitation, 2m temperature, relative humidity, wind direction, wind speed	Description of data: Annex 7.5.6
Wolf Creek Research Basin, Yukon	Dr. Sean Carey/McMaster University	Station data	6 stations in Yukon	Point data	Varies with the station (from 1993 to 2018)	30 min.	n.a.	Carey (McMaster U.) leads the research in collaboration with Yukon government, ECCC, and others from GWF. Near-real-time graphs available for 3 stations at http://giws.usask.ca/telemetry/WolfCreek/mobile/Alpinechart_mob.html http://giws.usask.ca/telemetry/WolfCreek/mobile/Buckbrushchart_mob.html http://giws.usask.ca/telemetry/WolfCreek/mobile/Forestchart_mob.html Several links from GWF site: not clear which provides most up-to-date details https://ccrnetwork.ca/science-programme/wecc-observatories/wolf-creek.php http://giws.usask.ca/meta/Metadata_WolfCreek.html https://gwfnet.net/Metadata/Record/T-2021-02-27-M1M2i2h80VKUijFOFoBEM3wFw Summary slides about the observatory (2017) at https://gwf.usask.ca/documents/meetings/asm2018/TdeJong.pdf	Description of data: Annex 7.5.7

								Contact point: Tyler DeJong (tyler.dejong@mcmaster.ca) Available variables: precipitation, 2m temperature, relative humidity, wind direction, wind speed	
Baker Creek Research Site, Northwest Territories	Chris Spence/ECCC; University of Saskatchewan; Carleton University	Station data	7 stations in Northwest Territories	Point data	2005-2013	30 min.	n.a.	Details at: https://ccrnetwork.ca/science-programme/wecc-observatories/baker-creek.php http://giws.usask.ca/meta/Metadata_BakerCreek.html Available variables: precipitation, 2m temperature, relative humidity, wind direction, wind speed	Description of data: Annex 7.5.8

3.2 Snow and hydrology data

Lead Authors: Lawrence Mudryk (CRD/ECCC), Stephen Déry (University of Northern British Columbia), Emilia Diaconescu (CCCS/ECCC)

*Contributors: Michael Allchin (University of Calgary), Marco Braun (Ouranos), Brian Horton (Yukon University Research), Rajesh Shrestha (*WHERD/ECCC*), Tricia Stadnyk (University of Calgary)*

3.2.1 Snow related variables

Snow covers the Arctic land surface for up to nine months each year, and influences the surface energy budget, ground thermal regime, and freshwater budget of the Arctic. Snow also interacts with vegetation, affects biogeochemical activity, and influences migration and access to forage for wildlife, which impacts terrestrial and aquatic ecosystems. Even following the snow cover season, the influence of spring snowmelt timing persists through impacts on river discharge timing and magnitude, surface water, soil moisture, and fire risk. Snow can be characterized by multiple variables. Snow presence (important for the surface energy budget) can be characterized by how much area is covered by snow (**snow cover extent - SCE**) and how long snow remains on the land surface (**snow cover duration - SCD**). The amount of snow is more important for determining influences on the ground thermal regime and freshwater budget and timing. There are two main ways to measure snow on the ground: (1) measuring the total depth of snow on ground (this is reported as **snow depth** and it includes both new and old snow) or (2) measuring the liquid water content of snow from a gauge or from a core sample (this is reported as **snow water equivalent - SWE**). The SWE from a gauge corresponds to new snow that had fallen in 24 hours. The SWE from a core represents the new and the old snow. The SWE can be thought of as the depth of water that would theoretically result if you melted the entire snowpack instantaneously. Snow depth and SWE can also be estimated from satellite products, reanalyses or models.

In this section, we present an inventory of snow depth, SWE and snow cover data obtained using the three categories:

(1) In-situ measurements

(2) Satellite-derived products

(3) Analyses, reanalyses and reanalysis-driven products.

In the selection, we use datasets that are freely available online, represent an important source of information, cover at least a decade of data, and have supporting documentation. The datasets that provide only snow depth are summarised in the first table, those that provide only SWE are summarized in the second table, while the datasets that provide both snow depth and SWE are presented in the third table. The fourth table focuses on snow cover data.

Table 3.10: Snow Depth

Name	**Source**	**Type**	**Spatial Domain**	**Spatial Resolution**	**Temporal Coverage**	**Time Step**	**Format**	**Notes**	**Link to metadata description**
MSC Snow Depth Observations	MSC/ECCC	Station data	Canada	Point data	Variable (1970-2019)	Daily	CSV; GeoJSON	The number of stations in northern Canada is small and the records have missing values.	Description of data: CCCS data extractor
Canadian Historical Daily Snow Depth Data	CRD/ECCC	Station data	Canada	Point data; peak of ~2000 stations in 1980s; most data located south of ~55 N; rapid decline in station numbers after 1995	variable 1883-2017; Pan-Canadian coverage after ~1955	Daily	ASCII; NetCDF	Product based on quality controlled data from a variety of sources (e.g., COCORAHS), but mostly MSC Station Data. Mainly manual ruler observations (average of several measurements in open area free of drifting snow), but with more frequent SR50-equipped autostation observations in the period since ~2000. Dataset not updated regularly. Observations are made at	Description of data: Annex 7.5.10 Reference: Brown and Braaten (1998), Brown *et al.* (2021). Daily snow depth observations (without

Name	Source	Type	Spatial Domain	Spatial Resolution	Temporal Coverage	Time Step	Format	Notes	Link to metadata description
								open, grassed sites, often at airports, that may not be representative of snow conditions in the prevailing land cover. Manual ruler observations report systematically more snow than SR50 sensors.	QC) can also be downloaded from CCCS data extractor
ISD	NCEI/NOAA	Station data	Global	Point data; ~20,000 stations; NH coverage most dense over mid-latitudes	Variable, 1902 - present	Sub-daily; Daily	ASCII	The Integrated Surface Database (ISD) consists of global hourly and synoptic observations compiled from numerous sources into a single common ASCII format and common data model. ISD integrates data from over 100 original data sources, including numerous data formats that were key-entered from paper forms during the 1950s–1970s time frame.	Description of data: https://www.ncei.noaa.gov/products/land-based-station/integrated-surface-database Reference: Smith *et al.* (2011)
ANUSPLIN	CFS/NRCan	Gridded observations	Canada	10 km x 10 km	1955-2017	Monthly	ASCII; NetCDF	This gridded dataset provides snow depth from 1955 - 2017 period at monthly time scales over Canada. It was generated using ANUSPLIN with a 300 arc-second (approximately 10 km) Digital Elevation Model and station observations from Environment and Climate Change Canada (ECCC) and NOAA.	Description of data: ANNEX 7.5.9 Reference: MacDonald and McKenney (2021)
Bennett Townsite, Yukon	Parks Canada	Station data	1 site	Point data	Since 2015	Hourly	n.a.	Less than 10 years of data.	Description of data: Annex 7.5.1 http://rwis.gov.yk.ca/stations/PCB/
Yukon Avalanche Association Weather Network	Yukon Avalanche Association	Station data	2 sites	Point data	Since 2011, 2018	n.a.	n.a.	Measures snow depth to support assessment of avalanche risk. It is not yet clear if data are stored and may be available.	Description of data: Annex 7.5.2 http://www.yukonavalanche.ca/wx

Name	Source	Type	Spatial Domain	Spatial Resolution	Temporal Coverage	Time Step	Format	Notes	Link to metadata description
White Pass Railway & River Divisions dataset, Yukon	Yukon Research Centre	Station data	25 stations, from coast to interior Yukon - Skagway to Dawson and Wernecke	Point data	Earliest start Apr. 1902, latest finish Dec. 1957: median 25 yrs, max. 55.7 yrs	Daily	Excel files	Manual snow depth (ruler). Data transcribed and stored in separate .xls file per station.	Transcribed data available at http://yukonresearch.yukoncollege.yk.ca/public/wpyr
Kluane Lake Research Station	Arctic Institute of North America/University of Calgary	Station data	Single weather station	Point data	June 2017 to present	30 min.	CSV; Excel files; NetCDF	SR50 snow depth. Data currently available on request: intention is to link station to Arctic Sensor Web database to ensure near-real-time updates	Description of data: Annex 7.5.3 Data available through Global Cryosphere Watch (currently from sporadic multi-month manual downloads) Temporary URI: https://sulzfluh.slf.ch/kluane.nc.html

Table 3.11: SWE

Name	Source	Type	Spatial Domain	Spatial Resolution	Temporal Coverage	Time Step	Format	Notes	Link to metadata description
CanSWE	CRD/ECCC	Station data	Canada	Point data; Transects, network peaks at ~2000 surveys in period 1965 - 1985; most data located south of ~55 N	1928 - 2020	Daily	NetCDF	Pillows (British Columbia/Alberta) and GMON (Quebec, Newfoundland and Labrador), manual snow transects elsewhere which includes Yukon, Northwest Territories, Nunavut. Includes manual and automated pan-Canadian observations of SWE collected by national, provincial and territorial agencies as well as hydropower companies and their partners. This new dataset	Description of data: Annex 7.5.11 10.5281/zenodo.4734372 Reference : Vionnet *et al.* (2021)

Name	Source	Type	Spatial Domain	Spatial Resolution	Temporal Coverage	Time Step	Format	Notes	Link to metadata description
								supersedes the previous Canadian Historical Snow Survey dataset published by Brown et al. (2019).	
AMSR-E Historical Algorithm	NSIDC	Satellite data	The Northern Hemisphere	25 km EASE (equal area)	2002-06-19 to 2010-08-27	Daily; Weekly; Monthly	HDF	Passive microwave (PMW) only. Not suitable for use.	Description of data: Annex 7.5.24 https://nsidc.org/data/amsre
AMSR-E Operational Algorithm	NSIDC	Satellite data	The Northern Hemisphere	25 km EASE (equal area)	2010-08-27 to 2011-10-3	Daily; Weekly; Monthly	HDF	Passive microwave (PMW) only. Not suitable for use.	Description of data: Annex 7.5.24 https://nsidc.org/data/amsre
GlobSnow	ESA	Gridded hybrid data: observations, satellite	The Northern Hemisphere	25 km EASE1 (equal area)	1979-2018	Daily; Weekly; Monthly	Matlab; NetCDF	A series of versions exists: v1.0, v2.0, v2.1, v3.0. NRT version also exists. Version 3.0 is close to Snow CCI, Combination of climate station snow depth observations and forward microwave emission model simulations with SMMR and SSM/I satellite passive microwave data. Version 3.0 includes several enhancements: (1) inclusion of lake ice; (2) revised modelling of forest canopy Tb; (3) enhanced surface observations and quality control. A V3 bias-corrected version includes corrections based on snow. Data is available at daily time step after 1987, every other day before that with some gaps. Also available weekly and monthly.	Description of data: Annex 7.5.12 http://www.globsnow.info Reference : Takala *et al.* (2011); Pulliainen *et al.* (2020)
Snow CCI	ESA	Gridded hybrid data: observations, satellite	The Northern Hemisphere	25 km; 12.5 km EASE2	1979-2018	Daily	NetCDF	Related to GlobSnow product but developed under ESA CCI+. Snow CCI v1.0 resembles GlobSnow 3.0. Subsequent releases of Snow CCI differ more. Data is available at daily time step after 1987, every other day before that with some gaps.	Description of data: Annex 7.5.13 https://climate.esa.int/en/odp/#/project/snow Reference:

Name	Source	Type	Spatial Domain	Spatial Resolution	Temporal Coverage	Time Step	Format	Notes	Link to metadata description
									Venäläinen *et al.* (2021)

Table 3.12: Snow Depth and SWE*

*Generally both SWE and snow depth are available from reanalysis output, but sometimes only one is provided along with snow density by which the other can be computed.

Name	Source	Type	Spatial Domain	Spatial Resolution	Temporal Coverage	Time Step	Format	Notes	Link to metadata description
Crocus-ERA5	Météo-France	Model based on reanalyses	Global	0.25° x 0.25°	Jan 1981--present (ongoing, annual updates)	Daily	NetCDF	SWE: the mass of surface snow on the land portion of the grid cell divided by the land area in the grid cell; excludes snow on vegetation canopy or on sea ice. Snow depth: daily grib-box average of the snow thickness on the ground (excluding snow on canopy).	Will be available on public data server by 2022 . Contact point: bertrand.decharme@meteo.fr
ERA5-Land	ECMWF	Land surface reanalysis/ model	Global	0.1° x 0.1° (9 km)	Jan 1950--present (ongoing, ~3 month latency)	Hourly; Monthly	GRIB; NetCDF	SWE: Water equivalent depth using snow from the snow-covered area of a grid box. The ECMWF Integrated Forecast System represents snow as a single additional layer over the uppermost soil level. The snow may cover all or part of the grid box. Snow depth: Instantaneous grib-box average of the snow thickness on the ground (excluding snow on canopy). It does not assimilate any observations so it does not contain the snow discontinuity present in ERA5.	Description of data: Annex 7.5.14 Reference: Muñoz-Sabater *et al.* (2021)

Name	Source	Type	Spatial Domain	Spatial Resolution	Temporal Coverage	Time Step	Format	Notes	Link to metadata description
								The output is interpolated to 0.10 deg lon/lat from the native model grid of 9 km. DOI: 10.24381/cds.e2161bac	
NARR	NCEP	Regional reanalysis	North America	32 km x 32 km	1979/01/01 to May 31, 2021	3h; Daily; Monthly	GRIB; NetCDF	It is initialized and driven by NCEP/NCAR Global Reanalysis 2. Based on the Noah land surface process model and assimilated snow depths from US Air Force daily snow depth analysis.	Description of data: Annex 7.5.15 Reference: Mesinger *et al.* (2006)
RDRSv2.1	CCMEP/ECCC	Regional reanalysis	North America	10 km x 10 km	2000 - 2017, (1980 - 1999 pending)	Hourly	RPN	Data are not available in previous versions because of an error discovered in the code for snow depth affecting RDRS (version 1.0 or "RDRS-1.0") and RDRS_v2 (or "RDRS-2.0"). Snow output should only be used from the present release RDRS_v2.1.	Description of data: Annex 7.5.16 Reference: Gasset *et al.* (2021)
NLDAS LSM	NASA	Land surface reanalysis/ model	Central North America (25-53 North).	0.125 deg.	1979 - present	Hourly; Monthly	GRIB	Mosaic, Vic, Noah and SAC LSMs forced with output from NLDAS-2. **Covers just a small area of northern Canada.**	Description of data: http://ldas.gsfc.nasa.gov/nldas/NLDAS2model_download.php Reference: Xia *et al.* (2012)
ERA5	ECMWF	Global atmospheric reanalysis	Global	0.25° x 0.25°	1950 - present	Hourly; Monthly	GRIB; NetCDF	2D-OI using SYNOP snow depth observations. IMS assimilation for snow extent starting in 2004. HTESSEL land surface scheme (single snow layer). Discontinuity in 2004 with assimilation of IMS-4km snow cover extent (Orsolini et al. 2019; Mortimer et al. 2020).	Description of data: Annex 7.5.17 Reference: Hersbach *et al.* (2020)

Name	Source	Type	Spatial Domain	Spatial Resolution	Temporal Coverage	Time Step	Format	Notes	Link to metadata description
ASRv2	Byrd Polar Research Center/The Ohio State University; UCAR/NCAR	Regional reanalysis	Arctic	15 km x 15 km	2000/01 to 2016/12	3h; Monthly	NetCDF	Is using the Polar Weather Research and Forecasting Model (PWRF) and High Resolution Land Data Assimilation (HRLDAS) systems and it is initialized and driven by ERA-Interim. Snow cover and snow albedo are assimilated from the National Environmental Satellite, Data, and Information Service (NESDIS) observations and vary seasonally to represent melting and freezing.	Description of data: Annex 7.5.18 Reference: Bromwich *et al.* (2010)
MERRA-2	NASA	Global atmospheric reanalysis	Global	0.625° x 0.5°	1980-present	Hourly; Daily; Monthly	NetCDF	Catchment land surface model. SWE diagnosed from MERRA, 2 fields with multilayer, physical snow pack mode. Performance comparable to MERRA and ERA-Interim Land. Brown et al. (2018) found MERRA-2's ability to capture interannual variability in maximum annual SWE over southern Quebec was degraded compared to MERRA.	Description of data: Annex 7.5.19 Reference: Gelaro *et al.* (2017)
JRA-55	JMA	Global atmospheric reanalysis	Global	0.6258° x 0.6258°	1958 - present	3h; 6h; Monthly	GRIB	2D-OI using SYNOP snow depth observations; JMA Simple Biosphere model (single snow layer); passive microwave derived snow extent starting in 1987; 4D-Var data assimilation. Includes the same snow data sources as JRA-25 plus additional snow depth data over USA, Russia and Mongolia.	Description of data: Annex 7.5.20 Reference: Kobayashi *et al.* (2015)
20CRv3	CIRES; NOAA; DOE	Global atmospheric reanalysis	Global	T254 (approximately 75 km at the equator)	20CRv3.SI is available for years 1836-1980 and 20CRv3.MO is available for years 1981-2015	3h; Daily; Monthly	NetCDF	NCEP Global Spectral Model atmosphere coupled to Noah land surface model (single snow layer). Assimilates only surface observations of synoptic pressure and boundary conditions of pentad sea surface temperature and monthly sea ice concentration and time-varying solar, volcanic, and carbon dioxide radiative forcings are prescribed. More information is provided by Slivinski et al. (2019)	Description of data: Annex 7.5.21 Reference: Compo *et al.* (2011)

Name	Source	Type	Spatial Domain	Spatial Resolution	Temporal Coverage	Time Step	Format	Notes	Link to metadata description
CFSR + CFSv2	NCEP	Global atmospheric reanalysis	Global	0.5° x 0.5°	1979-2010 (CFSR) 2011-present (CFSv2)	Hourly; 6h; Monthly	GRIB	3DVAR assimilation using snow simulated by Noah 4-layer land surface process model, SWE obs from US Air Force daily snow depth analysis and snow cover analysis from IMS. Klehmet et al. (2013) found CFSR to underestimate SWE over most of Siberia compared to GlobSnow and surface observations. Problems with snow depth were noted during the following dates: Dec 26, 1980 Dec 25,27-28 1999 All days between Jan 1, 2009 and Jan 1, 2011 Jan 25, 2011	Description of data: Annex 7.5.22 Reference: Saha *et al.* (2014)
GLDAS-2.0 (Noah LSM)	NASA	Land surface reanalysis/ model	Global	0.25° x 0.25°	1948-2014	3h; Monthly	GeoTIFF; KMZ; NetCDF	Noah land surface model driven offline by GLDAS-2 forced with the global meteorological dataset from Princeton University (Sheffield et al., 2006). Abnormally high SWE values over Greenland and other points with conditions conducive to land ice formation. These need to be masked out. Excepting these locations, this product has anomalously low climatological SWE compared to most other products. Infrequent updates. Online documentation (Rui and Beaudoing 2014): https://data.mint.isi.edu/files/raw-data/GLDAS_NOAH025_M.2.0/doc/README_GLDAS2.pdf	Description of data: http://ldas.gsfc.nasa.gov/gldas/ http://disc.sci.gsfc.nasa.gov/hydrology/data-holdings Reference: Rodell *et al.* (2004)
Liston and Hiemstra (2011) dataset	UCAR/NCAR	Model based on reanalyses	Northern Hemisphere land area, north of ~55 N	10 km x 10 km	1979-2009	3h	CTL; Gdat	Snow model driven by 10 km downscaled MERRA output. Incorporates SnowTran blowing snow model. No land/sea mask provided. SWE set to zero over water points. Provides data for snow precipitation, snow-season timing and length, maximum snow water equivalent depth (SWE), average snow density, snow sublimation, and rain-on-snow events.	Description of data: http://data.eol.ucar.edu/codiac/dss/id=106.309
USDA snow courses	NRCS/US Dept. of Agriculture	Station data	Western US, Canada, and Alaska	Point data; 1,111 courses concentrate	1935--	Monthly	n.a.	Manually measured snow courses. Online data updated monthly; Data used for monthly water supply forecasts. Data available at monthly	Description of data:

Name	Source	Type	Spatial Domain	Spatial Resolution	Temporal Coverage	Time Step	Format	Notes	Link to metadata description
				d in mountains of western USA, Canada and Alaska				timestep, from January to June. Contact Mike Strobel (michael.strobel@por.usda.gov)	http://www.wcc.nrcs.usda.gov/snow/ http://www.wcc.nrcs.usda.gov/webmap/index.html
Yukon Snow Survey Network	Department of Environment/ Yukon Government	Station data	Yukon-wide; 57 active sites, 28 discontinued	Point data	Variable (~1975-05-01 - present)	One or several times per year	CSV	Manual snow survey sampling from snow courses consisting of 10 measurement points. Measurements of SWE, and snow density are expressed as an average across the snow course. Measurements are taken three times a year at the start of March, April, and May.	Description of data: https://open.yukon.ca/data/datasets/yukon-snow-survey-network
Northwest Territories dataset	Department of Environment and Natural Resources/GNWT	Station data	Northwest Territories Wide; approx 67 sites.	Point data	Information not available	One or several times per year	n.a.	Done in partnership with Northwest Territories Power corp and GNT Lands District Offices. The Government of the Northwest Territories (GNWT) measures the volume of snow at the end of the season (April) at a network of survey sites. Values are converted to a SWE to enable annual data to be compared from one year to the next. An annual spring bulletin is distributed to various government agencies and industry to inform them of anticipated freshet conditions.	Description of data: https://www.enr.gov.nt.ca/sites/enr/files/enr_snow_survey_locations_jan_2016.pdf
Scotty Creek Research Site, Northwest Territories	Bill Quinton/Wilfred Laurier University	Station data	Scotty Creek, Deh Tah region of Northwest Territories	Point Data	Since 1995	n.a.	n.a.	https://ccrnetwork.ca/science-programme/wecc-observatories/scotty-creek.php http://giws.usask.ca/meta/Metadata_ScottyCreek.html http://www.scottycreek.com	Description of data: Annex 7.5.4
Trail Valley Creek Research Site,	Dr. Phil Marsh/Wilfred Laurier University	Station data	Trail Valley Creek, Northwest Territories	Point data	Since 1991: not every year included	Annual	n.a.	Login required or available by request at Phil Marsh	Description of data: Annex 7.5.5

Name	Source	Type	Spatial Domain	Spatial Resolution	Temporal Coverage	Time Step	Format	Notes	Link to metadata description
Northwest Territories.									
Havikpak Creek Research Site, Northwest Territories	Dr. Phil Marsh/Wilfred Laurier University	Station data	Havikpak Creek, Northwest Territories	Point data	Since 1991: not every year included	Annual	n.a.	https://ccrnetwork.ca/science-programme/wecc-observatories/havikpak-creek.php http://giws.usask.ca/meta/Metadata_HavikpakCreek.html Login required or available by request at Phil Marsh	Description of data: Annex 7.5.6
Yukon Water Resources Meteorological Network	Yukon Government	Station data	Of a total of 4 active AWSs, 2 have 30+ yr records - Tagish (09AA-M1), Withers Lake (09DB-M1).	Point data	Installed 1989, 1991	n.a.	n.a.	SWE from snow scales (historically snow pillows); depth from sonic sensor. Not contributing to ECCC network. Dataset available on request (but no guarantees on response time). Provided by Yukon Govt: Anthony.Bier@yukon.ca	
Wolf Creek Research Basin, Yukon	Dr. Sean Carey/McMaster University	Station data	Wolf Creek, Yukon	Point data	Various: observatory has been operating since 1992 Note, though, that some individual instrumentation arrays have been more permanent, than others- the latter more sporadic, to support specific projects.	Monthly	n.a.	Monthly surveys of SWE, snow depth; 10 SWE instruments in total Carey (McMaster U.) leads research here, in collaboration with YG, ECCC, others (through GWF) Several links from GWF site: not clear which provides most up-to-date details https://ccrnetwork.ca/science-programme/wecc-observatories/wolf-creek.php http://giws.usask.ca/meta/Metadata_WolfCreek.html https://gwfnet.net/Metadata/Record/T-2021-	Description of data: Annex 7.5.7

Name	Source	Type	Spatial Domain	Spatial Resolution	Temporal Coverage	Time Step	Format	Notes	Link to metadata description
								02-27-M1M2i2h80VKUijFOFoBEM3wFw Near-real-time graphs available for 3 stns at http://giws.usask.ca/telemetry/WolfCreek/mobile/Alpinechart_mob.html http://giws.usask.ca/telemetry/WolfCreek/mobile/Buckbrushchart_mob.html http://giws.usask.ca/telemetry/WolfCreek/mobile/Forestchart_mob.html Some from GWF WISKI (login required): some by request from Yukon Govt (no guarantees on response times) Summary slides about the observatory (2017) at https://gwf.usask.ca/documents/meetings/asm2018/TdeJong.pdf Contact point: Tyler DeJong (tyler.dejong@mcmaster.ca)	
Baker Creek Research Site, Northwest Territories	Chris Spence/ECCC; University of Saskatchewan; Carleton University	Station data	Baker Creek, Northwest Territories	Point data	from 2004	Annual	n.a.	Eight 25 point snow courses over five land cover types conducted in the first week of April. https://ccrnetwork.ca/science-programme/wecc-observatories/baker-creek.php http://giws.usask.ca/meta/Metadata_BakerCreek.html GWF WISKI (login required) or by request from C. Spence	Description of data: Annex 7.5.8

Table 3.13. Snow cover fraction

Name	Source	Type	Spatial domain	Spatial resolution	Temporal coverage	Time step	Format	Comments	Link to metadata description
ERA5-Land	ECMWF	Land surface reanalysis/model	Global	0.1° x 0.1° (9 km)	Jan 1950--present (ongoing, ~3 month latency)	Hourly; Monthly	GRIB; NetCDF	Uses a revised version of the Tiled ECMWF Scheme for Surface Exchanges (TESSEL) scheme that incorporates land surface hydrology (H-TESSEL); The low atmospheric forcing is provided by the ERA5 reanalysis, with additional lapse-rate correction. Observations are thus indirectly incorporated through the ERA5 4D-VAR data assimilation system. The output is interpolated to 0.10 deg lon/lat from the native model grid of 9 km.	Description of data: Annex 7.5.14 Reference: Muñoz-Sabater *et al.* (2021)
NARR	NCEP	Regional reanalysis	North America	32 km x 32 km	1979/01/01 to May 31, 2021	3h; Daily; Monthly	GRIB; NetCDF	Based on the Noah land surface process model and assimilated snow depths from US Air Force daily snow depth analysis.	Description of data: Annex 7.5.15 Reference: Mesinger *et al.* (2006)
ASRv2	Byrd Polar Research Center/The Ohio State University; UCAR/NCAR	Regional reanalysis	Arctic	15 km x 15 km	2000/01 to 2016/12	3h; Monthly	NetCDF	Is using the Polar Weather Research and Forecasting Model (PWRF) and High Resolution Land Data Assimilation (HRLDAS) systems and it is initialized and driven by ERA-Interim. Snow cover and snow albedo are assimilated from the National Environmental Satellite, Data, and Information Service (NESDIS) observations and vary seasonally, again, to represent melting and freezing.	Description of data: Annex 7.5.18 Reference: Bromwich *et al.* (2010)
MERRA-2	NASA	Global atmospheric reanalysis	Global	½° latitude x ⅝° longitude	1980-present	Hourly; Daily; Monthly	NetCDF	Catchment-based land surface model.	Description of data: Annex 7.5.19 Reference: Gelaro *et al.* (2017)

20CRv3	CIRES; NOAA; DOE	Global atmospheric reanalysis	Global	T254 (approximately 75 km at the equator)	20CRv3.SI is available for years 1836-1980 and 20CRv3.MO is available for years 1981-2015	3h; Daily; Monthly	NetCDF	NCEP Global Spectral Model atmosphere coupled to Noah land surface model (single snow layer). Assimilates only surface observations of synoptic pressure and boundary conditions of pentad sea surface temperature and monthly sea ice concentration and time-varying solar, volcanic, and carbon dioxide radiative forcings are prescribed. More information is provided by Slivinski et al. (2019)	Description of data: Annex 7.5.21 Reference: Compo *et al.* (2011)
CFSR + CFSv2	NCEP	Global atmospheric reanalysis	Global	0.5° x 0.5°	1979-2010(CFSR) 2011-present (CFSv2)	Hourly; 6h; Monthly	GRIB	3DVAR assimilation using snow simulated by Noah 4-layer land surface process model, SWE obs from US Air Force daily snow depth analysis and snow cover analysis from IMS.Klehmet et al. (2013)	Description of data: Annex 7.5.22 Reference: Saha *et al.* (2014)
MODIS *Terra* / *Aqua*	NSIDC; NASA	Interpreted/diagnosed from optical imagery	Global	500 m (nominal) on sinusoidal grid 0.05° Climate Modelling Grid	*Terra*: 24 Feb. 2000 - present *Aqua*: 4 Jul. 2002 - present	Sub-daily; Daily; Monthly	GeoTIFF; HDF	NDSI generated from optical images, with several additional filters. Data available as 5-min. swath scene, daily, 8 days and 1-month, in HDF-EOS2 format. Note that areas viewed under Polar Night are presumed to be snow-covered.	Description of data: Annex 7.5.23 https://modis.gsfc.nasa.gov/data/dataprod/mod10.php https://nsidc.org/data/modis/data_summaries
NOAA Climate Data Record of Northern Hemisphere Snow Cover Extent version 1	NCEI/NOAA; Rutgers U.	Interpreted/diagnosed from optical imagery	Northern Hemisphere	89 x 89 grid: cell size varies with latitude, from ~10,700 km² near lat. 0° to ~41,800 km² near lat. 90°N	Record begins in 1966 (but more reliable from 1970)	Weekly	NetCDF	Binary classification based on 50% threshold. Initially mapped by manual analysis: more automated system adopted from 1999. Data available as NetCDF (legacy ASCII data from rutgers website). Full details in Estilow et al. (2015)	Description of data: Annex 7.5.25 https://doi.org/10.7289/V5N014G9 http://climate.rutgers.edu/snowcover/

Rutgers Northern Hemisphere 24 km Weekly Snow Cover Extent	Rutgers U.; NSIDC	Interpreted/diagnosed from optical imagery	Northern Hemisphere	1024 x 1024 grid: Cell areas range from ~159 km^2 at the equator to ~651 km^2 near the pole	Sept 1980 - present	Weekly	NetCDF	As above, but in this dataset snow charts used before 1999 are digitized at 24 km resolution starting from late 1980. Starting in 1999, Northern Hemisphere snow charts are produced at 24 km resolution on a daily basis using the IMS data.	Description of data: https://nsidc.org/data/g10035

Scales of snow data

While many processes combine at a variety of scales to influence the spatial heterogeneity of snow, in the following description we roughly divide snow depth and SWE datasets into two groups based on a single scale break: L ~ 1 km:

1. Datasets constructed from point data or grouped data representative up to a spatial scale of several hundred metres.

2. Datasets representative of spatial scales L >1 km.

Snow data characterized by spatial scales <1 km are influenced by wind redistribution and local scale topography or vegetation (e.g., wind-related drifting of snow or deep vs shallow snow in low vs high relief; Brown *et al*. 2010; Mott *et al*. 2018). The influence of these processes begins to reduce at scales of several kilometres as these effects are averaged out and the primary source of spatial variability becomes the distribution of synoptic scale events (i.e. where and when snowfall occurs in a given year, and where and when melt occurs). The relative influence of these different processes means that comparisons between point data and gridded output is frequently not possible as they sample fundamentally different variability.

The above separation is appropriate for regions of non-complex topography. In mountainous regions, the terrain has more intrinsically complex variability on smaller scales (e.g., small scale variability in slope and aspect). Furthermore, the larger-scale aspects of mountains act to alter the local weather patterns as well: e.g., precipitation is preferentially deposited on windward slopes, while leeward slopes experience precipitation shadows; the leeward slopes also experience wind-related warming due to adiabatic effects, while the higher elevations experience much colder temperatures, which together lead to complex spatial patterns in precipitation phase and melt. Because these effects operate at a hierarchy of spatial scales, mountainous regions (i.e. defined by complex topography, high terrain slope, high elevations, or a combination of these), intrinsically require finely resolved observational data and are not well represented by most gridded data presently available.

Appropriate use of data:

Based on the above information, we recommend separate consideration of small (<1 km) vs large (>1 km) scale snow depth and SWE data sets. Typically, datasets based on point data or small-scale spatial data will be temporally and spatially discontinuous. Datasets based on spatial scales > 1 km, even if based on point information, have typically been merged into more spatially or temporally continuous formats. This merging process will average out some of the variability due to fine-scale processes yielding products more consistent with large scale gridded datasets. Gridded datasets based on satellite data or reanalysis or model output will also be fully or near-fully continuous, both spatially and temporally.

Uses of point data: for the very specific locations these data represent, they should reflect accurate amounts of snow depth or SWE (excepting standard measurement errors and/or recording errors) and its local scale variability to the extent it is temporally sampled. Overall, observations are too spatially and temporally sparse in the Canadian North to properly assess whether one gridded/modelled dataset is better or worse than another for this region, particularly for SWE and snow depth.

Uses of gridded data: depending on their sources, these data may or may not reflect accurate amounts of snow and may or may not represent snow variability accurately as follows:

a. Merged from point/in situ observations to larger scales (e.g., ANUSPLIN snow depth): should accurately reflect amounts and larger-scale variability (although may depend on the quantity of measurements incorporated in the process of merging to larger scales).

b. Satellite/in situ blended SWE data (e.g., GlobSnow all versions and Snow CCI all versions): should reflect accurate amounts and larger-scale variability depending on the local amount of in-situ data ingested – this are less in more northern regions.

c. Snow presence is reliably detected by satellites with optical sensors (versus passive microwave sensors used to estimate SWE or snow depth). Hence, visible satellite observations from MODIS, IMS, or integrated data sets like the NOAA Climate Data Record can be used to validate snow cover fraction and snow extent over the Canadian North (e.g., Wang *et al*. 2005).

d. Reanalysis/offline historically forced models: will not necessarily reflect accurate amounts (due to poorly constrained snow mass balance), but has been shown to accurately reflect spatial and temporal variability (excepting temporal inhomogeneities in some datasets; known inhomogeneities are noted for particular datasets). Different datasets tend to have uncorrelated error components, therefore averaging multiple datasets together will typically yield more accurate results, but systematic biases present in all datasets would still remain. This result (lower RMSE, better correlation) was shown for Northern Hemisphere SWE in Mortimer *et al*. (2020). While the validation data used for this study includes locations in tundra and other land classes present in northern Europe/Siberia and Canada/Alaska, the majority of stations are situated in more southern locations. Therefore, conclusions are true for the hemispheric view, and could potentially apply to the Canadian North. A similar method can be used with focus on the Canadian North and also on other variables (e.g., snow depth, snow cover) to confirm the findings for this region.

e. Climate model output: will not necessarily reflect accurate amounts (again due to poor constraints on the balance of snowfall, melt and sublimation); will not reflect historical spatial or temporal variability due to the strong influence of natural variability on the distribution of synoptic scale events (typical climate models are not configured to replicate historical natural variability). Output should represent the climatological spatial pattern of snow, and may represent long-term trends in regions and over periods of time for which climate forcing dominates the trend signal over the influence of natural variability.

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3.2.2 River Discharge

This section focuses on one of the hydrological variables with many practical applications: river discharge. Information on river discharge is needed to optimize the design of various types of structures such as bridges, culverts, pipeline crossings, dams, reservoirs, hydroelectric plants, dykes and other water-related industrial structures. River discharge represents the volume of water per unit time as measured at a given location along a waterway. Historical datasets on river discharge rely mainly on in situ measurement of water level, which is converted to discharge using a rating curve (i.e. a stage-discharge relationship). River discharge measurements integrate over space and time at the catchment-scale efflux of freshwater to the coastal ocean. It also transports heat, sediments, dissolved oxygen, nutrients and contaminants to the coastal ocean. River discharge, like other hydrometeorological variables, responds to climatic change and variability. In particular, rising air temperatures and changes in precipitation patterns affect river discharge. Anthropogenic activities including fragmentation of river systems through dams, reservoirs and diversions, in addition to land use and land cover changes, also impact river discharge. As such, many data providers report whether a given site is considered regulated or “natural”. The Water Survey of Canada also maintains a series of hydrometric gauges that are part of the Reference Hydrometric Basin Network (RHBN) with minimal human influences. The RHBN sites are particularly useful to assess the impacts of climate change on river discharge.

The following table summarizes the river discharge datasets in northern Canada.

Table 3.14 River Discharge Datasets

Name	Source	Type	Spatial Domain	Spatial Resolution	Temporal Coverage	Time Step	Format	Comments	Link to metadata description
WSC Observations	WSC/ECCC	Station data	Canada	basin-scale data	variable	Daily	CSV; TXT	Hydrometric gauging station data	Description of data: Annex 7.6.1
ERA5-Land	ECMWF	Land surface reanalysis/ model	Global	0,1° x 0,1° (9 km)	Jan 1950-- present (ongoing, ~3 month latency)	Hourly; Monthly	GRIB; NetCDF		Description of data: Annex 7.6.2 Reference : Muñoz-Sabater *et al.* (2021).
GLoFAS discharge reanalysis	Copernicus	Model based on reanalyses	Global	0.10° x 0.10°	1980-2018	Daily	n.a.	Gridded hydrological model forced by ERA5 and calibrated with discharge observations	Description of data: Annex 7.6.3 https://www.globalfloods.eu/
R-ArcticNet	University of New Hampshire	Station data	Pan-Arctic (North America and Eurasia)	Basin-scale data	Variable. Time series end in 2000	Daily; Monthly	TXT	Hydrometric gauging station data sourced from the Water Survey of Canada among other data providers	Description of data: Annex 7.6.4 https://www.r-arcticnet.sr.unh.edu/v4.0/abstract.html
'Centre d'Expertise Hydrique du Québec' dataset	Quebec Gouvernement	Station data	Québec including Nunavik	Basin-scale data	Variable	Daily	TXT	Hydrometric gauging station data	Description of data: Annex 7.6.6 http://www.cehq.gouv.qc.ca/hydrometrie/historique_donnees/info_validite.htm
Hydro-Québec Station data	Hydro-Québec	Station data	Québec (regulated waterways)	Basin-scale data	Variable	Sub-daily; Daily	Excel files	Hydrometric gauging station data	Description of data: Annex 7.6.7 Proprietary data, available upon request
Ontario Power Generation dataset	Ontario Power Generation	Station data	Ontario (regulated waterways)	Basin-scale data	Variable	Sub-daily; Daily	Excel files	Hydrometric gauging station data	Proprietary data, available upon request. https://www.opg.com/powering-ontario/our-

									generation/hydro/river-system-data/
Manitoba Hydro dataset	Manitoba Hydro	Station data	Manitoba (regulated waterways)	Basin-scale data	Variable	Sub-daily; Daily	Excel files	Hydrometric gauging station data	Proprietary data
Cape Bounty Arctic Watershed Observatory	Queen's University	Station data	Paired watersheds (East and West) Cape Bounty, Melville Island	Basin-scale data	2003-present	Sub-daily	n.a.	Hydrometric gauging station data	Description of data: Annex 7.6.5
Polar Bear Pass dataset	York University	Station data	Paired watersheds (Windy and Landing Strip creeks), Bathurst Island	Basin-scale data	2007-present	n.a.	n.a.	Hydrometric gauging station data	Description of data: Annex 7.6.8
GeoYukon Water Resources Branch, Yukon Hydrometric Network	Yukon Government	Station data	Individual watersheds	Basin-scale data	16 active stns: Mean yrs: 15 Median yrs: 15 Max yrs: 36 8 ≥ 20 yrs 1 ≥ 30 yrs Min start 1983 12 inactive stns: Mean yrs: 5 Median yrs: 3 Max yrs: 13 Min Start 1975 Also 4 inactive stns for level only - short duration	n.a.	n.a.	16 active discharge gauges - (not part of WSC network)	Description of data: ftp://ftp.geomaticsyukon.ca/GeoYukon/
Phil Marsh dataset for basins in Nunavut	Phil Marsh/ McMaster University	Station data	Individual watersheds	Basin-scale data	Baker Creek at Outlet of Lower Martin Lake 4/1/1991 to 11/1/2015 Flat River near mouth 1/1/1996 to 11/1/2015	Hourly	n.a.	Hourly water level and flow. Daily values are available on HYDAT at the Water Survey of Canada.	Possible available from Global Water Futures - seems to be password-controlled http://giws.usask.ca/meta/

					South Nahanni River above Virginia Falls 1/1/1996 to 11/1/2015 Scotty Creek at Highway No. 7 1/1/1996 to 11/1/2015 Havikpak Creek near Inuvik 1/1/1996 to 11/1/2015 Trail Valley Creek near Inuvik 1/1/1996 to 11/1/2015				

Forthcoming datasets: The Surface Water and Ocean Topography (SWOT) mission, scheduled to launch in 2022, is an international satellite program that will survey 90% of the Earth's surface water, observe the fine details of the ocean's surface topography, and measure how lakes, rivers, reservoirs and oceans are changing over time. One of the hydrology objectives is to evaluate discharge variations in rivers. SWOT will provide complete coverage of most lakes and rivers up to four times every three weeks, including northern Canada, where very few measurements are currently available. This first global inventory of Canadian waters will serve to improve our water management and assist in prediction of floods and drought (https://www.asc-csa.gc.ca/eng/satellites/swot.asp).

Appropriate use of data: There are several options available to researchers and end users in regards to river discharge data in northern Canada. For the most part, however, there are few overlaps in terms of spatial or temporal coverage between the various datasets identified in Table 3.14. In Canada, the primary data provider for daily river discharge is the Water Survey of Canada that operates most hydrometric gauges across Northern Canada in conjunction with its territorial and provincial partners. Record lengths and continuity vary between sites, but generally good records exist starting from the 1960s onward for northern Canada’s primary waterways. Spatial coverage degrades moving northward across the three territories and is especially poor across the Canadian Arctic Archipelago. Data quality varies throughout the year, with degraded measurements during ice-on and backwater conditions or during high flows. Some hydrometric gauges remain operational only during the warm season as smaller waterways may freeze to the bottom in winter or measurements are particularly difficult underneath the ice cover. R-ArcticNet assembles all available Water Survey of Canada data, along with other international agencies, in a user-friendly, web-based portal but temporal coverage ends in 2000. This database has the advantage of providing simple graphics of river discharge time series and hydrographs of mean monthly flows, plus overall discharge statistics along with relevant site metadata.

Discharge measurements are also available for regulated waterways from several hydropower companies. These data, however, are often not available from the Water Survey of Canada's Hydrometric Database (HYDAT), remain unpublished and/or are considered proprietary. Nevertheless, data can generally be acquired upon request from the hydropower companies. Additional discharge data are available in northern Québec/Nunavik through the provincial Centre d'Expertise Hydrique du Québec (CEHQ) and from the Yukon Government's Water Resources Branch, which are not necessarily available on HYDAT. Experimental watersheds have also been established at several sites in the Canadian Arctic by university researchers filling key gaps in other networks. These records, however, are relatively short in duration, typically spanning no more than one to two decades.

Model-based and reanalysis gridded products provide continuous runoff datasets across all land surfaces. Distinct advantages of these datasets are their complete temporal and spatial coverage across northern Canada spanning multiple decades. However, the datasets often just provide runoff at the grid-scale rather than routed streamflow at the watershed-scale. Their relatively coarse spatial scale may impede their application for smaller watersheds. Due to model inaccuracies and the lack of robust validation studies, these datasets are to be used with caution and only when observational data are lacking.

Thus preference is given to Water Survey of Canada observational data where and when available. When insufficient or simply unavailable, other sources including from hydropower companies, experimental watersheds maintained by academic institutions and government agencies, and reconstructed streamflow data may be employed. In all cases, however, users should be aware of potential errors, biases or deficiencies in all datasets and apply them with caution.

References – Hydrology data

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3.3 Sea ice data

Lead Authors: Jennifer Lukovich (University of Manitoba), Stephen Howell (CRD/ECCC), Alex Crawford (University of Manitoba)

Contributors: Emilia Diaconescu (CCCS/ECCC), Ryan Hennessey (CCCS/ECCC), Paul Kushner (University of Toronto), Jack Landy (Bristol University), Lindsay Mattews (CCCS/ECCC)

3.3.1 Introduction

Sea ice is an important feature in northern Canada. It consists of seasonal ice that forms and melts each year (referred to as first-year ice) and ice that is present all-year round (referred to as multi-year ice). The amount and type of sea ice present, and the total minimum area it covers during the summer season, impacts human activity and biological habitat. Lying at the interface between ocean and atmosphere, it is influenced by the temperature of the air and the water, as well as by surface winds and ocean currents. In turn, the presence or absence of sea ice has a profound impact on the water below it and the air above it.

Between 1968 and 2020, summer sea ice area in the Northern Canadian Waters declined at a rate of 7.5% per decade (Source: Environment and Climate Change Canada (2020) Climate Research Division). Arctic sea ice is very sensitive to climate change because of the sea ice-albedo feedback that influences how much solar radiation is absorbed into the sea ice-ocean system. Research has shown that the loss of Arctic sea ice is a very significant contributor to the recent amplification of Arctic temperature change compared to the global average.

Changes in the amount of sea ice, the location of ice edges and the timing of seasonal ice formation and melt have complex, cascading ecosystem impacts. Sea ice decline results in a loss of wildlife habitat, as it serves as hunting platforms for polar bears and as resting grounds and nursery areas for walruses and seals. Algae that grow on the underside of sea ice are also important to the marine food supply. Duration of open-water season, and ice formation and breakup dates are also of high importance for maritime transportation and shipping planning.

Sea ice is described by the area it covers, its thickness, its age, and its movement with the winds and ocean currents. This chapter will focus on three of those characteristics:

- Sea ice concentration (the fraction of ocean covered with sea ice)
- Sea ice thickness (or volume/mass)
- Sea ice drift

3.3.2 Sea ice concentration

Sea ice concentration is defined as the fraction of ocean covered with sea ice and is typically measured in tenths or as a percent. The relevance of climate data to users for a variety of applications is determined by a range of spatial and temporal scales (Figure 3.3) (Wagner *et al*., 2020). Sea ice concentration datasets are commonly used for monitoring and mapping, especially to estimate sea ice extent and sea ice area, which are the most widely used indictors to assess long-term climate change for sea ice (e.g., Comiso *et al*., 2017; Derksen *et al*., 2019). Sea ice concentration data is also a vital input for reanalysis products and forecasting models (Guemas *et al*., 2014; Chavellier *et al*., 2016). Finally, a variety of stakeholders (e.g., cruise operators, commercial traders, fishery operators, researchers, and resource extraction companies, to name but a few) also rely on sea ice concentration data for planning purposes (Wagner *et al.*, 2020). Sea ice concentration data in northern Canada is primarily available through the Canadian Ice Service (CIS) digital ice charts and passive microwave satellite observations. The following provides a brief overview of these two primary data sources for potential interest to data users in Northern Canada, in addition to references comparing the datasets and limitations. These datasets are featured in light of their availability, decades-long duration, and regional and global coverage; they are also widely used in deriving global sea ice climate indicators (i.e. sea ice extent and area).

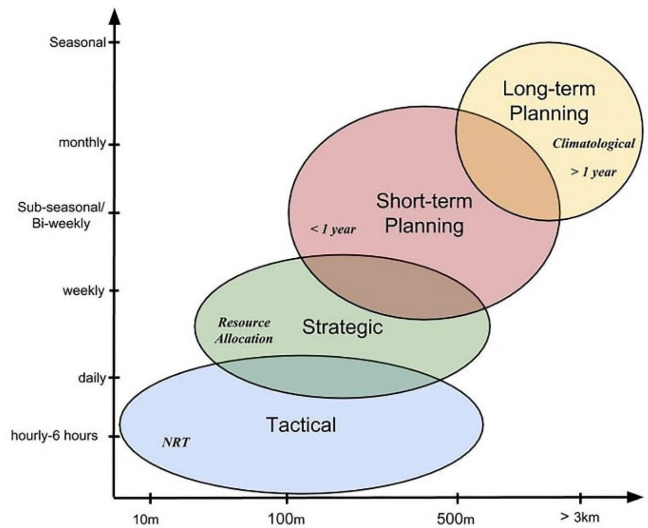

Figure 3.3. The range of spatial and temporal scales relevant for various applications and operations. [Source: Wagner *et al.*, 2020].

Table 3.15 Table of sea ice concentration products

Name	Source	Type	Spatial domain	Spatial resolution	Temporal coverage	Time step	Format	Links to data
CIS Ice Charts, Ice Atlas and the Icegraph tool	MSC/ECCC	Gridded hybrid data: observations, satellite	Canada	200 m	Canadian Western Arctic (1968 to present), Canadian Eastern Arctic (1968 to present), Hudson Bay (1971 to present) and the East Coast of Canada (1968 to present)	Weekly	Digital charts; Shapefiles; DEX; GIG; CSV; Interactive web-tool images	CIS Ice Charts Ice Atlas Icegraph tool
Sea Ice Index Version 3	NSIDC	Satellite data	Global	25 km x 25 km	1978 to present	Daily	PNG; Shapefiles; CSV; GeoTIFF	Sea Ice Index Version 3

NOAA/NSIDC Climate Data Record of Passive Microwave Sea Ice Concentration Version 4 and the sea ice tools	NSIDC	Satellite data	Global	25 km x 25 km	1978 to present	Daily	NetCDF; CSV; Interactive web-tool images	NOAA/NSIDC Climate Data Record of Passive Microwave Sea Ice Concentration Version 4 Sea ice tools
OSI-SAF version 2	EUMETSAT	Satellite data	Global	25 km x 25 km	1979 to present	Daily	NetCDF	OSI-SAF version 2

a) Canadian Ice Service digital ice charts

The CIS Digital Ice Charts is a compilation of all weekly ice charts produced by the CIS which include estimates of sea ice concentration for the Canadian Western Arctic (1968 to present), Canadian Eastern Arctic (1968 to present), Hudson Bay (1971 to present) and the East Coast of Canada (1968 to present). The digital ice charts are derived from 1:4 million scale hard copy charts that have been digitized in a topologically complete polygon database in an Arc/Info Geographic Information System. Each digital chart covers a sea surface area of 1.2-2.2 million km^2 (i.e. spatial resolution of ~200 m) and comprises all the information contained in the WMO international sea ice code (Figure 3.4). They are based on an analysis and integration of all available data on ice conditions, including weather and oceanographic information, visual observations from shore, ship and aircraft, airborne radar, satellite imagery and climatological information (Tivy *et al*., 2011). CIS sea ice charts provide a local and regional interpretation of ice conditions that can be used for long-term analysis but they are relevant for tactical and strategic considerations, including navigation during the open-water season and weekly forecasts. The CIS ice charts have been found to be more accurate than passive microwave ice concentration estimates that can underestimate sea ice concentration by as much as 44% during the shoulder seasons (Agnew and Howell, 2003).

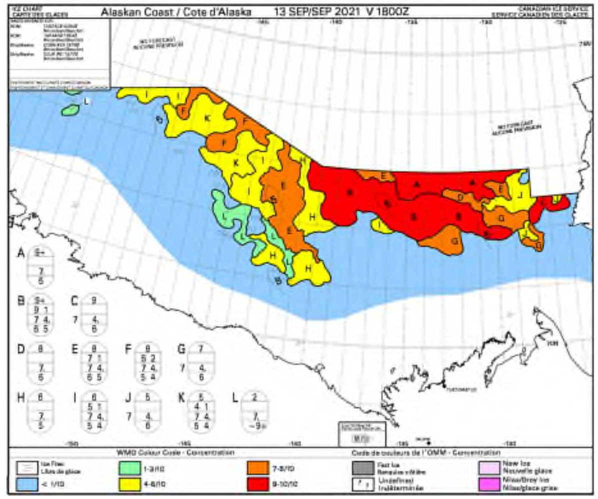

Figure 3.4. Example of a daily CIS sea ice chart for the western Arctic on 13 September, 2021, depicting contiguous sea ice concentration regimes in the Beaufort Sea region.

Considerations and Limitations

A consideration that needs to be taken into account when using the CIS digital ice charts is that their temporal domain has changed with time. Specifically, the Canadian Western Arctic, Canadian Eastern Arctic, and Hudson Bay ice charts were produced on a weekly basis only during summer season up until 1981. In 1982, monthly ice charts during the winter seasons were included for aforementioned regions. Beginning in March 2006, that frequency was increased to twice a month during the winter. Since the fall of 2011, Canadian Western Arctic, Canadian Eastern Arctic, and Hudson Bay ice charts have been issued weekly year-round. Finally, ice charts for the East Coast are produced on a weekly basis during the winter season only.

Another consideration of the ice charts is that the data sources have changes over time as well as changes in regional focus due to the emergence of important shipping routes. Tivy *et al*. (2011) performed an extensive evaluation of the CIS ice charts and found no evidence of time-varying biases in the period since 1979. However, pre-1979 overestimation of sea ice concentration in the northern regions of the Canadian Eastern and Western Arctic are possible.

A final consideration with respect to the CIS ice charts is that high spatial resolution RADARSAT imagery from RADARSAT-1 (1996-2013), RADARSAT-2 (2007-2020), and the RADARSAT Constellation Mission (2020 to present) has been the primary sensor used in the production of the ice charts since 1996. Therefore, ice charts from 1996 to present are expected to be more representative and of higher quality with respect to their sea ice concentration estimates (e.g., Cheng *et al*., 2020)

Climate data products and tools for CIS regional ice charts

Climate data products and online tools to explore CIS regional ice charts exist through the Ice Atlas and icegraph tool. In particular, the Ice Atlas provides: (a) regional analyses based on climate normals for the 1981-2010 timeframe, (b) a description of techniques and indicators used characterize ice conditions for the 1981-2010 timeframe, (c) atmospheric and oceanic contributions to regional changes in sea ice, (d) regional descriptions of freeze-up and break-up seasons, and (e) ice charts and supporting information for the eastern, western, and northern Canadian Arctic and Hudson Bay. Icegraph is an interactive tool used to generate ice coverage bar graphs and data tables for specified time intervals and regions of interest.

b) Passive Microwave Satellite Observations

Sea ice concentration has been monitored from space almost continuously since 1978 using passive microwave measurements from the Scanning Multichannel Microwave Radiometer (SMMR) instrument on the Nimbus-7 satellite and the Special Sensor Microwave/Imager (SSM/I) and Special Sensor Microwave Imager/Sounder (SSMIS) satellite platforms. Spatial and temporal uniformity in passive microwave satellite observations over several decades provides a regional and global interpretation of ice conditions relevant for climatological assessments and planning on daily, weekly and seasonal timescales. Passive microwave sea ice concentration datasets are also the most common datasets to calculate long-term trends in sea ice extent and area. Sea ice extent indicates the area of a region covered by ice exceeding a 15%, and sea ice area indicates the area of an ice-covered region multiplied by the fractional sea ice concentration.

Microwave emissions can pass through cloud, but are slightly affected by snow and rain. An empirical relationship between microwave brightness temperatures at different wavelengths is used to distinguish sea ice from open water. The sea ice fraction is calibrated using observations (tie points) of 100% open water and 100% ice-covered. As a result, there are many different algorithms used to estimate sea ice concentration and hence many different sea ice concentration products (e.g., Kern *et al*., 2019). However, the most widely used sea ice concentration datasets are the Sea Ice Index Version 3 (Fetterer *et al*., 2017), NOAA/NSIDC Climate Data Record of Passive Microwave Sea Ice Concentration, Version 4 (Meier *et al*., 2021) and Satellite Application Facility on Ocean and Sea Ice (OSI-SAF) Version 2 (Lavergne *et al*., 2019). Figure 3.5 depicts the Sea Ice Index and near-real-time sea ice concentration from NSIDC and OSI-SAF products.

Sea Ice Index

This dataset includes monthly sea ice concentration, anomaly (departures from the 1981-2010 median value), trend (from 1981 to the present year), and sea ice extent images; daily sea ice concentration and extent images, in addition to calculated values for hemisphere-wide monthly and daily sea ice extent and area, and daily average sea ice extent from 1981-2010. The dataset is created by estimating sea ice concentration from the NASA Team algorithm (Cavalieri *et al*. 1997) which converts brightness temperatures to gridded ice concentration estimates. The sea ice index is perhaps the most well-known dataset as it is used for the NSIDC Arctic Sea Ice News (http://nsidc.org/arcticseaicenews/). The data is available daily from 26 October 1978 to present.

Climate data products and tools for NSIDC passive microwave dataset

Sea Ice Data Analysis and Tools further provides online tools to explore the NSIDC passive microwave dataset, including interactive sea ice graphs showing daily sea ice extent for specified years, spreadsheets with the data, interactive maps, and animations.

NOAA/NSIDC Climate Data Record of Passive Microwave Sea Ice Concentration

This dataset provides a Climate Data Record of sea ice concentration from passive microwave data. The Climate Data Record algorithm output is a rule-based combination of ice concentration estimates from two well-established algorithms: the NASA Team algorithm (Cavalieri *et al*. 1984) and NASA Bootstrap algorithm (Comiso, 1986). The Climate Data Record is a consistent, daily and monthly time series of sea ice concentrations from 25 October 1978 through the most recent processing for both the north and south hemispheres.

OSI-SAF

Sea ice concentration estimates for OSI-SAF are retrieved using dynamic tie points that capture the time evolution of surface characteristics of the ice cover. This also allows for potential calibration differences between satellite missions to be accounted for. ERA-Interim data is used for a correction of the atmospheric influence on brightness temperatures. OSI-SAF sea ice concentration estimates are available from January 1979 to present.

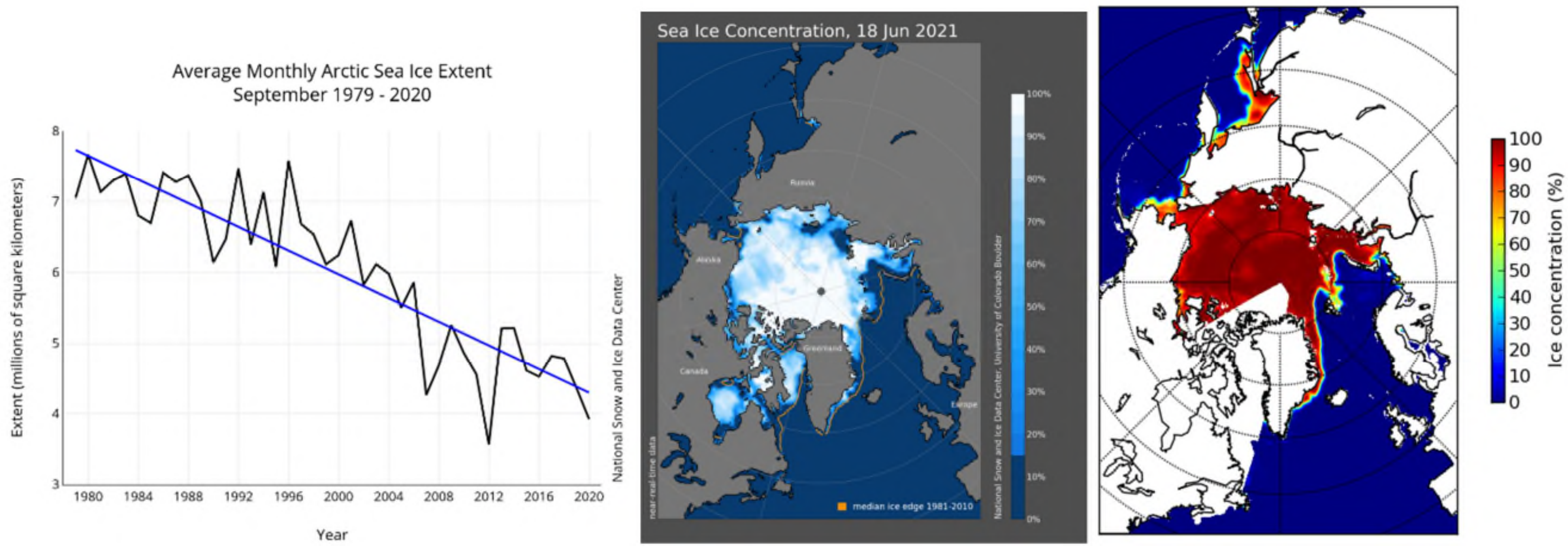

Figure 3.5. Examples of sea ice concentration products including (from left), Monthly September ice extent for 1979 to 2020 shows a decline of 13.1 percent per decade from the Sea Ice Index dataset, map of near-real-time NSIDC sea ice concentration and median 1981-2010 ice extent, and OSI-SAF sea ice concentration for June 18, 2021.

Considerations and Limitations

Data employ different assumptions and corrections to account for differing surface conditions and the effects of snow and rain. Users of sea ice data should be aware of the differences between algorithms, their attributes, and the methods for combining different source data into long-term datasets (i.e. Kern *et al*., 2019; Meier and Stewart, 2019). Resolving the position of ice edge or marginal ice zone, coastal contamination, thin ice and melt ponds forming on the surface of the sea ice are the primary sources of uncertainty (Ivanova *et al*., 2015; Kern *et al*., 2016; Comiso *et al*., 2017). Further, construction of a 40+ year sea ice extent record requires combing sensors together as their operational lifetime eventually fails and therefore uncertainty can vary temporally depending on the quality of sensor intercalibration (e.g., Eisenman *et al*., 2014). Although today the passive microwave record has a daily resolution, it had a 2-day resolution prior to July 1987.

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3.3.3 Sea Ice Thickness

Sea ice thickness is the result of cumulative thermodynamic and dynamic processes that change the sea ice cover depth and distribution (Thorndike *et al*., 1975, Stroeve and Notz, 2018, Kwok, 2018). Thermodynamic contributions include sea ice growth and melt in pursuit of a mean state, in contrast to dynamical contributions which include mechanical deformation in the sea-ice cover that gives rise to extremes associated with open water (divergence) and ridging (convergence). Freeboard and draft characterize sea ice thickness, where freeboard is defined as the height of the surface elevation, while draft is the depth of sea ice below the sea surface (Figure 3.6). The satellite record of sea ice thickness provides an indicator of the health of Arctic sea ice as a result of climate change (Tilling *et al.*, 2015; Kwok and Cunningham, 2015; Petty *et al.*, 2020). However, sea ice thickness also influences sea ice compressive strength, heat and gas exchange (Kurtz *et al.*, 2011, Renner *et al.*, 2017) sea ice motion (thinner ice moves faster and is deformed more readily than thicker ice, e.g., Hakkinen *et al.*, 2008; Spreen *et al.*, 2011), freshwater circulation and upper ocean stratification (due to melt through changes to ice volume, a signature of freshwater storage, e.g., Jensen *et al.*, 2016, Carmack *et al*, 2016), ice volume budgets (Kwok, 2018), productivity rates, navigation and maritime routing (e.g., Haas and Howell, 2015; Mudryk *et al.*, 2021), sea ice forecasts (Balan-Sarojini *et al.*, 2021), and community travel (i.e. SmartICE, Sea Ice Monitoring and Information Inc; https://oceansadvance.net/member/smartice-sea-ice-monitoring-information-inc/).

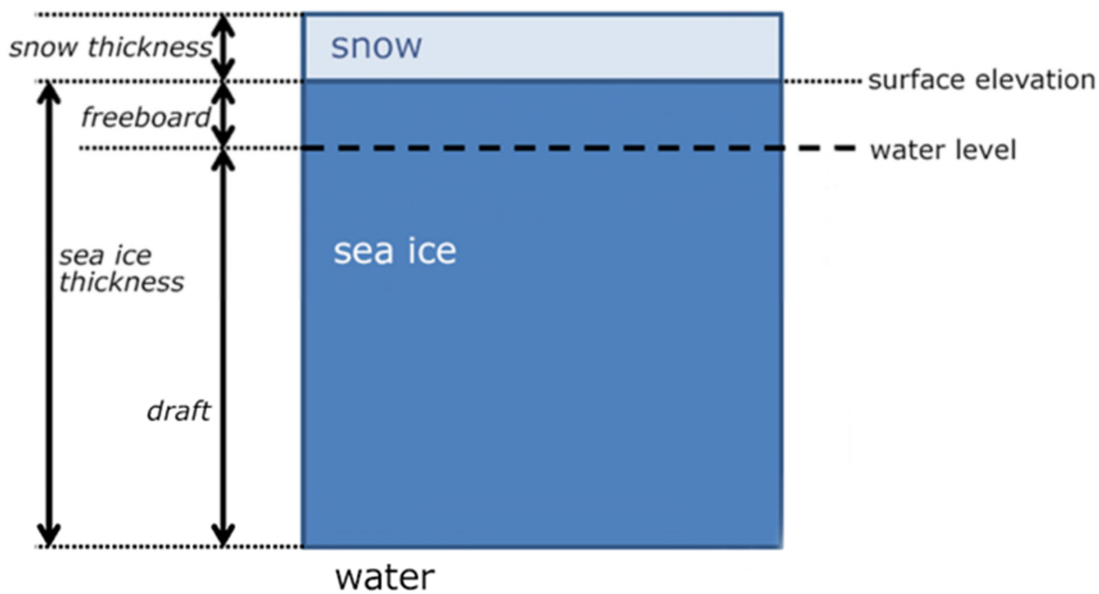

Figure 3.6. Schematic demonstrating elements that define sea ice thickness, including freeboard (ice height above sea level and below snow-ice interface) and draft (ice depth below sea level), in addition to snow thickness, which influences sea ice thickness retrievals. Image courtesy of National Snow and Ice Data Centre (NSIDC), https://nsidc.org/sites/nsidc.org/files/cryosphere/glossary/glossary_freeboard.png

Sea ice thickness data exist in the form of gridded products based on satellite retrievals, including NASA's Ice, Cloud and land Elevation Satellite (ICESat-1 and -2) and CryoSat-2, as well as in situ observations, including upward looking sonars on submarines and fixed moorings and ground-and aircraft-based electromagnetic induction measurements like Operation IceBridge, which has flights and tracks over the CAA, and in particular along the Northwest Passage in 2010 (Haas, 2004; Haas *et al*., 2009). It should be noted that satellite laser altimetry (like ICESat-1 and -2) measures the snow+ice freeboard (height of ice and snow cover above sea level), whereas satellite radar altimetry (like CryoSat-2) measures the sea ice freeboard (sea ice height above sea surface). To derive the sea ice thickness through the assumption of hydrostatic equilibrium both techniques require auxiliary estimates of the snow depth, snow density, and ice density (Stroeve and Notz, 2018). The following provides a brief overview of sea ice thickness data of potential interest to data users in northern Canada, in addition to references comparing recent datasets and limitations. As for other sea ice variables, these datasets are featured due to their availability, and local and global coverage, although a comparatively short record of satellite-derived thickness exists relative to satellite-derived sea ice concentration and drift vectors.

Table 3.16 Table of sea ice thickness products

Name	Source	Type	Spatial domain	Spatial resolution	Temporal coverage	Time interval	Format	Links
Canadian Ice Thickness Program	MSC/ECCC	Station data	Canadian Arctic	Point data	1947 – 2002; 2002 – present (limited number of stations), during ice-cover season	Weekly	Excel files	Canadian Ice Thickness Program
Unified Sea Ice Thickness Climate Data Record	R.W. Lindsay; A. Schweiger; NSIDC	Gridded hybrid data: observations, satellite	Arctic	50 km x 50 km	1947 - 2017	Monthly	ASCII	Unified Sea Ice Thickness Climate Data Record https://nsidc.org/data/G10006/versions/1
Operation Ice Bridge	NASA	Aircraft surveys	Arctic Antarctic Alaska	40 m x 200 m	March and April, 2009 – 2020	Variable	ASCII	Operation Ice Bridge https://nsidc.org/data/idcsi2
Ice, Cloud and land Elevation Satellite (ICESat) Geoscience Laser Altimeter System	NASA; NSIDC	Satellite data	Global	25 km x 25 km	Two to three times per year in winter months; 01/2003-02/2010	One or several times per year	PNG; Binary; GeoTIFF; ASCII	Ice, Cloud and land Elevation Satellite (ICESat) https://nsidc.org/data/NSIDC-0393 https://nsidc.org/data/icesat
ICESat-2	NASA; NSIDC	Satellite data	Global	25 km x 25 km	Two to three times per year in winter months; 09/2018 - present	One or several times per year	PNG; Binary; GeoTIFF; ASCII	ICESat-2 https://nsidc.org/data/icesat-2/data-sets

Arctic sea ice thickness climate data record	Copernicus	Satellite data	Polar	25 km x 25 km	October to April, 2003 – present	Monthly	NetCDF	Arctic sea ice thickness climate data record
CryoSat-2	Helmholtz Center for Polar and Marine Research/AWI	Satellite data	Polar	25 km x 25 km	October to April, 2010 - present	Monthly	NetCDF	CryoSat-2
SMOS	ESA	Satellite data	Polar	12.5 km x 12.5 km	October to April, 2010 - present	Daily	NetCDF	SMOS https://earth.esa.int/eogateway/catalog/smos-l3-sea-ice-thickness
SMAP	NASA	Satellite data	polar	36 km x 47 km	2015 - 2020	Daily	HDF	SMAP

a) Canadian Ice Thickness Program

Landfast sea ice thickness together with snow depth on sea ice measurements have been made regularly at many coastal stations throughout Canada since about 1950. The dataset is available on the Canadian Ice Service web site (https://www.canada.ca/en/environment-climate-change/services/ice-forecasts-observations/latest-conditions/archive-overview/thickness-data.html). Measurements were recorded in situ to the nearest centimeter using ice augers and hot wire thickness gauges. The measurements are taken once per week, starting after freeze-up when the ice is safe to walk on and continuing until breakup or when the ice becomes unsafe. This product is also included in the Unified Sea ice thickness data record, described further in the next section.

The Canadian Cryospheric Information Network (CCIN) provides a useful resource for visualization of changes in sea ice thickness from the Canadian Ice thickness program (in addition to ice age as a proxy for ice thickness, satellite-derived thickness from ICESat, and modelled thickness from PIOMAS) at specific locations in the Canadian Arctic (https://ccin.ca/ccw/seaice/current/thickness).

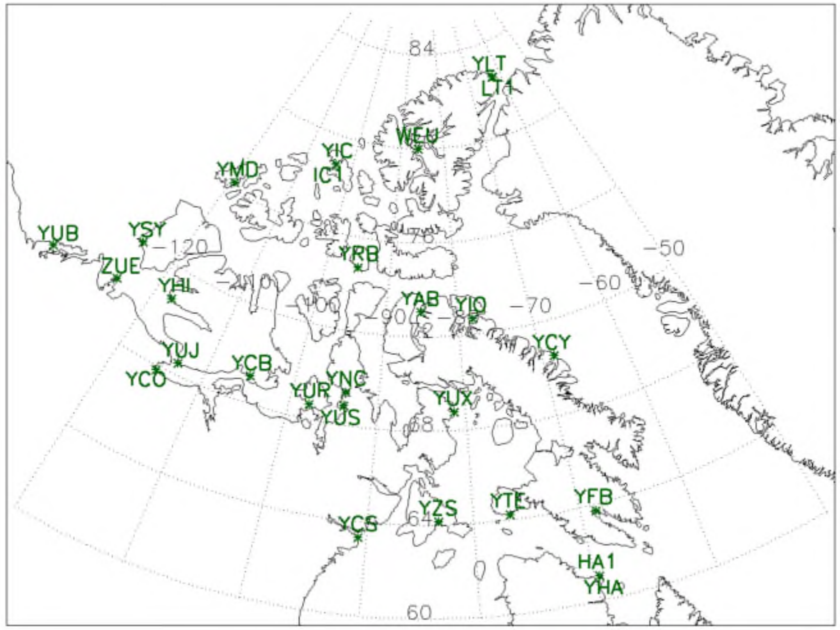

Figure 3.7 Canadian Ice thickness program coastal station locations. Source: Unified Sea Ice Thickness Climate Data Record, University of Washington, http://psc.apl.uw.edu/sea_ice_cdr/figures/canadian_coatal/station_locations.png

Considerations and limitations

This dataset has been used in the evaluation of spatial and temporal variability in landfast ice thickness in the Canadian Arctic (Brown and Cote, 1992; Howell *et al*., 2016). However, the original Canadian Ice Thickness program ended in 2002 due to a decline in the number of recording sites, and was reinstated in fall, 2012 with a subset of stations. As a result, the sparse spatial distribution and temporal consistency in the dataset limits evaluation of changes in sea ice thickness (and snow depth on sea ice) to particular locations and time intervals. Specifically, there are only a few sites (Cambridge Bay, Resolute, Eureka, and Alert) that provide consistent measurements over the entire record.

b) Unified Sea Ice Thickness Climate Data Record

Sea ice draft, thickness, and sea ice and snow thickness are provided in this dataset from a collection of satellite (freeboard) and in-situ (draft) observations, including upward-looking sonars (ULS) on anchored moorings or submarines, drill hole measurements, airborne and land-based electromagnetic induction (EM) measurements from 1975-2012 (Lindsay and Schweiger, 2015). Evaluation of thickness estimates from 1975-2012 in the central Arctic combined using a curve-fitting approach with this dataset demonstrated a 65% decrease in sea ice thickness in the central Arctic over this timeframe. Comparison amongst observations demonstrated reasonable agreement between ICESat and ULS measurements, with values on the order of 0.11 m.

Considerations and limitations

Limited spatial and temporal sampling hinder long-term evaluation of changes in sea ice thickness at arbitrary locations provided by a gridded product. Uncertainty associated with individual instruments and measurements will also be required in analyses that use this product. Sources of uncertainty include sampling errors, measurement errors, systematic errors, and errors associated with the regression procedure used to combine multiple data products (Lindsay and Schweiger, 2015). An absence of continuous spatial and temporal coverage could be addressed in part by a Lagrangian interpretation of changes in sea ice thickness such as is provided by drifting ice mass balance buoys.

c) Satellite-derived sea ice thickness products (CryoSat-2 and ICESat-1/ICESat-1/2)

CryoSat and ICESat retrievals require pre-processing of altimetry data to derive surface elevation and subsequently sea ice thickness. For altimetry data from CryoSat-2, specular (peaked) and diffuse (broadly distributed) radar echoes distinguish leads/thin ice and ocean waveforms, respectively (Tilling *et al*., 2018). Diffuse echoes are further characterized as ice floes in regions exceeding 75% sea ice concentration derived from a 25 km grid. Ice types are identified from OSISAF, and separate retracking techniques are applied to specular and diffuse echoes, from which the ocean surface elevation of the leads and surface elevations of the sea ice floes are determined. Radar freeboard is determined from the elevation difference between leads and sea ice floe surfaces. For altimetry data from ICESat-1 and -2, snow+ice freeboard heights are computed from the difference between surface elevation and sea surface elevation associated with leads in 10 km intervals for regions located 25 km from the coastline where sea ice concentrations exceed 50% (Kwok *et al*., 2020). Assuming hydrostatic balance, sea ice thickness is calculated from the freeboard by accounting for the snow loading on the sea ice (i.e., the depth multiplied by the density), and using sea ice and ocean densities to determine how much of the ice is sitting below sea level. Conventional methods have used a long-term climatology (i.e., averaged) snow depth and density maps compiled from direct measurements at Russian drifting stations in the 1950-1990s to make the conversion from freeboard to thickness (Warren *et al*., 1999). A limitation of altimetry is that sea ice thickness data rely on regular measurements of the sea surface height at leads, which are sparse in the narrow channels of the Canadian Arctic, so data are often missing or unreliable for these regions. Cryosat-2 data is available from 2010 to present, ICESat-1 from 2003-2008, and ICESat-2 from 2018 to present. Snow+ice freeboard, snow depth, and sea ice thickness were provided by the airborne survey Operation IceBridge during the gap between the ICESat-1 and ICESat-2 missions (Kurtz *et al*., 2013; Tschudi *et al*., 2016).

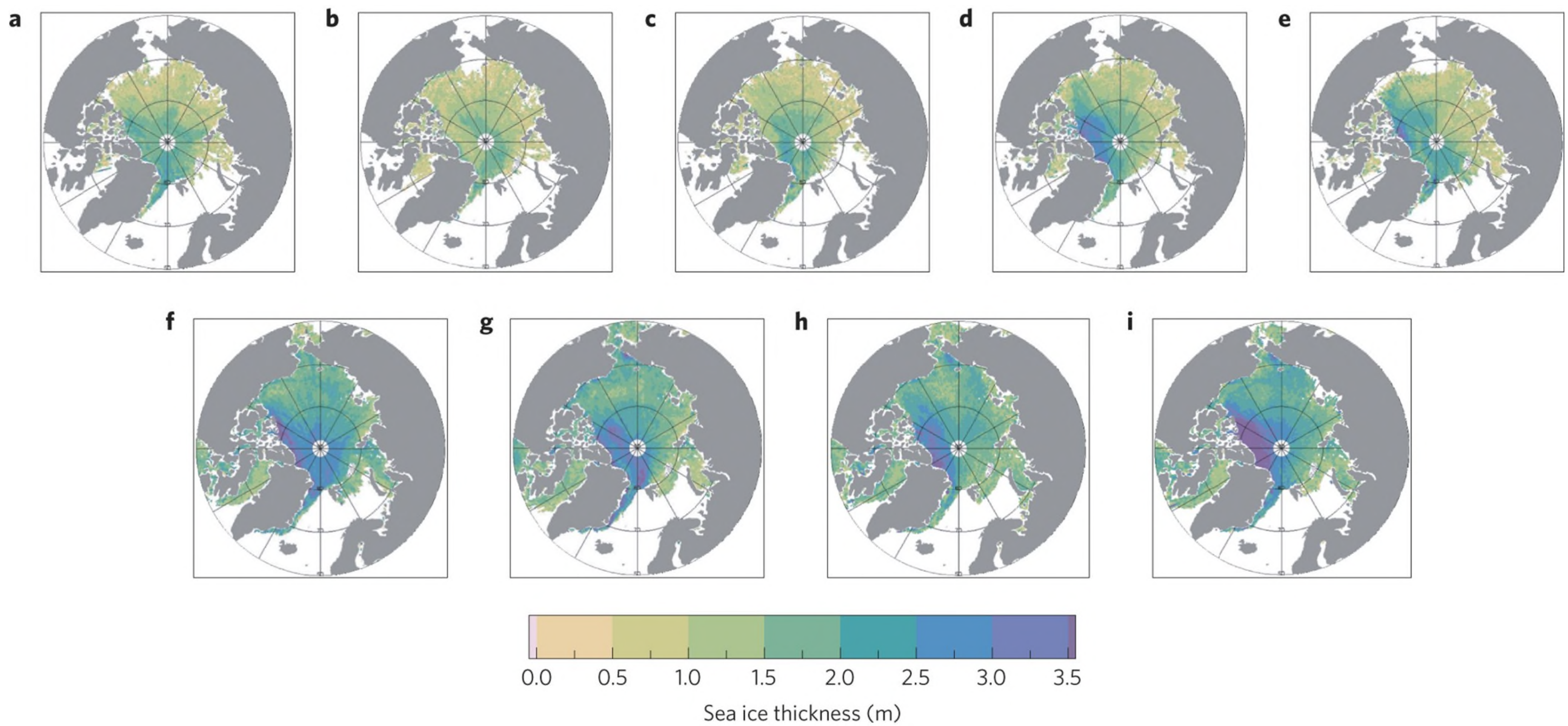

Figure 3.8 Maps of sea ice thickness derived from CryoSat-2 during autumn (October – November; top row) from 2010-2014, and spring (March – April; bottom row) from 2011-2015. [Source: Tilling *et al*., 2018.]

d) SMOS/SMAP

Soil Moisture and Ocean Salinity (SMOS)–derived sea ice thickness is computed from brightness temperatures recorded by the L-Band radiometer on the mission, and is effective in identifying thin ice (Kaleschke *et al*., 2012). NASA's Soil Moisture Active Passive (SMAP) -derived sea ice thickness is also derived from brightness temperatures observed by a scanning radiometer with a fixed incidence angle onboard the satellite (Patilea *et al*., 2019).

<u>Considerations and Limitations</u>

A notable source of error for radar altimeters (i.e., CryoSat-2) is the location of the radar scattering horizon in the snow-ice system. An error source for both radar and laser altimeters (i.e., CryoSat-2 and ICESat-1/2) is the snow depth on the sea ice (Giles *et al*., 2007). The temporal limitation with satellite altimetry is that sea ice thickness estimates are not available during the summer melt season and do not cover a long temporal domain. Spatially, the estimates are limited to areas in close proximity to leads and therefore are less reliable for landfast regions (i.e. Canadian Arctic Archipelago). A recent comparison of sea ice thickness satellite and in situ observations demonstrated that CryoSat-2 provided a reliable estimate of thicknesses ranging from 0.5 to 4 m, while a combined CrysoSat-2 and Soil Moisture and Ocean Salinity product provided a reasonable estimate of thin ice (Salilla *et al*., 2019). Also SMOS/SMAP are limited by sensor resolution (~62 km) in the CAA channels.

e) Arctic Sea Ice Thickness Climate Data Record

Monthly sea ice thickness data for winter months from 2002 based on satellite radar altimetry observations (C3S thickness product, from Envisat and CryoSat-2 satellite imagery) is derived using sea ice freeboard, constant sea water density, snow density and depth from a climatology (with 50% snow depth over first-year sea ice; Warren *et al*., 1999), and sea ice density categorized based on ice type (first-year ice and multi-year ice; C3S Algorithm Theoretical Basis Document). This is a gridded product that includes a variety of measurements and is comparable to the Unified Sea Ice Thickness Climate Record of in situ thickness observations.

An additional product of interest that simulates sea ice thickness is the Pan-Arctic Ice-Ocean Modeling and Assimilation System (PIOMAS; Zhang and Rothrock, 2003), a coupled ice-ocean model that has the ability to assimilate satellite sea ice concentration and velocity data, and sea surface temperature observations (Schweiger et al., 2011). The sea ice model simulates sea ice ridging following the Thorndike et al. (1975) sea ice thickness distribution theory, and consists of thermodynamic and dynamic components that characterize sea ice growth/decay and sea ice drift, deformation, and redistribution, respectively. PIOMAS sea ice thickness agrees reasonably well with satellite laser altimetry and submarine data observations (Schweiger et al., 2011). Currently, PIOMAS provides the most realistic estimate for sea ice thickness in the absence of satellite observations for sea ice thickness in summer.

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3.3.4 Sea Ice Drift

Sea ice motion is provided through zonal (east-west) and meridional (north-south) vector components to describe movement in the sea ice cover. Specifically, sea ice motion data depicts sea ice dynamics, namely drift (transport) and deformation (gradients in sea ice motion; divergence/convergence capturing opening/closing associated with what are referred to as flaw leads and polynyas, in addition to rafting and ridging in the sea-ice cover). Forces that contribute to sea ice motion include winds on daily and weekly timescales, ocean currents on monthly and seasonal timescales and longer, the Coriolis force due to the Earth's rotation, internal ice stress which measures ice strength determined by ice thickness (i.e. stronger/weaker ice is associated with thicker/thin ice), and sea surface tilt due to the undulating and dynamic ocean surface.

Ice motion is of high importance for activities on a short temporal horizon, including daily and weekly monitoring, forecasting and prediction. Specific applications include pollutant and contaminant transport, age of ice (tracking ice that survives the summer season), search and rescue, navigation (vessels can be trapped by moving ice floes) and planning for fishing and shipping routes and ice hazard detection in regions of construction (offshore structures can be damaged by the strength and momentum of moving ice) (Natural Resources Canada, 2021). Sea ice dynamics in the vicinity of coastal regions can contribute to sediment transport through advection following landfast ice break-up, and deformation where ice keels can redistribute shelf sediment (Barnhart *et al*., 2014). Recent development of SAR-derived sea ice drift on spatial scales of several kilometres enables landfast ice and stamukhi detection, relevant from the perspective of coastal erosion and permafrost degradation (Selyuzhenok and Demchev, 2021). For climate-related questions, realistic representation of sea ice dynamics from both an Eulerian and Lagrangian perspective is integral to reliable overall sea ice simulations. In particular, Lagrangian studies of sea ice drift (i.e. following ice floe trajectories) demonstrate a reduction in ice travel times with a transition from multi-year to perennial ice (Pfirman *et al*., 2004), with implications for freshwater transport and Arctic navigation (DeRepentigny *et al*., 2020). Eulerian studies of sea ice drift over several decades demonstrate acceleration in sea ice drift due to increased responsiveness of a weaker sea ice cover to surface winds, with implications for stratification and deep convection that would lead to a new CO2 sink (Hakkinen *et al*., 2008). More recently, age of ice studies using sea ice drift fields demonstrated a reduction of thick, multi-year ice north of Greenland in a region traditionally recognized as the last refuge for multi-year ice (Schweiger *et al*., 2021).

Historical Arctic sea ice motion observational data exist in the form of gridded (Eulerian; OSISAF, CERSAT, Polar Pathfinder) and Lagrangian (IABP) products. The following provides a brief overview of sea ice motion data of potential interest to data users in northern Canada, in addition to references comparing recent datasets and limitations. As for other sea ice variables, these datasets are featured due to their availability, decades-long duration, and local and global coverage; a subset is also used in deriving the global sea ice climate indicator of sea ice age.

Table 3.17 Table of sea ice drift products

Name	Source	Type	Spatial domain	Spatial resolution	Temporal coverage	Time interval	Format	Links
IABP	University of Washington	Station data	irregular	Point data	1979 to present	Variable (sub-daily to daily)	ASCII; NetCDF	IABP
Low Resolution OSISAF OSI-405 series	EUMETSAT	Satellite data	Global	62.5 km x 62.5 km	12/2009 – 07/2021 Summer data available following 2017	Daily	NetCDF	OSISAF OSI-405 series https://osi-saf.eumetsat.int/products/osi-405-c

Medium-resolution OSISAF OSI-407 series	EUMETSAT	Satellite data	Global	20 km x 20 km	12/2009 – 07/2021 Summer data available following 2017	6h	NetCDF	Medium-resolution OSISAF OSI-407 series https://osi-saf.eumetsat.int/products/osi-407
CERSAT	IFREMER	Satellite data	Global	62.5 km x 62.5 km	10/1999 – 05/2020	Daily; Weekly; Monthly	NetCDF	CERSAT and additional description
Polar Pathfinder 25 km daily EASE-grid sea ice motion vectors	NSIDC	Satellite data	Global	25 km x 25 km	25/10/1978 – 30/12/2020	Daily; Weekly	PNG; NetCDF	Polar Pathfinder 25 km daily EASE-grid sea ice motion vectors

a) International Arctic Buoy Program (IABP) buoy data

Of interest at local spatial scales and high frequencies are sea ice beacon trajectories associated with the (Lagrangian) International Arctic Buoy Program (IABP) product. IABP data provides latitude and longitude coordinates recorded by buoys as direct measurement of ice floe movement and displacements (Figure 3.9). Sea ice motion vector components are computed by dividing beacon displacements in the zonal and meridional directions by elapsed time. IABP data are used both in an operational and research capacity. Operational applications include the use of beacon data in ice charts, to forecast weather and sea ice conditions (Rigor and Wallace, 2004), validate satellite forecasts, and incorporate in atmospheric reanalysis products to provide insight at local (several km) scales. Research applications include the use of beacon data to assess changes in sea ice drift and deformation in response to a changing climate over the past four decades, and to validate weather and climate models, as well as satellite-derived sea ice motion products, as is described in the next section.

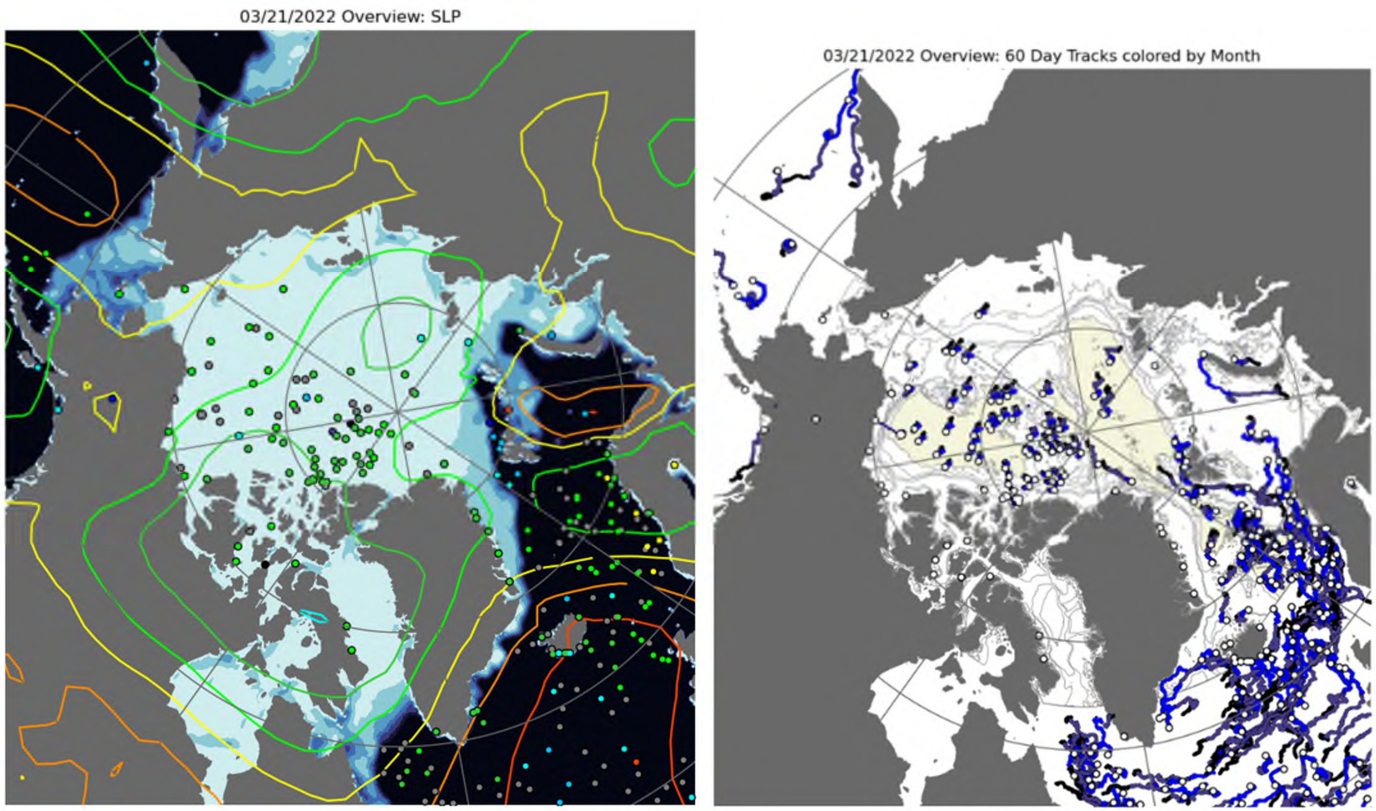

Figure 3.9. Example of (left) IABP sea ice beacon locations, NSIDC sea ice concentration, and NCEP SLP on March 21, 2022, and (right) 60 day tracks of sea ice buoy.

Considerations and Limitations

The IABP dataset is beneficial for assessments of local and regional sea ice drift and deformation for timescales ranging from several hours to months. By tracking ice floe movement, IABP data also captures small-scale features including loops, meanders, and eddies in response to atmospheric and oceanic forcing and ice strength at various locations and dates during the forty-year record. Furthermore, data is provided during summer months for the past four decades in contrast to satellite-derived ice motion data. However, spatial and temporal inhomogeneity in the beacon observations limit comparison of changes in ice dynamics for a given location over several decades, or regional differences in sea ice drift at a given instant or for a specific interval in time. Very few (if any) buoys reach waters outside of the Arctic Ocean (i.e. CAA, Hudson Bay, East Coast).

b) Satellite-Derived Sea Ice Motion

Gridded (Eulerian) sea ice motion products derived from satellite observations provide continuous spatial and temporal coverage of the Arctic over the past several decades. Sea ice motion is derived from a combination of passive microwave, scatterometer, radiometer, IABP buoy, and NCEP/NCAR wind data, using algorithms associated with the maximum cross-correlation technique that result in a daily merged product and a corresponding uncertainty.

Low-resolution OSI SAF Sea Ice Drift

The Ocean and Sea Ice Satellite Application Facility (OSISAF) EUMETSAT sea ice drift product is derived using a 'continuous maximum cross correlation' method applied to sub-images and designed to reduce tracking noise (Lavergene *et al*, 2010).. Uncertainties are also included for the x- and y- (2-day) displacements, and depict standard error. Yearly, hemispheric accuracy for the Arctic ranges from 2.5 km to 4.5 km for the single-sensor products, and approximately 2.6 km for the merged product. Only the multi-sensor product is appropriate for analysis during the summer months (May 1st to November 1st in the Northern Hemisphere), with reduced accuracy due to surface melting that hinders retrievals from instruments used to derive the ice-drift products. The x and y displacements, dx and dy (along the grid y-axis) are provided in units of km for the 2-day elapsed time intervals. The coarse resolution of this product (62.4 km), which captures regional scale sea ice motion, is not well resolved in small channels such as in the Canadian Arctic Archipelago.

NSIDC Polar Pathfinder 25 km sea ice drift, version 4

Trends and the global climate indicator of sea ice age (https://nsidc.org/data/NSIDC-0611/versions/4) can be respectively computed and derived from the decades-long Polar Pathfinder daily 25 km sea ice drift dataset, version 4, produced by the National Snow and Ice Data Centre (NSIDC). This product is derived from the merging of several datasets and sensors, including AVHRR, buoy, NCEP/NCAR, and passive microwave (SMMR, SSM/I, SSMIS, AMSR-E instruments) data using optimal interpolation and a cokriging estimation method. The final error variance in the merged sea ice motion product is based on a source- and distance-weighted average computed according to cross correlations between the individual sea ice motion estimate and buoy vector, and distance from the point being estimated (Tschudi *et al*., 2019). Differences between the interpolated and buoy components are on the order of 0.1 cm/s for the zonal component and 0.4 cm/s for the meridional component with root-mean-square errors of 3.36 cm/s and 3.4 cm/s respectively (Measuring sea ice motion, NSIDC, https://nsidc.org/sites/nsidc.org/files/technical-references/MeasureSeaIceMotion-0116-0748.pdf).

Considerations and Limitations

Sumata *et al*. (2014) provide a comprehensive low-resolution product description and inter-product comparison for satellite-derived sea ice motion data. Here it is shown that larger error in satellite-derived sea ice drift is associated with higher drift speeds, and in regions of low sea ice concentrations and thickness. Inter-product comparisons further demonstrated maximum differences in ice-drift speeds on the order of 12% in Fram Strait, and in sea ice deformation on the order of 24% in winter and 37% in summer in the Amerasian Basin. It was also highlighted that all products, with suitable uncertainty estimates, were appropriate for sea ice dynamics (drift and deformation) model validation and data assimilation, with NSIDC and OSISAF showing lower uncertainties than CERSAT due to low ice drift speed bias in the latter. Cloud cover also hinders sea ice detection, resulting in missing data. Vector fields for all products are less accurate during summer than for fall, winter, or spring. The coarse resolution of this product for regional scale sea ice motion is not well resolved in small channels such as in the Canadian Arctic Archipelago.

As for atmospheric data products, discontinuities exist in sea ice drift data due to the merging of multiple data sources over a range of spatial and temporal scales. This is manifest in the NSIDC sea ice motion data set as circular, persistent features associated with the merging of buoy with satellite data.

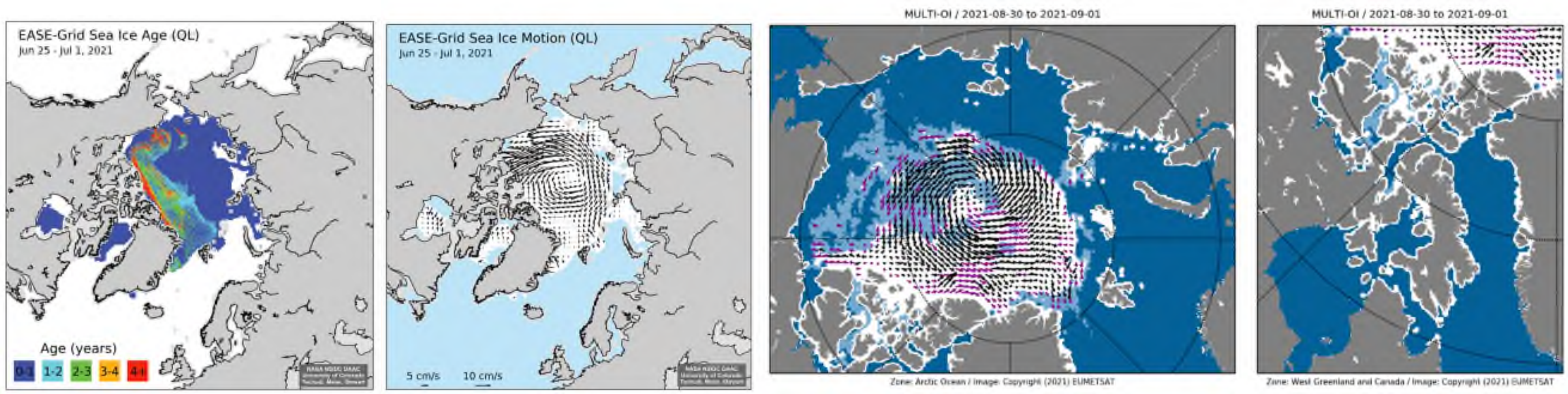

Figure 3.10 Examples of NSIDC (left) sea ice age derived from (middle) Polar Pathfinder 25 km sea ice motion from June 25 – July 1, 2021, and (right) OSI SAF sea ice drift for August 31, 2021 based on time elapsed from August 30 to September 1, 2021. [Source: https://daacdata.apps.nsidc.org/pub/DATASETS/nsidc0749_ql_iceage/,

https://daacdata.apps.nsidc.org/pub/DATASETS/nsidc0748_ql_icemotion/,

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3.3.5 Other Data Portals

Local sea ice information can be supplemented with in-situ measurements such as are found through the Polar Data Catalogue (PDC), SIKU, and Smart-ICE initiatives. The Polar Data Catalogue (https://www.polardata.ca/) provides an online archive/repository of Arctic measurements. SIKU (https://siku.org/) is an application that allows community members to provide and extract relevant environmental information on local conditions. SmartICE (https://smartice.org/) in addition provides thickness measurements and in particular information on landfast ice relevant to coastal communities.

3.4 Permafrost data

Lead Authors: Stephan Gruber (Carleton University), Brendan O'Neill (NRCan/GSC), Ashley Rudy (NTGS)

Contributors: Feresteh Ghiami-Shomami (Carleton University), Silvie Harder (CCCS/ECCC), Ryan Hennessey (CCCS/ECCC), Brian Horton (Yukon Research Centre), Galina Jonat (Carleton University), Hannah Macdonell (Carleton University)

3.4.1 Introduction

Permafrost is part of the climate system and is defined as ground (soil or rock and included ice and organic material) that remains at or below 0°C for at least two consecutive years. It usually contains ice – often for a long time (e.g., thousands of years), and can bring about geomorphic, geotechnical, hydrologic, and ecologic changes during thaw. Permafrost thaw refers to the progressive loss of ground ice, usually due to the input of heat.

Permafrost is a subsurface phenomenon traditionally studied with geologic methods, as it is largely not observable using satellite and airborne sensors. Relevant variations in permafrost characteristics and change occur on spatial scales on the order of tens of metres. The spatial distribution and transient changes of permafrost are best understood and predicted using a combination of approaches from atmospheric science and geology. Corresponding capabilities, capacity, data, and services relating to permafrost information are rare at present. As a result, gaps in this section may be more prominent than in others and can motivate and guide further work.

This initial report lists and explains permafrost data sets of ground temperature, subsurface ice content, and permafrost extent (areal proportion). Permafrost change is also described in terms of landform inventories, as well as ground subsidence and active-layer thickness, but these metrics are only briefly described here.

3.4.2 Ground Temperature

While permafrost is defined via ground temperature, interest in permafrost is based on the phenomena of thaw, i.e., ice loss in the ground. When thaw occurs, ground temperature often stagnates just below 0°C due to latent heat transfer. As such, ground temperature is a challenging metric of permafrost change as it often requires the counter-intuitive and difficult interpretation of relating less change to a presumed greater thaw. Ground temperature data is often not shared or shared in non-standardized form and only for individual sites and studies. As such, the current compilation is incomplete and represents a starting point for future work. Work toward data interoperability and standards is underway in NSERC PermafrostNet (https://www.permafrostnet.ca/data/). Ground temperature, along with other relevant permafrost conditions, varies widely over scales of metres to tens of metres. This makes the interpretation of observations difficult even for nearby locations and it also makes interpretation of gridded data in a local context difficult. Ground temperature data can support local planning and engineering design, the quantification and analysis of change, and the testing of computer models.

Table 3.18 Summary of large observation-based historical datasets with ground temperature. Many other sites exist and are accessible individually.

Name	Source	Type	Spatial domain	Spatial resolution	Temporal coverage	Time step	Format
GTN-P	IPA	Station data	Global	Point data	Variable (1950 to present)	Daily; Annual	CSV
Permafrost Ground Temperature for the Northern Hemisphere, v3.0	CEDA Archive/ESA Permafrost CCI+	Model based on reanalyses	North of N30º	1 km x 1m	A: 2003–2019 B: 1997–2002	Annual	NetCDF
Borehole and near-surface ground temperatures in northeastern Canada	CEN	Station data	Northeastern Canada	Point data	Variable 1990-present	n.a.	CSV
Map and summary database of permafrost temperatures in Nunavut	GEOSCAN	Station data	Nunavut	Point data	Variable 1995 - 2012 Summary statistics	Variable	Excel files
Air and near-surface ground temperatures for Mackenzie Valley Corridor	GEOSCAN	Station data	Northwestern Canada	Point data	1993-2012	Daily; Monthly	CSV
N.W.T. Permafrost Database	Northwest Territories Geological Survey/GNWT	Station data	NWT	Point data	Variable	Variable	CSV
Yukon Permafrost Database	Yukon Geological Survey/Yukon Government	Station data	Yukon	Point data	variable	Variable	CSV

3.4.2.1 Data sources

Global Terrestrial Network for Permafrost (GTN-P): http://gtnpdatabase.org/boreholes GTN-P is the primary international program concerned with monitoring permafrost parameters. This database provides metainformation for borehole sites as well as some time-series data.

Permafrost Ground Temperature for the Northern Hemisphere, v3.0 (Westermann *et al.*, 2020): https://catalogue.ceda.ac.uk/uuid/b25d4a6174de4ac78000d034f500a268 Mean annual ground temperatures at the ground surface and 1 m, 2 m, 5 m and 10 m depth are derived from CryoGrid 3. In the data product A, the model is driven by a combination of MODIS Land Surface temperature observations and downscaled ERA near-surface air temperature data. In data product B, the same thermal model is driven by ERA5 near-surface temperature data. CryoGrid 3 includes land-atmosphere coupling and a subsurface heat transfer model. Snowfall and snowmelt are represented by a degree-day based snow model driven by downscaled ERA5 reanalysis. The land cover is expressed as a fractional coverage of seven land cover classes (ESA landcover_cci). Each 1x1 km pixel is using an ensemble approach on land cover fraction to statistically account for natural variability of snow depth. The model has been tested at permafrost sites in Russia and Norway. Uncertainties are introduced in the pre-processing step of the input dataset and through simplified process representation (due to computation cost). The scarcity of validation sites for input parameters, such as stratigraphy, introduces an additional factor of uncertainty.

Borehole and near-surface ground temperatures in northeastern Canada: http://www.cen.ulaval.ca/nordicanad/dpage.aspx?doi=45291SL-34F28A9491014AFD Nordicana-D data are from 11 sets of locations in Nunavik and Nunavut, northeastern Canada. The available datasets cover the period from 1988 to 2019. There are a total number of 46 boreholes with the depth ranging from 0.02 to 20 m. Almost half of the boreholes have near-surface depth (2–5 cm) and 12 boreholes are drilled deeper than 10 m. Among those, 29 boreholes cover Akulivik, Aupaluk, Kangiqsualujjuaq, Puvirnituq, Quaqtaq, Tasiujaq, Umijuaq, Iqaluit, Pangnirtung and Île Bylot regions while other 17 boreholes are located in Salluit region. 14 boreholes have more than 20 years of data while 15 boreholes have data records shorter than 15 years.

A map and summary database for permafrost temperatures in Nunavut:

https://geoscan.nrcan.gc.ca/starweb/geoscan/servlet.starweb?path=geoscan/fulle.web&search1=R=292615. This dataset is from 20 sites in Nunavut where measurements were made in 111 boreholes located within a few tens of metres to a few kilometres of each other. Borehole depth range from 3 to 36 m with 56 boreholes deeper than 20 m and 22 less than 10 m depth. The mine site boreholes account for almost 80% of the boreholes included in the database. Data on ground temperature has been compiled into a MS Excel Spreadsheet (NUGT.xls). Most of the data is available for 2010s.

Air and near-surface ground temperatures Mackenzie Valley Corridor: https://doi.org/10.4095/294835 This dataset included near-surface ground temperatures, indices and summary statistics from 1993 to 2012 for the Mackenzie Valley Corridor, Northwest Territories.

NWT Permafrost Database: Contains ground temperature data collected for a variety of purposes including but not limited to linear and vertical infrastructure, government and academic research sites and community planning. Represents ground temperatures from boreholes with varying depths and captures relevant terrain information useful for interpreting ground temperature data. The database is currently in the testing phase and development of the web portal will begin soon. This will make NWT ground temperature data available for download to the public (Contact Niels Weiss: niels_weiss@gov.nt.ca)

Yukon Permafrost Database: (https://service.yukon.ca/permafrost/, contact Derek Cronmiller: Derek.Cronmiller@yukon.ca) Contains 80 sites currently with data that includes roads, airstrips, mining projects and academic research sites.

3.4.2.2 Strengths and limitations of datasets

Station data: Ground temperature data associated with station data represents a single point on the landscape and is unlikely to reflect conditions at a regional scale. Relationships between station data and surface and terrain information may be used to extrapolate relations but caution is required as ground temperature is very site-specific. Station data provide accurate information on local conditions.

Gridded data: Ground temperature data is represented by spatially defined grids. It can be derived from interpolated station data, thermal models and satellite data. Limitations include regional biases due to poor spatial coverage of station data and model shortcomings. The spatial resolution of gridded data will depend on the spatial resolution of the sensor.

Reanalyses and Reanalysis-Based Datasets: Ground temperature data available as part of reanalyses has not been systematically evaluated for permafrost areas. ERA5-Land, and likely ERA5, exhibit strong and spatially variable bias (Cao *et al.,* 2021).

References – Ground Temperature

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3.4.3 Subsurface Ice Content

Ground ice is a key component of permafrost landscapes. The formation and melt of subsurface ice can alter topography, damage infrastructure, and modify hydrological processes. The quantity and type of ground ice control the terrain response to climate change, especially in areas with ice-rich permafrost. For example, ice-rich permafrost thaw in flat terrain commonly results in subsidence of the ground surface and ponding; on hillslopes, ground ice melt can initiate landslides or gullying.

Ground ice occurs in different forms and accumulates due to a variety of processes. Segregated ice forms as lenses or layers due to the migration of unfrozen water toward colder ground and subsequent freezing. Wedge ice accumulates when permafrost ground cracks due to extreme cold. In spring, water fills the crack and freezes, forming an ice vein. Repeated cracking, infilling, and freezing forms large wedges of ground ice over centuries to millennia. Glacier ice may become buried by sediment and preserved as large ice bodies in permafrost. Hydraulic pressure in unfrozen aquifers can also cause the formation of injection ice in permafrost. Given the various types of processes involved in its formation, ground ice content is controlled by several factors including surficial geology, climate, glacial history, vegetation, and moisture conditions.

Table 3.19 Summary of observation-based historical datasets with subsurface ice content for two types of data: station data (boreholes) and modelling/mapping.

Name	Source	Type	Spatial domain	Spatial resolution	Temporal coverage	Time step	Format

Circum-Arctic Map of Permafrost and Ground-Ice Conditions, Version 2	NSIDC	Map, manual delineation	Global	Polygons from 1:10,000,000 paper map	Variable	n.a.	Shapefiles
Ground ice map of Canada	NRCan	Map, manual and heuristic rules	Canada	Polygons from 1:5,000,000 digital maps	Late 20th century	n.a.	GeoTIFF; WMS
Permafrost Map of Canada	NRCan	Map, manual delineation	Canada	Polygons from 1:7,500,000 map	n.a.	n.a.	PDF
Permafrost Information Network	NRCan	Station data	Canada	Point data	Variable, 1953-2009	n.a.	n.a.
N.W.T. Permafrost Database	Northwest Territories Geological Survey/GNWT	Station data	NWT	Point data	Variable	n.a.	CSV
Permafrost and ground ice conditions of northwestern Canada	NRCan	Map, manual delineation	Northwest Canada	1:1,000,000	n.a.	n.a.	PDF
Yukon Permafrost Database	Yukon Geological Survey/Yukon Government	Station data	Yukon	Point data	Variable	n.a.	n.a.

3.4.3.1 Data sources

Circum-Arctic Map of Permafrost and Ground-Ice Conditions, Version 2: https://nsidc.org/data/ggd318. (Brown *et al.*, 2002). Northern hemisphere representation of ground ice conditions. The relative abundance of visible ground ice in the upper 10-20 m is estimated in percent volume (>20 percent, 10-20 percent, <10 percent, and 0 percent for areas with thick overburden; and >10 percent, <10 percent for areas with thin overburden).

Ground ice map of Canada (https://doi.org/10.4095/330294) National-scale modelling of segregated, wedge, and relict (buried glacier) ice. Modelling methodology described in O'Neill *et al*. (2019). The modelling uses an expert-system (rules-based) approach that employs datasets on surficial materials, paleovegetation, deglacial history, and modern permafrost distribution. GeoTIFF data layers are accessible on NRCan's GEOSCAN repository and WMS are available.

Permafrost map of Canada (Heginbottom *et al*., 1995). The Permafrost map of Canada, published in the 5th Edition (1978 to 1995) of the National Atlas of Canada, is a 1:7,500,00 map showing permafrost zones and ground ice information. The legend includes ground ice represented as the % by volume of visible ice in the upper 10-20 m of ground as with the IPA map. The classes include high (>20%), medium (10-20%), low (<10%) and nil (0%). The geospatial data is not currently (21 July 2021) available on a public portal, but digital files have been prepared and will be available shortly on Open Maps.

Permafrost Information Network (https://pin.geosciences.ca/en/map) The Permafrost Information Network (PIN) is a web portal in early development to access permafrost-related information from the Geological Survey of Canada (Natural Resources Canada). Currently, the portal includes records from ~14,000 geotechnical boreholes from northern Canada. These borehole logs contain information related to ground ice such as: descriptions of visible ground ice, gravimetric moisture content, and in some cases, excess moisture content. The borehole logs also include useful information for permafrost thermal modelling applications, such as the % fractions of sand/silt/clay for many boreholes. PIN also displays the ground ice mapping layers of O'Neill *et al*. (2019 and 2020).

NWT Permafrost Database Permafrost and ground ice conditions are available through borehole data compiled from geotechnical datasets. Datasets represent geotechnical data from industry, construction of linear infrastructure and government, and academic research projects. Borehole logs contain information related to ground ice such as: fractions of sand/silt/clay, volumetric ice content, in some cases excess ice content and descriptions of visible ice. (Contact Niels Weiss: niels_weiss@gov.nt.ca)

Permafrost and ground ice conditions of northwestern Canada (Heginbottom and Radburn, 1992) The mapping provides a qualitative assessment of ground ice abundance in northwestern Canada at 1:1,000,000 scale. The assessment is based mainly on previous surficial geological and geomorphological mapping sources at scales of 1:100,000 to 1:250,000.

Yukon Permafrost Database (Release imminent; contact Derek Cronmiller: Derek.Cronmiller@yukon.ca) Compilation of about 15,000 boreholes including several compilations: The Alaska Highway Borehole Database (8818 holes) compiled by the Yukon Geological Survey in 2010, based on logbooks 1970–1990. The boreholes were drilled approximately every 100 m down centerline, averaging 6 m deep; approximately 1/3 record some form of permafrost. **HPW-TEB GINT/Holebase** (1743 holes) 2011–2019. EBA GINT (4408 holes) compilation from contracts carried out up to 2010. Mineral Industry (380 holes) from Western Copper-Casino, BMC Minerals-Kudz Ze Kayah, Clinton Creek Mine. Additionally, the Permafrost Information Network (PIN) has 633 sites for Yukon that are not included in this compilation.

3.4.3.2 Strengths and Limitations of Datasets

Station data (boreholes): Sources of ground ice information include compilations of geotechnical borehole logs. Point-scale borehole records provide direct and spatially explicit observations and are thus valuable for the characterization of local ice conditions. However, the type and detail of ground ice information vary depending on the purpose of the geotechnical drilling campaign. For example, some records may include only a visual description of ice conditions, whereas others may include measurements of ice content.

Modelling/mapping: Ground ice mapping products provide estimates of ground ice content over large areas, informed by available field information on ground ice and extrapolations to areas with similar environmental conditions. Given the general lack of ground ice information over much of the Canadian landmass for calibration and validation and the coarse resolution of basemaps used for mapping and modelling, these can provide only a rough estimate of average ground ice conditions within the map units. The ground ice information for Canada from the IPA map and Permafrost map of Canada is based on extrapolation of expected ground ice conditions to a basemap of large physiographic regions. The recently published Ground ice map of Canada uses a more detailed national-scale surficial geology dataset as a basemap. This provides a more detailed depiction, but in some regions, the abundance of frost-susceptible sediments is underrepresented compared to bedrock, which affects the spatial accuracy of the modelling/mapping (Wolfe *et al*., 2021). Nonetheless, these products are the only available information suitable for use in spatial modelling.

References – Subsurface Ice Content

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Wolfe, S.A., H.B. O'Neill, and C. Duchesne, 2021: A Ground Ice Atlas of Canada. Geological Survey of Canada, doi.org/10.4095/328115.

3.4.4 Permafrost extent

Permafrost extent (Obu, 2021) expresses the areal proportion of ground underlain by permafrost. It usually assumes that no temporal change occurs (equilibrium). Model results are often referred to as indices (Gruber, 2012; Boeckli *et al*., 2012) as the relationship with true extent is unknown. Permafrost extent, sometimes classified into zones such as 'continuous permafrost' or 'extensive discontinuous permafrost', is the most widely used permafrost data product.

Permafrost extent cannot be directly observed. Therefore, data products are based on heuristics or models (commonly relations with air temperature) resting on observations of ground temperature at few locations only, and the quality of data products is difficult to quantify. Relating permafrost extent (a spatial aggregation of a binary variable) to conditions at specific locations is difficult and usually requires additional guidance (see Boeckli et al., 2012). Simulating changes of permafrost extent on inter-annual to century scales usually involves extreme simplification (depth, ice content) that limits the interpretability of results. The difficulty inherent in defining and interpreting permafrost extent and zones is well known (e.g., Zhang *et al*., 2000; Heginbottom, 2002; Gruber, 2012; Gruber, 2016; Obu, 2021).

Maps of permafrost extent can communicate where permafrost may exist and approximately what proportion of the area is expected to have permafrost (see Gruber 2016). Permafrost extent can be aggregated into summaries of total permafrost area. This can inform teaching, policy making, and help decide if permafrost needs to be investigated in more detail during the early stages of land-use projects when the permafrost status of a location is unknown.

Table 3.20 Summary of historical datasets for permafrost extent. The table presents two types of data reflecting the mode of generation: manual delineation as polygons and gridded models that rely on computer simulation.

Name	Source	Type	Spatial domain	Spatial resolution	Temporal coverage	Time step	Format
Circum-Arctic Map of Permafrost and Ground-Ice Conditions, Version 2	NSIDC	Map, manual delineation	Global	Polygons from 1:10,000,000 paper map	mid-late 20th century	n.a.	Shapefiles
Permafrost Map of Canada	NRCan	Map, manual delineation	Canada	Polygons from 1:7,500,000 map	mid-late 20th century	n.a.	PDF
Permafrost Zonation Index	University of Zurich	Model based on reanalyses	Global	~1 km x 1 km	equilibrium 1960–1990	n.a.	WMS; Binary
Circumpolar permafrost maps	Published in Scientific Data	Model based on reanalyses	North of N30º	~1 km x 1 km	equilibrium 2000–2014	n.a.	GeoTIFF
Permafrost extent for the Northern Hemisphere, v3.0	CEDA Archive/ESA Permafrost CCI+	Model based on reanalyses	North of N30º	~1 km x 1 km	A: 2003–2019 B: 1997–2002	Annual	NetCDF

3.4.4.1 Data sources

Circum-Arctic Map of Permafrost and Ground-Ice Conditions, Version 2: https://nsidc.org/data/ggd318. This is a digitized version of Brown *et al*. (1997). The map itself is based on a compilation of heuristic, and mostly manual, delineation and some homogenizations of differing mapping systems (see Gruber, 2012). This is the most widely used spatial depiction of permafrost.

Permafrost Map of Canada: "Permafrost" 1:7,500,00 in the 5th Edition (1978 to 1995) of the National Atlas of Canada, https://ftp.maps.canada.ca/pub/nrcan_rncan/raster/atlas_5_ed/eng/environment/land/mcr4177.pdf

Global Permafrost Zonation Index Map (Gruber 2012): https://www.geo.uzh.ch/microsite/cryodata/pf_global/. This dataset casts rules used in Brown *et al*. (1997) – the Circum-Arctic Map of Permafrost and Ground-Ice Conditions – in a simple model and applies it to gridded mean annual air temperature for the period 1961–1990. Transient effects are not represented. In mountains, lapse rates are applied on a grid spacing of about 1 km.

Circumpolar permafrost maps (Karjalainen et al., 2018): https://doi.pangaea.de/10.1594/PANGAEA.893881. This dataset contains a baseline map for the period 2000–2014 at about 1 km resolution that has been derived based on statistical modelling with climate data and observed ground temperature.

Permafrost extent for the Northern Hemisphere, v3.0: https://catalogue.ceda.ac.uk/uuid/6e2091cb0c8b4106921b63cd5357c97c. This dataset contains annual maps of permafrost extent north of 30°N at about 1 km resolution. They are derived from a transient thermal model and fractional coverage of seven land cover classes (Westermann et al., 2020). For 2003–2019 this is based on MODIS Land Surface Temperature (LST) merged with ERA5 air temperature and for 1997–2002 it is based on ERA5 air temperature and bias correction with the MODIS LST 2003–2019. Annual permafrost extent in this product is derived from ground temperature at 2 m depth, and as such, permafrost can persist at depth in higher fractions than indicated for years to centuries.

3.4.4.2 Strengths and Limitations of Datasets

Manual delineation: Expert knowledge (i.e., perceived permafrost extent and its relationship with physiography and climate) is used as a heuristic for delineation of polygons in the generation of national and international maps. The rules and entities used (see Heginbottom 2002; Gruber, 2012) for drawing lines differ and are difficult to compare between regions, or to reproduce accurately. The use of permafrost zones is well established. Such maps enjoy great popularity and often trust, even though it is unclear in many areas how reliable the mapping is. Transient effects are not represented and the period for which this data is valid is not specified explicitly.

Gridded model: Quantitative data from reanalysis, interpolated observations, or remote sensing is used as input for model simulations. Relying on quantitative spatial data makes these types of data reproducible and more consistent spatially than those derived from manual delineation. The models used contain assumptions about the subgrid characteristics of microclimate, snow, land surface, and subsurface. The appropriateness of these assumptions is difficult to ascertain.

References – Permafrost Extent

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3.4.5 Landform Inventories

Permafrost landform inventories provide information on subsurface processes through their surface expression as landforms and are a reflection of the glacial, periglacial, and climatic history of a region. This insight into past processes also contributes to anticipating future trajectories of change. Landform inventories can contribute to better understanding ground ice distribution, testing and validating remote sensing tools and predictive models, as well as facilitating the assessment of landscape change.

Landform inventories exist for different areas of the Canadian Arctic (Lewkowicz and Way, 2019; Segal *et al*., 2016 a,b,c; Sladen *et al*., 2020; Sladen *et al.*, 2021; Rudy *et al*., 2020), however, these have not been systematically collected and are often tied to specific research questions. As a result, there is no standardization between inventories that rely on different data models (legends) and mapping protocols. Inventories are also collected through an array of methods i.e. on the ground mapping, air photo interpretation, semi and automatic detection using remote sensing, and may be represented as points (spatial coordinates), lines, or polygons. There is a need to define landforms objectively and reproducibly. However, nomenclature in regards to different landforms may vary across disciplines (experts), certain landforms are easier to identify than others, and certain landscapes allow for feature identification more readily (Evans, 2012).

Table 3.21 Summary of historical datasets for permafrost landforms. This is not an exhaustive list, many inventories are not made available when published in a journal.

Name	Source	Type	Spatial domain	Spatial resolution	Temporal coverage	Format
Geomorphologic feature mapping methodology for the Dempster Highway and Inuvik to Tuktoyaktuk Highway corridors	NRCan	Map, manual delineation	Dempster Highway and Inuvik to Tuktoyaktuk highway corridors	0.6 m	2004–2016	PDF
N.W.T. Thermokarst Collective	Northwest Territories Geological Survey/GNWT	Map, manual delineation	Northwest Territories	7.5 km	2018	Shapefiles
Broad-scale mapping of terrain impacted by retrogressive thaw slumping in Northwestern Canada	Northwest Territories Geological Survey/GNWT	Map, manual delineation	Northwest Territories	15 km	2005-2010	Shapefiles
Inventory of active retrogressive thaw slumps on eastern Banks Island, N.W.T.	Northwest Territories Geological Survey/GNWT	Map, manual delineation	Eastern Banks Island, NWT	10 m	2016-2017	Shapefiles
Inventory of active retrogressive thaw slumps in the Peel Plateau, N.W.T.	Northwest Territories Geological Survey/GNWT	Map, manual delineation	Peel Plateau, NWT	10 m	2016-2017	Shapefiles
Inventory of retrogressive thaw slumps in the Willow River watershed, mapped using 1986, 2002, and 2018 Landsat imagery	Northwest Territories Geological Survey/GNWT	Map, manual delineation	Willow River Watershed, NWT	30 m	1986, 2002, 2018	Shapefiles
Inventory of retrogressive thaw slumps on the Peel Plateau and on southeastern Banks Island, N.W.T. using 2017 Sentinel imagery	Northwest Territories Geological Survey/GNWT	Map, manual delineation	Peel Plateau and southeastern Banks Island, NWT	10 m	2017	Shapefiles
An inventory of rock glaciers in the central B.C. Coast Mountains, Canada, from high resolution Google Earth imagery	University of Victoria	Map, manual delineation	Central British Columbia	15 cm – 15 m	2004/2005	CSV
Extremes of summer climate trigger thousands of thermokarst landslides in a High Arctic environment	University of Ottawa	n.a.	Banks Island, NWT	30 m or 60 m	1984–2016	CSV

3.4.5.1 Data sources

Geomorphologic feature mapping methodology developed for the Dempster Highway and Inuvik to Tuktoyaktuk Highway corridors: The terrain mapping utilized recent high-resolution imagery: Worldview (2012-15), orthophotos (2004, 2011), SPOT (2016), and LiDAR (2011) data to identify geomorphological features and landscape types within the 10-km-wide and 875-km-long corridor. Methodologies include rendering Worldview imagery in three dimensions with Summit 3D software, and digitizing features directly into ArcGIS using DAT/EM's Capture Interface LiDAR data, where available, is used in combination with associated orthophotos and features are digitized directly into ArcGIS (https://doi.org/10.4095/328181).

NWT Thermokarst Collective: The objective of the NWT Thermokarst Mapping Collective is to establish a collaborative approach to develop and implement a mapping methodology to generate NWT-wide thermokarst and permafrost feature inventory maps. Three landform themes are the focus: periglacial, hydrological and mass wasting features. Outputs will provide information relevant to all NWT regions, inform and validate modelling efforts, and support community climate change adaptation. (Contact: Steve Kokelj, steve_kokelj@gov.nt.ca)

Broad-scale mapping of terrain impacted by retrogressive thaw slumping in Northwestern Canada: Mappable cells were created using a 15 km by 15 km grid covering a land area of more than 1.2 million km^2. Trained technicians assessed several disturbance and landscape attributes for each grid cell by viewing the georeferenced SPOT 5 and SPOT 4 orthomosaics from 2005-2010 (NWT Centre for Geomatics, 2013; Latitude Geographics Group Ltd., 2014). (Contact: NTGS@gov.nt.ca)

Inventory of active retrogressive thaw slumps on eastern Banks Island, Northwest Territories: All active retrogressive thaw slumps in the eastern Banks Island study region were digitized on-screen using georeferenced imagery in Google Earth, ESRI ArcMap (versions 10.0 and 10.1), and the NWT Spatial Data Warehouse Geospatial Portal (NWT Centre for Geomatics 2013; Latitude Geographics Group Ltd.). Slumps were identified based on the presence of exposed sediments, poorly developed vegetation, and a well-defined headwall. (Contact: NTGS@gov.nt.ca)

Inventory of active retrogressive thaw slumps in the Peel Plateau, Northwest Territories: All active retrogressive thaw slumps in the Peel Plateau study region were digitized on-screen using georeferenced imagery in Google Earth, ESRI ArcMap (versions 10.0 and 10.1), and the NWT Spatial Data Warehouse Geospatial Portal (NWT Centre for Geomatics 2013; Latitude Geographics Group Ltd.). Slumps were identified based on the presence of exposed sediments, poorly developed vegetation, and a well-defined headwall (Contact: NTGS@gov.nt.ca)

Inventory of retrogressive thaw slumps in the Willow River watershed, mapped using 1986, 2002, and 2018 Landsat imagery: Retrogressive thaw slumps were digitized using Landsat images (30 m resolution) from 1986, 2002, and 2018. Thaw slumps were identified as slope disturbances characterized by a well-defined headwall, exposed sediments or poorly-developed vegetation. The extent of each feature was digitized in ArcMap. Mapper interpretations were verified by field reconnaissance during the summer of 2019. (Contact: NTGS@gov.nt.ca)

Inventory of retrogressive thaw slumps on the Peel Plateau and on southeastern Banks Island, Northwest Territories using 2017 Sentinel imagery: Retrogressive thaw slumps were digitized using 2018 Sentinel (10 m resolution) imagery. Thaw slumps were identified as slope disturbances characterized by a well-defined headwall, exposed sediments and poorly-developed vegetation. The extent of each feature was digitized in ArcMap. (Contact: NTGS@gov.nt.ca)

An inventory of rock glaciers in the central British Columbia Coast Mountains, Canada, from high resolution Google Earth imagery: The rock glacier inventory was completed using high-resolution Google Earth satellite imagery (2004/2005). Google Earth uses SPOT or products from DigitalGlobe (e.g., IKONOS or Quickbird). Only snow-free and cloud-free imagery was used in the survey, and identification was supplemented with field validation where access permitted. (Data in Charbonneau & Smith, 2018: 10.1080/15230430.2018.1489026)

Extremes of summer climate trigger thousands of thermokarst landslides in a High Arctic environment: Google Earth Engine Timelapse data, covering the period 1984–2016 was accessed through a web-based interface to generate novel information regarding RTS activity. Documented here are the year of feature initiation, the longevity of RTS, the location of initiation in the landscape (Fig. 1b), and the relation of RTS activity to other landscape change over an area of 70,000 km^2 . (Data in Lewkowicz & Way, 2019: https://doi.org/10.1038/s41467-019-09314-7)

3.4.5.2 Strengths and Limitations of Datasets

Manual delineation/identification: Expert knowledge (i.e., ability to identify an array of permafrost landforms) is used to identify, classify, and delineate the extent of permafrost landforms or add a point on the feature of interest. This process is time-consuming and its accuracy is limited by the expertise of the mapper, image resolution, and the ability to include quality control (independent mappers, e.g., Schmid *et al*., 2015) in the data generation process. Datasets are valuable when used as inputs to train and validate models and remote sensing tools.

Gridded mapping: Mapping is done using grids, with spatial resolution often differing between studies. Landforms are identified by presence/absence and in some cases, an approximate extent or count is attributed to a grid cell. Datasets are empirically based and highlight landscape forms and their patterns at a regional and broad scale.

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3.4.6 Ground Subsidence and Active-Layer Thickness

Datasets exist on the thickness of the active layer, the layer above permafrost that freezes and thaws annually, and subsidence of the ground surface due to ice-rich permafrost thaw. The Circumpolar Active Layer Monitoring (CALM) program is the primary program for long-term active-layer measurements (https://www2.gwu.edu/~calm/). This program aims to observe the response of the active layer and near-surface permafrost to climate change over multi-decadal time scales. Increases in active-layer thickness cause ground surface subsidence where sediments are ice-rich. Because this subsidence represents a loss of ground ice and a net export of latent heat, observations of surface subsidence are an important

– but currently rare – component of monitoring that observed active-layer thickness and/or ground temperature change in boreholes (O'Neill *et al*., 2019; Gruber, 2020).

Though studies of subsidence of more than a decade (and longer) have been published recently, there is currently no organized repository to access data from various sources. In Canada, the Geological Survey maintains a network of thaw tubes that measure active layer thickness, thaw penetration, and ground surface subsidence, with records available since 1991 (e.g., Duchesne *et al*., 2015). Recently, ground surface subsidence in permafrost areas has been inferred using seasonal and multi-year datasets from in-situ observations (O'Neill *et al*., 2019; Gruber, 2020) as well as differential interferometric synthetic aperture radar. Integration of subsidence information using different sources would improve knowledge of landscape changes associated with permafrost thaw in ice-rich terrain.

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4 Assessment of northern historical climate simulations and future projections

4.1 Overview of climate models for the Canadian North.

Lead Author: Elaine Barrow (CCCS/ECCC)

Contributors: Emilia Diaconescu (CCCS/ECCC) and Paul Kushner (University of Toronto)

There is an ever-increasing amount of climate model data available for download, and navigating the data sources and understanding the limitations of the data is a critical part of the decision-making process. This section outlines the most recent climate model experiments and the caveats to be considered when selecting climate model data for use in, for example, climate change adaptation applications. Much of the material in this section is based on Cannon *et al*. (2020), which provides a thorough background to climate model information and its limitations. One of the major recommendations for using climate model simulations is to consider multiple climate models and multiple emissions scenarios – known as ensembles. Table 4.1 summarizes the most recent climate model ensembles and provides information on the variables available for download, and links to webpages offering detailed descriptions of the data.

Table 4.1 Ensembles of simulations available for download

Name	Description	No. models	Spatial extend	Spatial resolution	Temporal extend	Scenarios	Category of variables	Download information (e.g., variables, temporal resolution, format)	Details
CMIP6 raw data	Ensemble of coupled atmosphere-ocean general circulation models. This is the most recent phase of the CMIP project (**not completed in August 2021**).	Up to 68 distinct climate models across 49 different modelling groups. (the number of models varies with the scenarios and the variable) Summary table of currently available data.	Global	Varies from model to model (AGCM: 0.125° x 0.125° to 5° x 5°; OGCM: 0.25° to 2.5°)	Historical period: 1850–2014 Future period: 2015–2100 Some models provide simulations up to 2300	Tier 1: SSP1-2.6 SSP2-4.5 SSP3-7.0 SSP5-8.5 Tier 2: SSP1-1.9 SSP4-6.0 SSP4-3.4 SSP5-3.4-OS (details here)	**Meteorological** (all variables analyzed in this report) **Snow related** (all variables analyzed in this report) **Hydrological** (runoff) **Sea ice related** (all variables analyzed in this report; see Notz *et al.* (2020), for details)	The complete archive of CMIP6 output is accessible from any one of the following portals: • PCMDI/LLNL: https://esgf-node.llnl.gov/projects/cmip6/ • IPSL : https://esgf-node.ipsl.upmc.fr/projects/cmip6-ipsl/ • DKRZ: https://esgf-data.dkrz.de/projects/cmip6-dkrz/ • CEDA: https://esgf-index1.ceda.ac.uk/projects/cmip6-ceda/ CMIP6 data can be downloaded using Thiago Loureiro's CMIP6 downloader (https://doi.org/10.5281/zenodo.3966556).	Dedicated website on CMIP6 hosted by PCMDI. Diagnostic and performance metrics with the ESMValTool for CMIP6 simulations.

Name	Description	No. models	Spatial extend	Spatial resolution	Temporal extend	Scenarios	Category of variables	Download information (e.g., variables, temporal resolution, format)	Details
								A subset of variables are available in netCDF format on Copernicus at daily and monthly temporal resolution: - **daily**: near-surface wind, maximum, minimum and mean daily temperature, near-surface specific humidity, mean precipitation flux) - **monthly**: 10m wind, 10m v and u components of wind, mean, minimum and maximum temperature, near-surface specific and relative humidity, sea ice mass per area, sea ice thickness, sea-ice area percentage on ocean grid, snowfall, snow depth, mean precipitation flux, runoff and others. A subset of variables at monthly timescale is also available at KNMI Climate Explorer.	
CMIP5 raw data	Ensemble of coupled atmosphere-ocean general circulation models. This is the most recently **completed** phase of the CMIP project.	More than 60 models (the number of models varies with the scenarios and the variable)	Global	Varies from model to model (AGCM: 0.188° x 0.187° to 4.1° x 5.0°; OGCM: 0.25° to 2.5°)	Historical period: 1850-2005 Future period: 2006-2100 Some models provide simulations up to 2300	RCP 2.6 RCP 4.5 RCP 6.0 RCP 8.5	**Meteorological** (all variables analyzed in this report) **Snow related** (all variables analyzed in this report) **Hydrological** (runoff) **Sea ice related** (sea ice volume per grid cell area, or equivalent sea ice thickness (sit); sea ice drift: siu (zonal component), siv (meridional component) and speed (sispeed); see Notz *et al.* (2016).)	All of the CMIP5 model output can be accessed through any one of the following Earth System Grid Federation (ESGF) gateways: • PCMDI: http://esgf-node.llnl.gov/ • BADC: http://esgf-index1.ceda.ac.uk • DKRZ: http://esgf-data.dkrz.de • NCI: http://esgf.nci.org.au The DDC Reference snapshot (http://www.ipcc-data.org/sim/gcm_monthly/AR5/Reference-Archive.html) is available at the World Data Center for Climate (WDCC, https://cera-www.dkrz.de/WDCC/ui/cerasearch/q?general_key_ss=IPCC-DDC): 60 models, **many variables**, annual, monthly, daily, 6-hourly, 3-hourly and sub-hourly (depending on variable), netCDF format. A subset of variables are available in netCDF format on Copernicus at daily and monthly timescale:	Dedicated website on CMIP5 hosted by PCMDI. Diagnostic and performance metrics with the ESMValTool for CMIP5 simulations.

Name	Description	No. models	Spatial extend	Spatial resolution	Temporal extend	Scenarios	Category of variables	Download information (e.g., variables, temporal resolution, format)	Details
								- daily: **10m wind, maximum, minimum and mean daily temperature, near-surface specific humidity and relative humidity, mean precipitation flux**, snowfall and surface solar radiation - monthly: **10m wind, 10m v and u components of wind, mean, minimum and maximum temperature, near-surface specific and relative humidity, sea ice fraction, sea ice thickness, snow depth over sea ice, surface snow amount, mean precipitation flux, runoff, sea ice plus snow amount,** snowfall, and others. A subset of variables at monthly timescale is also available at KNMI Climate Explorer.	
CMIP5 1° x 1° gridded data	A sub ensemble of 29 CMIP5 simulations have been regridded onto a common 1° x 1° global grid. Provides projected changes and absolute values.	29 simulations with 29 models (list of models)	Global	1° x 1°	Historical period: 1900-2005 Future period: 2006-2100	RCP2.6 RCP 4.5 RCP 8.5	**Meteorological** (surface air temperature, total precipitation, and near-surface wind speed) **Snow related** (snow depth) **Sea ice related** (sea ice thickness, sea ice concentration)	ECCC provide access to a subset of variables in netCDF and GeoTIFF formats at monthly, seasonal and annual timescale: **surface air temperature, total precipitation, sea ice thickness, sea ice concentration, snow depth, and near-surface wind speed**. Projected changes are expressed as anomalies with respect to the reference period of 1986-2005. A range of percentiles (the 5th, 25th, 50th, 75th and 95th percentiles) across the multi-model ensemble are available for download on https://dd.weather.gc.ca/climate/cmip5/, and https://climate-scenarios.canada.ca/?page=gridded-data (also individual models). Download of a single point value as a CSV or GeoJSON format is also available on https://climate-change.canada.ca/climate-data/#/cmip5-data	Technical notes

Name	Description	No. models	Spatial extend	Spatial resolution	Temporal extend	Scenarios	Category of variables	Download information (e.g., variables, temporal resolution, format)	Details
North America CORDEX– raw data	Ensemble of RCMs driven by GCM simulations from CMIP5.	The number of simulations depends on variables and scenarios. Overall, there are 7 RCMs driven by 9 GCM.	North America without the Northern part of Ellesmere Island	0.44° x 0.44°; 0.22° x 0.22°	Historical period: 1950-2005 Future period: 2006-2100	RCP2.6 RCP 4.5 RCP 8.5	**Meteorological** (surface air temperature, total precipitation, near-surface wind speed, near-surface humidity, surface radiation) **Snow related** (snow depth, snowfall) **Hydrological** (runoff)	Data for **meteorological variables** in netCDF format is available on the NA-CORDEX search page . Most variables are available at daily, monthly, seasonal and annual timescales. Some temperature and precipitation simulations are available at sub hourly time step. Data is also available in cloud-friendly Zarr format on AWS. CORDEX data (**including some snow and hydrological variables**) is also available on ESGF (all nodes provide links to the same files): • **SMHI-NSC, Sweden** • **DKRZ, Germany** • **BADC, UK** • **IPSL, France** A table showing the CORDEX data available on the ESGF is available here. North America CORDEX simulations are noted as NAM-22 (for 0.22° x 0.22° spatial resolution) and NAM-44 (for 0.44° x 0.44° spatial resolution).	https://na-cordex.org/ https://cordex.org/
Arctic CORDEX – raw data	Ensemble of RCMs driven by GCM simulations from CMIP5.	The number of simulations depends on variables and scenarios. Overall, there are 11 RCMs driven by 4 GCM.	Arctic region without Northeast Canada.	0.44° x 0.44°, 0.22° x 0.22°	Historical period: 1950-2005 Future period: 2006-2100	RCP2.6 RCP 4.5 RCP 8.5	**Meteorological** (surface air temperature, total precipitation, near-surface wind speed, near-surface humidity, surface radiation) **Snow related** (snow depth, snowfall) **Hydrological** (runoff)	CORDEX data (including some snow and hydrological variables) in netCDF format is also available on ESGF (all nodes provide links to the same files): • **SMHI-NSC, Sweden** • **DKRZ, Germany** • **BADC, UK** • **IPSL, France** A table showing the CORDEX data available on the ESGF is available here. Arctic CORDEX simulations are noted as ARC-22 (for 0.22° x 0.22° spatial resolution) and ARC-44 (for 0.44° x 0.44° spatial resolution).	https://climate-cryosphere.org/activities/polar-cordex/arctic https://cordex.org/

Name	Description	No. models	Spatial extend	Spatial resolution	Temporal extend	Scenarios	Category of variables	Download information (e.g., variables, temporal resolution, format)	Details
North America CORDEX Bias-adjusted data against Daymet	CORDEX simulations over Norther America bias adjusted using Cannon's MBCn algorithm against Daymet gridded observations.	The number of simulations depends on variables and scenarios. Overall, there are 7 RCMs driven by 9 GCM.	North America without the Northern part of Ellesmere Island	0.44° x 0.44°, 0.22° x 0.22	Historical period: 1950-2005 Future period: 2006-2100	RCP2.6 RCP 4.5 RCP 8.5	**Meteorological** (daily minimum and maximum temperature, precipitation, specific humidity, and incoming solar radiation; two derived variables are also provided: relative humidity and daily mean temperature.)	Data in netCDF format can be accessed from the NA-CORDEX search page by selecting mbcn-Daymet in Bias Correction section. **CAUTION:** There was previously an error affecting all of the bias-corrected data (all mbcn-gridMET and mbcn-Daymet files) in the NA-CORDEX archive. A description of the error can be found below. As of 2021-11-19, this error has been fixed. The bias-correction was re run for all data published through the NCAR Climate Data Gateway and verified that the error was no longer present. If you downloaded bias-corrected data before 2021-11-19, you should replace it with the new version. Bias-adjusted CORDEX data in netCDF format are also available on ESGF nodes under the "CORDEX-Adjust" project (from all CORDEX search options chose "Domain", "RCM Model", "Driving Model", "Downscaling Realisation" and "Bias-adjustment") at the following ESGF Tier 1 nodes: • **NSC/LIU-SMHI, Sweden (https://esg-dn1.nsc.liu.se)** • **DKRZ, Germany (https://esgf-data.dkrz.de/)** • **IPSL, France (https://esgf-node.ipsl.upmc.fr)**	Details about bias-adjustment methods applied to the CORDEX simulations are provided here.
BCCAQv2 ensemble over Canada	CMIP5 simulations statistically downscaled with the BCCAQv2 method over Canada against ANUSPLIN	24 simulations with 24 models (list of the models)	Canada	10 km x 10 km	Historical period: 1950-2005 Future period: 2006-2100	RCP2.6 RCP4.5 RCP8.5	**Meteorological** (daily minimum, maximum and mean temperature and total precipitation)	PCIC has available for download all daily data (for each of the 24 climate models) in netCDF and ASCII formats. ClimateData.ca permits the download of daily data (for each of the 24 climate models) for specific locations in netCDF or CSV format. The site also offers climate indices (annul, seasonal and monthly)	technical note.

Name	Description	No. models	Spatial extend	Spatial resolution	Temporal extend	Scenarios	Category of variables	Download information (e.g., variables, temporal resolution, format)	Details
	gridded observations.							based on the daily BCCAQv2 data, as well as the possibility to compute online indices with specific thresholds (the ensemble for indices is represented by the 5th, 25th, 50th, 75th and 95th percentiles). Data for a single point can be downloaded as a CSV or JSON. ECCC's climate scenarios page also provides access to various climate indices in netCDF format. The CCCS website permits to download the ensemble percentiles (5th, 25th, 50th, 75th and 95th) for the annual, seasonal and monthly absolute values of daily minimum, maximum and mean temperature and total precipitation as well as of anomalies computed with respect to the reference period of 1986-2005. This data is available in netCDF or GeoTIFF format for a region or CSV and JSON format for a point	
CanLEAD-CanESM2 from Canadian Centre for Climate Modelling and Analysis (ECCC)	Canadian Earth System Model Large Ensembles (CanESM2 LE) is statistically downscaled over North America using a multivariate bias adjusted (MBCn method) against two target datasets: S14FD (Iizumi *et al.*, 2017) and EWEMBI, (Lange, 2018).	Two ensembles, each of them with 50 simulations with one GCM (CanESM2); The difference between the ensembles is the target dataset used in bias correction.	North America	0.5° x 0.5°	Historical period: 1950-2005 Future period: 2006-2100	RCP8.5 (provide links to scaling to other scenarios)	**Meteorological** (Mean Relative Humidity, Precipitation, Wind Speed, Max temp, Min temp, sea level presure, Downwelling Shortwave, Donwwelling longwave)	Daily data in netCDF format for each simulation is available for download from CCCma at ECCC: - CanESM2_ALL-EWEMBI-MBCn/ folder contains the ensemble with the target dataset EWEMBI; - CanESM2_ALL-S14FD-MBCn/ folder contains the ensemble with the target dataset S14FD. (ALL stands for all radiative forcings).	Technical note Multivariate Bias Correction

Name	Description	No. models	Spatial extend	Spatial resolution	Temporal extend	Scenarios	Category of variables	Download information (e.g., variables, temporal resolution, format)	Details
CanLEAD-CanRCM4 from Canadian Centre for Climate Modelling and Analysis (ECCC)	Canadian Earth System Model Large Ensembles (CanESM2 LE) is dynamically downscaled over North America using the Canadian Regional Climate (CanRCM4 LE), which is next statistically downscaled using a multivariate bias adjusted (MBCn method) against two target datasets: S14FD (Iizumi *et al.*, 2017) and EWEMBI, (Lange, 2018).	Two ensembles, each of them with 50 simulations with one RCP driven by a different member of CanESM2 LE; The difference between the ensembles is the target dataset used in bias correction.	North America	0.5° x 0.5°	Historical period: 1950-2005 Future period: 2006-2100	RCP8.5 (provide links to scaling to other scenarios)	**Meteorological** (Mean Relative Humidity, Precipitation, Wind Speed, Max temp, Min temp, sea level presure, Downwelling Shortwave, Donwwelling longwave)	Daily data in netCDF format for each simulation is available for download from CCCma at ECCC: - CanRCM4-EWEMBI-MBCn/ folder contains the ensemble with the target dataset EWEMBI; - CanRCM4-S14FD-MBCn/ folder contains the ensemble with the target dataset S14FD.	Technical note Multivariate Bias Correction
Ouranos ensemble of statistically downscaled CMIP5 data (cb-oura_1.0)	CMIP5 simulations statistically downscaled for North America against ANUSPLIN and Livneh (2015) gridded observations, using a quantile-mapping method.	A total of 22 simulations comprising RCP4.5 and RCP8.5 from 11 models (list of the models)	Northern USA and Canada East of 121˚E and up to the northern bounds of Hudson Bay(Lat: 40˚-66.5˚N; Lon: 121˚ - 55˚E)	10 km x 10 km	Historical period: 1950-2005 Future period: 2006-2100	RCP4.5 RCP8.5	**Meteorological** (daily minimum and maximum temperature and total precipitation)	Daily data in netCDF format for each simulation (grouped as ncml) is available for download on PAVICS. Will be replaced by ESPO-G for North America based on CMIP6 (Ensemble Scenarios Polyvalent Ouranos - Global)	Technical note Data access: https://pavics.ouranos.ca/datasets.html
ESPO-R 1.0 Ensemble Scenarios Polyvalent	CORDEX-NA simulations statistically downscaled for	25 simulations from the CORDEX-	North America Limited in the North	0.1˚ x 0.1˚	Historical period: 1950-2005	RCP4.5 RCP8.5	**Meteorological** (daily minimum and maximum temperature total	Daily data in netCDF format for each simulation (grouped as ncml) is available for download on PAVICS	Data and documentation will be made available on

Name	Description	No. models	Spatial extend	Spatial resolutio n	Temporal extend	Scenarios	Category of variables	Download information (e.g., variables, temporal resolution, format)	Details
Ouranos (Regional) Ouranos' ensemble of dynamically downscaled CORDEX-NA data	North America against ERA-5 Land gridded reanalysis	North-America ensemble comprising simulations driven by RCP4.5 and RCP8.5	by the CORDEX domain at about 76˚N		Future period: 2006-2100		precipitation, planned: windspeed & direction, humidity)		PAVICS in spring 2022 https://pavics.ouranos.ca/datasets.html

4.1.1 *Climate models – GCMs and ESMs*

The CMIP community designs the protocol for a wide range of climate model simulations, including the three basic types performed to assess climate change impacts - the pre-industrial, historical and future scenario simulations. Results from these simulations inform the Intergovernmental Panel on Climate Change Assessment Reports. We are currently in the sixth phase of CMIP (i.e., CMIP6), with climate model results from this phase informing the recent IPCC Sixth Assessment Report (AR6; IPCC, 2021). The CMIP5 climate model results were reported in AR5 (IPCC, 2013a) and have been widely used to assess climate change impacts and in adaptation studies. The Canadian Centre for Climate Modelling and Analysis has been involved in climate model development for several decades, with versions of the Canadian ESM taking part in both CMIP5 (CanESM2) and CMIP6 (CanESM5). Details for the CMIP5 and CMIP6 ensembles are provided in Table 4.1.

1. Pre-industrial simulations (corresponding to year 1750 or 1850)

The pre-industrial simulation is designed to represent climate conditions which occurred prior to industrialization. The concentration of greenhouse gases (GHGs), land cover, emissions of atmospheric aerosols and other forcings are all set to their pre-industrial levels and the simulations then run for several hundreds of years. Even though there is no imposed change in external forcing (e.g., an increase in atmospheric CO_2) in these simulations, there is year-to-year variability in the simulated climate simply because of the natural variability of the climate system. The long-term climate, however, remains stable, i.e., there is no systematic increase or decrease ('drift') in temperature or other climate variables. The pre-industrial simulation serves as a control for comparison with the historical and future simulations both at the global and regional scale.

2. Historical simulations (generally from 1851 to 'present')

The pre-industrial simulations are also used to launch the historical simulations - any year in the pre-industrial simulation can be used as the starting point for the historical simulations since any year is representative of the pre-industrial climate. Each climate modelling centre will typically launch, or initialize, between 5 and 10 historical simulations[2] from different years of the pre-industrial simulation. Unlike the pre-industrial simulation, however, the historical simulation includes external forcings from increasing concentrations of GHGs in the atmosphere and increasing emissions of aerosols (i.e., soot, also associated with increasing use of fossil fuels), and from changes in land cover (associated with deforestation related to agriculture). In addition to these forcings, information about changes in solar activity and volcanic forcing are also included. While all these forcings affect the climate in different ways, the primary response of the climate system over the historical period to the combined effect of all these forcings has been warming.

While each historical simulation is distinct in terms of the year-to-year climate, over the long historical period they all show similar increases in temperature associated with increasing GHG concentrations in the atmosphere. Note that none of the historical simulations can be expected to correspond to the actual climate observed at corresponding dates in the past – the historical climate that we have observed is an individual realization of the highly chaotic climate system. To be able to reproduce the exact observed year-to-year variability, we need to know the exact state of all components of the climate system in 1850 (or any other year) to initialize a perfect climate model – neither nor which are possible. However, models simulate the overall statistical characteristics of the historical climate well (e.g., climate trends, time averages, amplitude of variability).

For CMIP5, the historical simulation was from 1850 to 2005; for CMIP6 it was from 1850 to 2014. Users should be aware that there are many other research-related experiments undertaken as part of the model intercomparison projects (MIPs; e.g., the atmospheric model intercomparison project - 'AMIP'; 'land-hist*' labels). If downloading raw climate data, users should select the 'historical' experiment label for climate adaptation analyses over the historical period.

The statistical results from historical simulations are usually compared with observations (e.g., for temperature and other climate variables) at the global scale, as well as at different geographical scales and at several time frequencies, e.g., annual, seasonal and monthly. Comparison with observations helps to evaluate model results and assess model limitations.

3. Future scenario simulations (e.g., from the 'present' to 2100)

The climate model simulations for the future are initialized from the historical simulations, in exactly the same way that the historical simulations are initialized from the pre-industrial simulations. For CMIP5, the future simulation period is 2006-2100; for CMIP6 it is 2015 to 2100. The main difference between the historical and future simulations is that the forcings (e.g., concentrations of GHG, of aerosols, changes in land cover) are known during the historical period but not for future.

The change in forcings for the future is dependent on human activities, which are uncertain. Prediction of future human activities comes under

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[2] The set of climate model results stemming from simulation experiments using the same forcing is generally known as an ensemble.

the purview of the environmental and energy policy analysis community, which uses integrated assessment models (IAMs) to consider the social and economic factors driving the emissions of GHGs. This community develops coherent and consistent descriptions of how future society may operate, particularly with regards to fossil fuel consumption, and uses IAMs to calculate anthropogenic emissions and concentrations of CO_2, methane (CH_4), nitrous oxide (N_2O) and other GHGs, atmospheric aerosols, as well as estimates of future agricultural area, for each emissions pathway they develop. These future emissions scenarios typically span a range of conditions, from low to moderate to high emissions, and some include mitigation actions. Each emissions scenario provides the necessary forcing information to drive climate models. The resulting simulations of future climate, known as climate scenarios, are all equally plausible descriptions of possible future states of the climate system in response to the prescribed forcing. None of the climate scenarios should be considered as a forecast or prediction, but rather as an example of a possible future climate. When using climate scenarios in adaptation planning, therefore, it is advisable to use multiple scenarios to capture the range of possible future climates.

There are many possible emission scenarios and it is not possible to run climate models for all of them. The CMIP experimental protocol recommends a core set of climate model experiments which consider emissions ranging from low, to moderate, to high.

4.1.2 Emissions scenarios – Representative Concentration Pathways (RCPs) and Shared Socio-Economic Pathways (SSPs)

The CMIP5 future simulations used a set of forcing scenarios known as Representative Concentration Pathways, or RCPs (Moss *et al*., 2010; van Vuuren *et al.*, 2011). The RCPs were developed specifically for the climate modelling community by the energy systems modelling community, as a shortcut in the detailed process of developing emissions scenarios, and consist of a set of scenarios of future radiative forcing[3] rather than the detailed socioeconomic storylines usually used to generate emissions scenarios. Thus, the RCPs were not associated with any particular unique socioeconomic pathway or related emissions scenarios (i.e., the radiative forcing scenario could be achieved by following different socioeconomic pathways or emissions scenarios).

There are four original RCPs spanning the plausible range of future climate, with each one describing a GHG emission trajectory, atmospheric GHG concentrations, and consequent radiative forcing by the year 2100. Figure 4.1 illustrates the global mean temperature change associated with RCP2.6 and RCP8.5, and end-of-century temperature change for all four RCPs. They are named after the amount of “radiative forcing” they cause by the end of the century. Under the high emissions pathway, RCP8.5, radiative forcing at 2100 is 8.5 Wm^{-2} greater than pre-industrial conditions. There are two intermediate ‘stabilization pathways’ in which radiative forcing is stabilized at 6 Wm^{-2} and 4.5 Wm^{-2} after 2100, and a single low-emission pathway where radiative forcing peaks at about 3 Wm^{-2} mid-century before dropping to 2.6 Wm^{-2} at the end of the century. All RCPs were considered to be equally plausible.

[3] Radiative forcing is a measure of the combined effect of greenhouse gases, aerosols, and other factors that affect the energy balance of the atmosphere. While GHGs act to trap additional heat in the atmosphere, the role of aerosols is more complicated. Some aerosols act to reflect more of the sun’s incoming radiation back out to space, while others act to trap solar energy in the atmosphere.

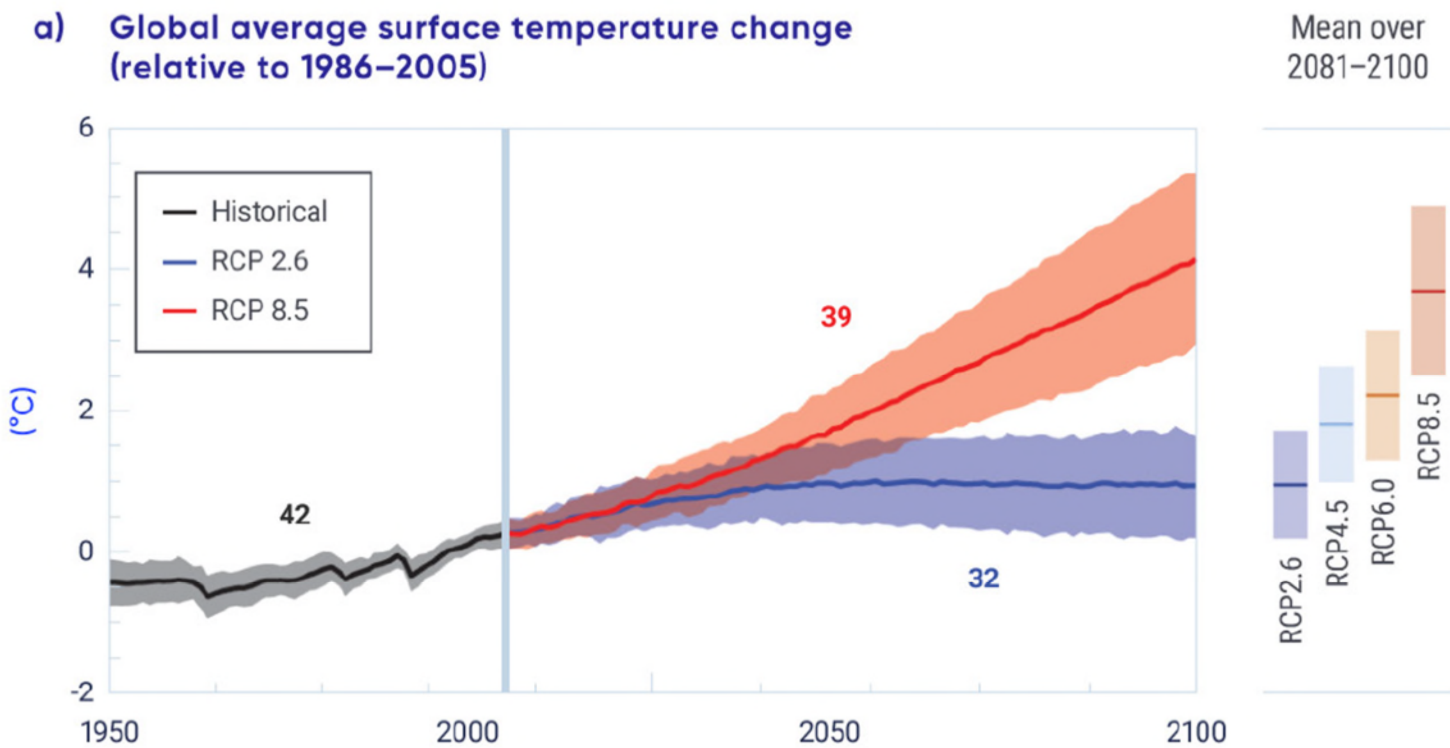


Figure 4.1: CMIP5 multi-model simulations of global average surface temperature change (°C) for 1950 to 2100, relative to 1986-2005 for RCP2.6 and RCP8.5. Bold lines indicate the multi-model mean and the numbers of CMIP5 models used to calculate this mean value are indicated. Coloured bars on the right-hand side indicate the range of end-of-century temperature change for all RCPs [Source: Bush and Lemmen, 2019, but adapted from SPM.7 IPCC, 2013b].

The Shared Socio-Economic Pathways (SSPs; van Vuuren *et al*., 2014; O'Neill *et al*., 2017), which have been used in CMIP6, are fully integrated scenario pathways with detailed socioeconomic storylines, including some that align with the original RCPs. They integrate different sets of assumptions about how, for example, population, economic growth, education, urbanization and the rate of technological development may change over the next century. The SSPs are based on five narratives (O'Neill *et al*., 2017; Riahi *et al.,* 2017) describing broad socioeconomic trends that could shape future society:

SSP1: Taking the Green Road – a world of sustainability-focused growth and equality (SSP1-1.9, SSP1-2.6)
SSP2: Middle of the Road – trends broadly follow their historical patterns (SSP2-4.5)
SSP3: Regional Rivalry – A Rocky Road – a fragmented world of 'resurgent nationalism' (SSP3-7.0)
SSP4: Inequality – A Road Divided – a world of ever-increasing inequality (SSP4-3.4, SSP4-6.0)
SSP5: Fossil-fueled Development – Taking the Highway – a world of rapid and unconstrained growth in economic output and energy use (SSP5-8.5).

In addition to four emissions scenarios comparable with the original RCPs, three further emissions scenarios have been developed for the SSPs. SSP1-1.9 is focused on limiting warming to below 1.5°C, the aspirational goal of the Paris Agreement. SSP4-3.4 represents an intermediate pathway between the stringent RCP2.6 and the less stringent mitigation efforts associated with RCP4.5. SSP3-7.0 represents the medium to high end of the range of future emissions and warming. Figure 4.2 illustrates the global mean temperature change associated with the main SSP emissions scenarios.

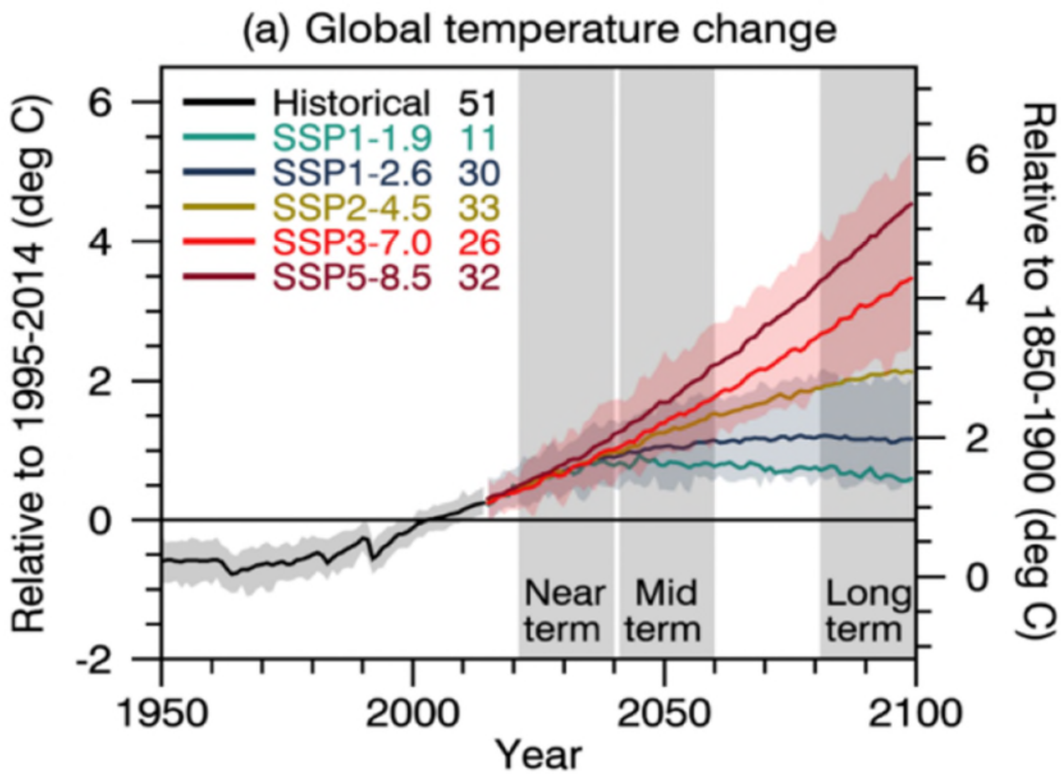


Figure 4.2: Global average temperature change associated with the SSPs. Numbers indicate the number of GCMs/ESMs undertaking experiments for each SSP [Source: Lee *et al.*, 2021].

While the original RCPs and the corresponding SSPs (so RCP2.6 and SSP1-2.6, RCP4.5 and SSP2-4.5, RCP8.5 and SSP5-8.5) have the same approximate level of radiative forcing at the end of the century, they exhibit different levels of warming because the distribution of emissions over time and the proportion of different GHGs and aerosols differ. In addition, the climate models themselves have been updated between CMIP5 and CMIP6, with the latest versions including more climate processes explicitly and operating at a higher spatial resolution. Figure 4.3 compares the annual mean temperature change over Canada associated with the three SSP-based scenarios used in CMIP6 with the RCPs used in CMIP5 (Sobie *et al.* 2021). The envelope of results from CMIP6 indicates, on average, larger increases in global mean temperature and a larger intermodel spread, particularly for SSP5-8.5 and RCP8.5. Similar results are obtained for global mean temperature in Tebaldi *et al*. (2021). The larger warming apparent in the CMIP6 simulations is a combination of the slightly different forcing and the presence of models which have higher climate sensitivities[4] in the CMIP6 ensemble than those in the CMIP5 ensemble. The higher climate sensitivities in CMIP6 become more critical for the higher forcings, such as SSP5-8.5 (Tebaldi *et al.,* 2021). A number of studies (e.g., Tokarska *et al*., 2020) have explored constraining the CMIP6 projections based on an evaluation of the CMIP6 ensemble's simulation of historical conditions. When constraints are applied, the CMIP6 projections are closer to those of CMIP5 (both the raw projections and those with similar constraints applied). In fact, the IPCC Sixth Assessment Report (Lee *et al*., 2021) uses constrained projections of global surface mean temperature, because of the higher climate sensitivities exhibited by some of the climate models.

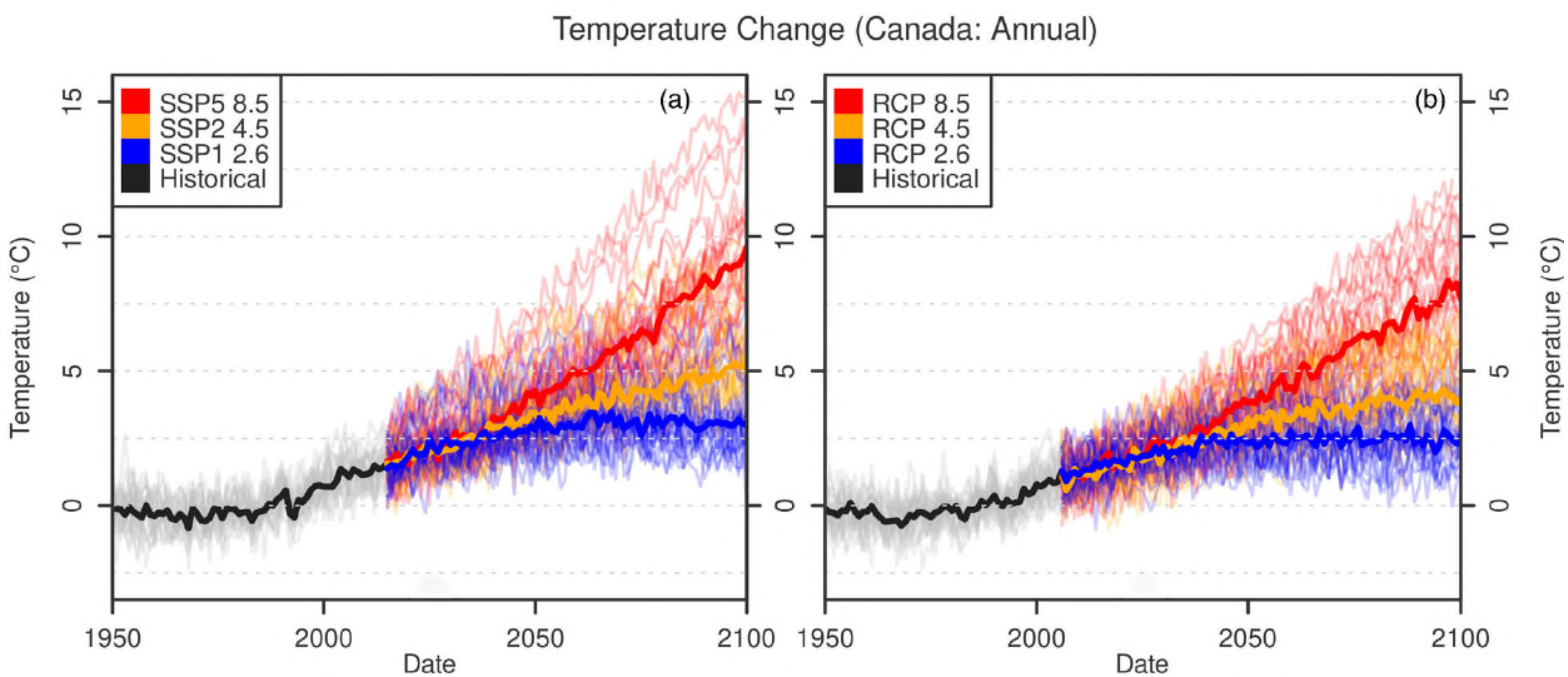


Figure 4.3: Annual average temperature anomalies for Canada from (a) CMIP6 and (b) CMIP5 relative to 1971–2000. Individual GCM simulations are displayed with thin lines and the corresponding ensemble medians are shown as thick lines for each emissions pathway. For CMIP6, the transition from the historical

[4] Equilibrium climate sensitivity refers to the amount of global surface warming that will occur in response to a doubling of atmospheric CO_2 concentration compared to pre-industrial levels and is estimated to be between 1.5°C and 4.5°C. This wide range is driven by uncertainties in climate feedbacks, including how water vapour, clouds, surface albedo and other factors will change as the Earth warms. Some GCMs exhibit more warming (high climate sensitivity) and others less (low climate sensitivity) in response to the same forcing.

simulation to future SSPs occurs in 2015 compared with 2006 in CMIP5 for the RCPs. The CMIP6 models with the highest temperature response are CanESM5, HadGEM3-GC31-LL, and UKESM1-0-L. [Source: Sobie *et al*., 2021]

Figures 4.2-4.3 illustrate the global and Canada average temperature change associated with the RCPs and SSPs. However, those values are not typically representative of the temperature change at any individual location. Warming is higher over land than over the oceans, and higher at higher latitudes than it is at low latitudes. Comparing Figures 4.2 and 4.3 shows that Canada as a whole has warmed, and is projected to continue to warm, at about twice the global rate. Northern Canada has warmed at almost triple the global rate (Bush and Lemmen, 2019). A major cause of this Arctic amplification is the melting of sea ice and reduction in snow cover, which reduces the surface albedo and leads to more absorption of incoming solar radiation, further enhancing the warming.

4.1.3 Uncertainty

As is apparent from Figures 4.2-4.3, there is uncertainty in the projections of future climate, which often leads to the question 'Which model should I use?' This uncertainty stems from the different model responses to the same forcing (model uncertainty), from the different emissions pathways (scenario uncertainty) and from natural variability (natural internal variability uncertainty). The relative influence of each of these sources of uncertainty depends on the climate variable, the spatial scale and the time horizon of interest (Hawkins and Sutton, 2009).

Figure 4.4 illustrates the role of these different sources of uncertainty in temperature simulations from 1950 to 2100, and shows the results at two different spatial scales for three different forcing scenarios (emissions uncertainty – RCPs 2.6, 4.5 and 8.5) from an ensemble of 29 CMIP5 GCMs. The results are also shown from a large ensemble (LE) experiment (50 simulations) using CanESM2, where a single forcing scenario (RCP8.5) was used to explore this model's range of natural internal climate variability. The bold lines in this figure indicate the ensemble-mean values for each RCP, while the finer lines show the individual model responses.

It is immediately apparent that there is a lot less variability at the global scale (Figure 4.4a) and that the end-of-century change in mean temperature is dominated by the future emissions uncertainty. For Canada (Figure 4.4), however, while the future emissions uncertainty also dominates at the end of the century, model uncertainty plays a larger role at this scale, as indicated by the larger range in results from individual model simulations (fine coloured lines) for each emissions pathway. The results from the CanESM2 LE simulations (purple lines) also show that the natural internal variability plays a larger role at this finer spatial scale. For other climate variables, e.g., precipitation, the role of natural variability may dominate in the near future, particularly at finer spatial scales (e.g., Hawkins and Sutton, 2010; Barrow and Sauchyn, 2019).

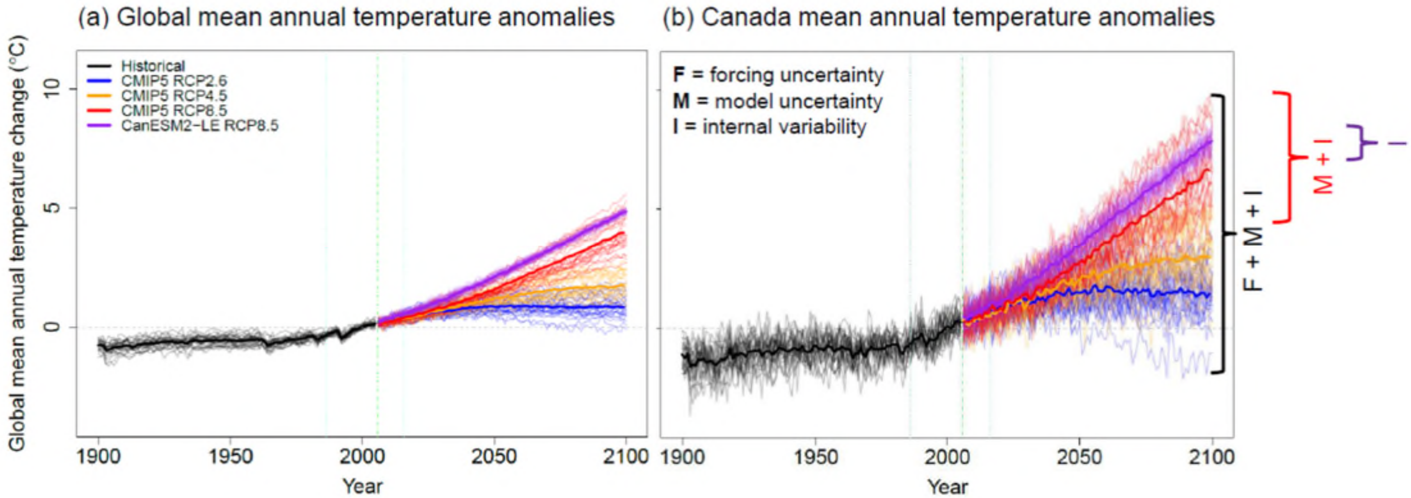


Figure 4.4: Time series of (a) global mean annual temperature anomalies with respect to 1986-2016), and (b) mean annual temperature anomalies for Canada and adjacent waters for 29 CMIP5 GCMs and RCPs 2.6, 4.5 and 8.5 forcing scenarios. The large ensemble experiments with a single GCM, CanESM2 LE are also shown. [Source: Cannon et al., 2020]

While it may seem that some emissions pathways are more likely than others, it is important to consider the range of projected climate from multiple emissions scenarios, rather than relying on a single one. Similarly, it is important to consider the results from multiple climate model simulations to address model uncertainty. By considering a range of possible futures, adaptation options will be more successful at reducing vulnerability and increasing resilience to climate change. While the RCPs are not associated with specific socioeconomic conditions, the more recent SSPs present detailed information about how society may develop, and thus present options for how specific global warming targets (e.g., the Paris Agreement) may be attained.

4.1.4 Levels of Global Warming

It is common practice to present future projections in time series format, such as is shown in Figure 4.4, or for fixed future time periods, e.g., the 2020s, 2050s and 2080s, under different forcing scenarios for different regions. When presented in the latter way, projections from GCMs with different equilibrium climate sensitivities[4] are combined, which makes it difficult to separate uncertainty due to natural internal variability and that due to model uncertainty. A way of presenting future projections which decouples information about regional projections from information about forcing scenarios and model sensitivity is to use fixed levels of global warming.

Seneviratne *et al*. (2016) showed that proportional changes in extreme temperature and precipitation over large regions are similar across scenarios and models when considered as a function of global mean temperature change. Since this work, other studies (e.g., Li *et al*., 2018; Schwingshakl *et al*., 2021) have shown that the relationship between different climate variables and indices and global temperature change generally remains constant. The connection between global mean temperature change and Canadian mean temperature change is shown in Figure 4.5 (left) and provides a way of estimating the implications of global change for Canada under alternative forcing scenarios. Impacts estimated under one forcing scenario can be scaled to approximate impacts under another forcing scenario, since the ratio of regional warming over Canada to global temperature change is roughly constant, in this case about double the global mean rate. Linking regional impacts to specified global warming levels avoids mixing regional projections from models with different climate sensitivities in fixed time periods. The other advantage of this method is that it provides a direct connection with global warming targets, such as the 2015 Paris Agreement to limit global warming to well below 2°C, preferably to 1.5°C.

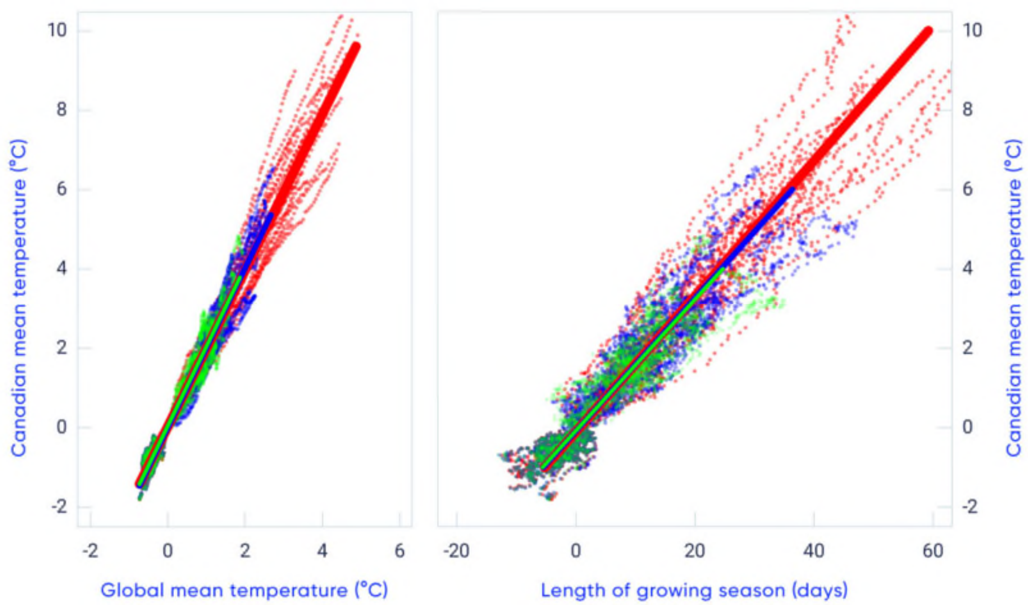


Figure 4.5: Left: Canadian mean temperature change plotted against global mean temperature change (°C for 20-year averages relative to 1986-2005) from CMIP5 GCMs for RCP2.6 (green), RCP4.5 (blue), and RCP8.5 (red). Bold lines are least squares fits, whereas thinner dashed lines are individual model results. **Right**: Changing length of the growing season (days) for warm season crops in the Canadian prairies as a function of changes in Canadian mean temperature. [Source: Bush and Lemmen, 2019, but adapted from Li *et al*., 2018]

This level of global warming approach has become more important with the release of the CMIP6 climate model simulations. A number of the CMIP6 climate models have a notably higher equilibrium climate sensitivity than the models in CMIP5. Of the 40 CMIP6 models which have the runs needed to calculate their equilibrium climate sensitivity[4], about a third of those models have a climate sensitivity higher than the upper end of the likely range of 1.5°C to 4.5°C. One quarter has a higher sensitivity than any of the models featured in CMIP5, including Canada's CanESM5, the UK Met. Office's HadGEM3 model and the Community Earth System Model 2 (CESM2). Research is currently underway to determine what is driving these high climate sensitivity values and initial results indicate that it may be due to their improved representation of clouds and aerosols. By presenting information by levels of global warming, however, allows the visualization of those models with higher climate sensitivity (Figure 4.6).

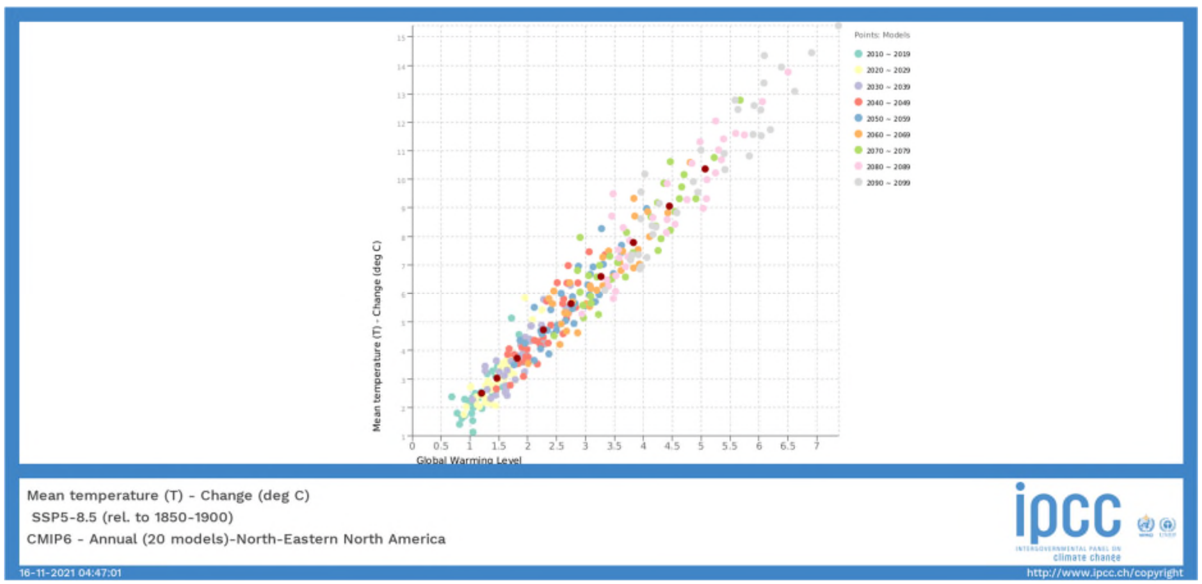


Figure 4.6: Annual mean temperature change (°C) for North-Eastern North America (vertical axis) plotted against global warming levels for SSP5-8.5 (relative to 1850-1900; horizontal axis). Each point represents a different climate model (which can be identified on the interactive page), and each colour indicates the time period when the level of global warming is reached. In this example, the largest increase in global warming is indicated by CanESM5 (top right-hand corner), and this region is warming at approximately twice the rate of the global mean temperature increase. [Source: IPCC Interactive Atlas]

4.1.5 Obtaining actionable climate model output - higher resolution climate information

Regional Climate Models

Regional Climate Models (RCMs) were originally developed to bridge the gap caused by a lack of computing power, which meant that GCMs could be run only at relatively coarse spatial resolutions (200-300km). While adequate for examining climate change at the global and continental scales, GCM output was generally not sufficient for studies at more regional scales. This led to the development of RCMs, which at that time, were much higher resolution climate models (typically between 10 and 50 km) operating over a limited domain, e.g., North America, Europe. Using RCMs to obtain finer-scale climate information is known as dynamical downscaling. Today, however, some GCMs/ESMs are run at even better spatial resolution than most RCMs, e.g., MIROC 4h and CMCM-CM (Tapiador *et al*., 2020). However, their number is still limited which prohibits constructing a high-resolution ensemble.

There are still many GCMs which are run at coarser spatial resolutions and RCMs are a means of dynamically downscaling this information to finer spatial scales. RCMs incorporate many of the same physical processes and parameterisations as GCMs, and in fact often share the same code. The increased spatial resolution, however, means that some climate processes, which are parameterised in a GCM, may be explicitly represented in the RCM. Finer spatial scales also mean that the underlying topography and land/water boundaries can be more accurately represented in an RCM.

Since they operate over limited spatial areas, they require information (e.g., pressure, temperature, wind and moisture) from a GCM at their lateral boundaries to drive the climate within the RCM. In this way, the RCM provides a physically based simulation of the climate within its boundaries which is consistent with that of its driving GCM, but at higher spatial resolution. It must be remembered though that the RCM inherits errors and biases that may be present in the driving GCM. Some of the more recent very high resolution RCMs (model resolution ≤ 4 km) are able to explicitly represent physical processes such as atmospheric convection (convection-permitting models) which can lead to much improved simulations of short-duration precipitation extremes (e.g., Kendon *et al*., 2017). The computing costs associated with these very high resolution models remains very high and currently limits their widespread use.

Regional climate modelling is overseen by CORDEX (Coordinated Regional Climate Downscaling Experiment), a framework implemented by the World Climate Research Program to advance and coordinate the science and application of regional climate downscaling through global partnerships. As is the case with the CMIP, this program oversees experiment design, collection and dissemination of RCM results for a number of continental-scale domains, including North America.

CMIP5 CORDEX experiments focussed on nine core model domains, including North America (NA-CORDEX), at a horizontal spatial resolution of about 45 km and about 25 km. Historical simulations used the same atmospheric forcing as the CMIP5 GCMs/ESMs, and focussed on RCP4.5 and RCP8.5 in the future simulations. The Canadian RCMs involved in NA-CORDEX are CRCM5-OUR, CRCM5-UQAM and CanRCM4, with spatial resolutions of between 0.11° and 0.44°.

For CMIP6, the CORDEX experimental protocol (Gutowski *et al*., 2016) recommends that RCM groups use the same historical atmospheric forcing as the CMIP6 GCMs/ESMs, but for the future simulations, starting in 2015, it recommends focussing on SSP1-2.6 and SSP3-7.0. After these experiments are complete, and if sufficient resources are available, dynamical downscaling of SSP2-4.5 and/or SSP5-8.5 is also recommended. The target horizontal spatial resolutions recommended for these experiments are 12.5 km and 25 km across 14 core domains, including North America and the Arctic.

Both CORDEX experimental protocols included an evaluation experiment using re-analysis data to drive the RCMs. For the CMIP5 RCMs, ERA-Interim was used for the 1979-2017 period, and ERA-5 for at least the 1979-2020 period for the CMIP6 RCMs.

Bias Adjustment and Downscaling

All climate models (GCMs, ESMs and RCMs) have one thing in common regardless of resolution: they exhibit some degree of bias – this means that they do not simulate the present-day climate perfectly. While the bias differs from model to model, there are some common consistencies. Bias correction, or adjustment, is particularly important when considering climate change impacts that depend on the crossing of absolute thresholds.

Different methodologies have been developed to deal with this bias, ranging from relatively simple (that apply to all variables) to very complex (that operate in most of the cases on the most popular meteorological variables). Many of the bias adjustment methodologies for meteorological variables also include a downscaling aspect, which leads to a bias-adjusted dataset at higher spatial resolution than the original GCM/ESM. One of the simplest approaches to minimize the effect of bias in the simulated present-day climate is to use the multi-model mean, generally known as the ensemble-mean, together with the 25^{th} and 75^{th} percentile values. Ensemble-mean values have been shown to compare best with observations (e.g., Flato *et al*., 2013). The interval of values defined by the percentiles of the ensemble corresponding to one emission scenario, or the uncertainty range, gives an indication of the range of possibilities for that emissions scenario. This simple method can be applied to all simulated variables.

The simplest way of addressing bias in climate models, however, is not to use absolute values, but rather the change, or anomalies, relative to the simulated historical mean (e.g., 1971-2000). The assumption here is that even if the present day climate is not perfectly simulated there is value in the simulated change (by assuming that the bias is the same in the present day and future simulations and so effectively cancels out when calculating the anomalies). The change, or anomalies, can be computed for all the simulated variables. Sometimes scenarios of future climate are obtained by adding these anomalies to the observed characteristics of spatial and temporal variability. This procedure is known as the 'delta change' method and requires a good estimation of historical variables over a long period of time, over the region of interest. The estimation of the historical characteristics constitutes an important issue for some variables over regions with sparse observation networks (e.g., the Canadian North).

Statistical bias adjustment methods are also available, again ranging from the relatively simple to the very complex. The more complex of these methods can correct systematic errors in model simulations of mean values, quantiles[5] of a distribution, or even the dependence between variables (e.g., Teutschbein and Seibert, 2012). However, all these methods require an observational climatology to target in the correction process. This 'target' dataset can be a station dataset if the bias correction is done at a local level, but in most cases a gridded historical dataset is required for corrections over regions.

The availability of an ensemble of bias corrected simulations depends on the availability of a good gridded dataset with historical observations. For Canada, bias corrected ensembles based on CMIP5 and CMIP6 simulations have been developed for maximum and minimum temperature and precipitation.

For example, researchers at the Pacific Climate Impacts Consortium (PCIC) and Environment and Climate Change Canada (ECCC) have developed a statistical methodology known as BCCAQv2 (Bias Correction with Constructed Analogues and Quantile Mapping, Version 2, Cannon *et al*., 2015) that has been used to bias adjust and downscale ensembles of GCM simulations for both CMIP5 and CMIP6. This method has been used to downscale maximum and minimum temperature and accumulated precipitation from the GCM resolution to a target grid of approximately 10 km for all of Canada. This method combines two separate downscaling methodologies – bias-correct climate analogues (BCCA; Maurer *et al*., 2010) and quantile delta mapping (QDM; Cannon *et al*., 2015) – and leverages strengths from each method to provide a final product that outperforms either individual method. This methodology has been extensively evaluated at the national scale using a wide range of climate indices (those identified by the Expert Team on Climate Change Detection and Indices [ETCCDI]) to determine its ability to capture the temporal sequence of events, the statistical distribution of values and also the spatial structure of values. However, there are no studies dedicated exclusively to Northern Canada.

For BCCAQv2 over Canada, the observational target dataset is the ANUSPLIN dataset, which is available at 300 arc second spatial resolution (1/12° grids, approx. 10 km) and consists of daily minimum and maximum temperature, and precipitation amount for 1950-2013 (Hopkinson *et al.,* 2011;

[5] Quantiles are values that divide the range of a probability distribution into intervals with each interval containing the same fraction of the total population.

McKenney *et al.,* 2011). A detailed description of the ANUSPLIN dataset is provided in annexes 7.1.15, 7.2.16, and 7.5.9.

The BCCAQv2 methodology downscales maximum and minimum temperature and precipitation independently. This assures statistical coherence but the day-to-day relationships between the corrected variables are not necessarily consistent and so should not be used to construct compound indices that require physical consistency between the input variables. In such cases, multivariate statistical downscaling which preserves the dependence between variables is necessary (e.g., Cannon, 2016).

4.1.6 ClimateData.ca and other web portals

There are many options available for accessing raw data for climate projections from the CMIP5 and CMIP6 experiments (see for example Table 3.1), but only a limited number of options for accessing bias-adjusted and downscaled datasets for Canada in easy-to-use formats for different applications.

The primary source of the BCCAQv2 downscaled CMIP5 and CMIP6 datasets is the Pacific Climate Impacts Consortium. The BCCAQv2 CMIP5 ensemble consists of daily bias-corrected and downscaled output from 24 GCMs for RCPs 2.6, 4.5, and 8.5, for the whole of Canada, and has been used as the basis of the climate projections currently available from the Canadian Centre for Climate Services (CCCS), ClimateData.ca[6] and the Climate Atlas of Canada (RCPs 4.5 and 8.5 only). This dataset is supplied at its original 6 x 10 km resolution on the CCCS website and on ClimateData.ca, but is offered at two map scales (1:250,000 and 1:50,000) on the Climate Atlas of Canada. The data was 'post processed', so that it can be delivered in manageable formats and file sizes. For example, the information from the ensemble of models is summarised by providing figures, graphics and data for the median and percentiles of the ensembles. This form is useful for a preliminary exploration of risk, and for communicating risk.

Both ClimateData.ca and the Climate Atlas of Canada have used the BCCAQv2 CMIP5 dataset to calculate a number of climate indices based on downscaled maximum and minimum temperature and precipitation. Both web portals provide map-based visualisation and allow users to search by location to view time series charts for the available climate variables, indices and RCPs. The downscaled data are presented in summary format, either as ensemble-mean (Climate Atlas) or ensemble-median values (ClimateData.ca) accompanied by information about the data range (10^{th} and 90^{th} percentile values). ClimateData.ca is planning to develop projections for climate impact drivers such as fire weather index and humidex.

Recognising that pre-defined thresholds for specific climate indices are not always meaningful, ClimateData.ca has developed the Analyze page which allows users to input custom threshold for a wide variety of temperature- and precipitation-based indices, including heat wave indices, and the number of days above or below specific maximum and minimum temperature or precipitation thresholds. ClimateData.ca also provides access

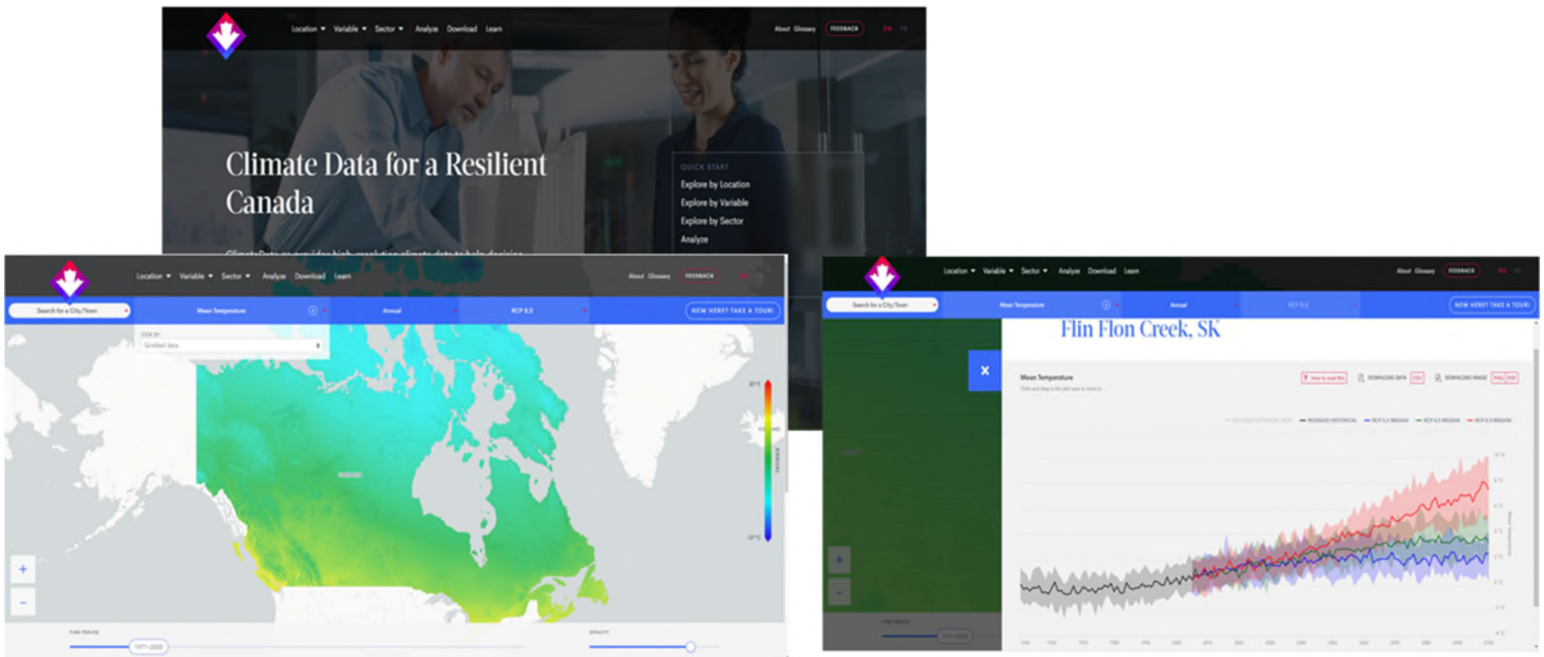
[6] ClimateData.ca is a partnership between Environment and Climate Change Canada, the major regional climate service providers in Canada and Centre de Recherche Informatique de Montréal and HabitatSeven.

to ECCC's station data catalogue, historical Intensity-Duration-Frequency (IDF) curves (and guidance on updating these curves for future conditions) and CMIP5-derived projections of relative sea level change for RCPs 2.6, 4.5 and 8.5.

The Climate Atlas of Canada has recently added a map layer detailing First Nations, Inuit and Métis communities. ClimateData.ca also provides data aggregated by health and census regions as well as watersheds. Both climate data portals will be updated to include the downscaled CMIP6 dataset in the next few months.

The BCCAQv2 dataset can also be accessed via the CCCS web page, which in addition provides access to (non-downscaled) annual and seasonal projections of mean temperature, precipitation, wind speed, sea ice thickness and concentration, and snow depth for the CMIP5 ensemble at 1°x1° resolution. Median and percentiles values are available for this CMIP5 ensemble.

(a)



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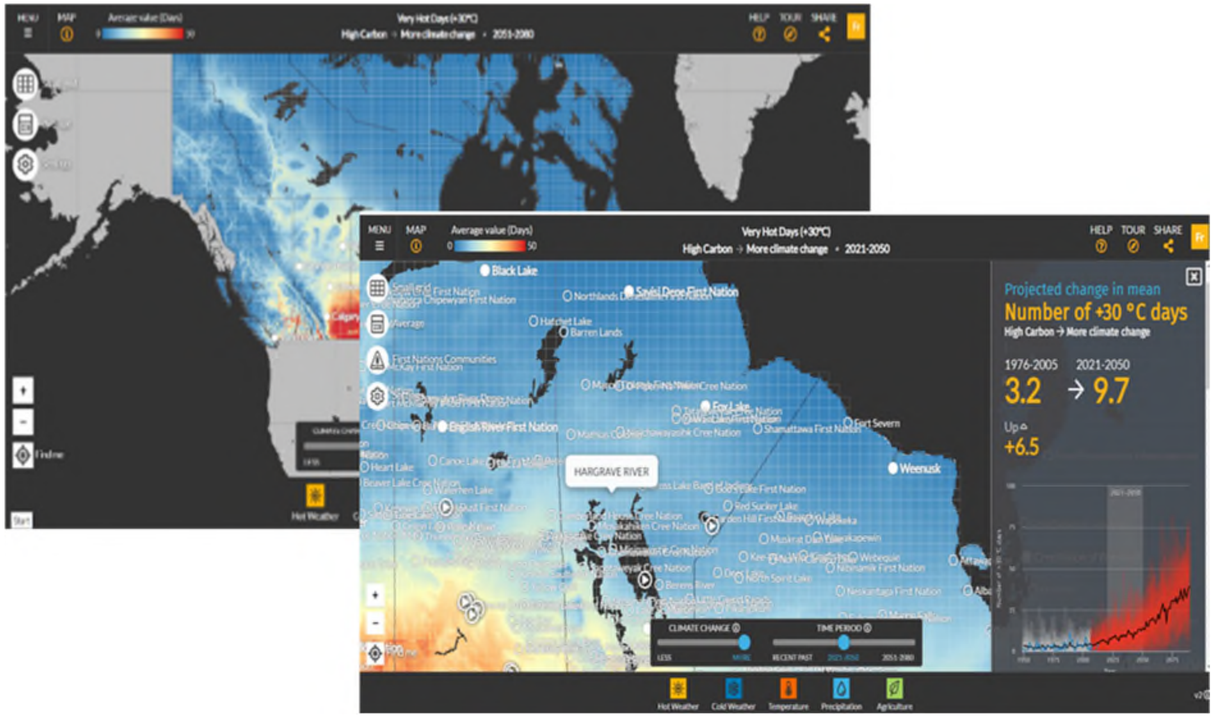

Figure 4.7: Examples of the (a) ClimateData.ca interface, and (b) the Climate Atlas of Canada

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4.2 Climate model analysis for categories of variables

4.2.1 Meteorological variables

Lead Authors: Emilia Diaconescu (CCCS/ECCC) and Elaine Barrow (CCCS/ECCC)

Historical evolution and future projections of meteorological variables are obtained as output from the atmospheric part of a climate model. Temperature is one of the prognostic variables (variables that a computer model estimates directly from physical equations) and there is high confidence in its estimation in models, since it is directly related to the radiation balance. Some systematic biases exist, however, since it is impossible to develop a perfect climate model. Precipitation, specific and relative humidity, and wind are variables in which we have lower confidence than we do for temperature (Cannon *et al.*, 2020). The simulation of precipitation depends strongly on parameterized processes, such as convection and clouds, used in the atmospheric model. Consequently, the biases in precipitation are generally larger than those for temperature. Analysis of model performance over the historical period is an important step in identifying those biases and choosing the appropriate method for constructing climate projections.

Table 4.1 provides information on the latest available climate projections for Canada, that adopt the multi-model approach and cover a range of emissions scenarios (from "low" or "moderate" to "high"), in recognition that no single climate change scenario can adequately capture the range of possible climate futures. Projections for the meteorological variables from those ensembles can be used to answer climate adaptation questions.

Considerations and limitations:

a) CMIP5 and CMIP6 ensembles

CMIP ensembles provide large-scale climate projections for a large spectrum of climate variables, including meteorological variables. However, because the data have a coarse resolution, they are often used just for a high-level and thematic understanding of climatic changes and for identifying the key vulnerabilities and risks at provincial levels (average values over large area). In order to address the issue of systematic biases from models, most studies based on CMIP raw data present maps of changes with respect to a historical reference period, or the time evolution of anomalies of the spatial mean over the large areas of interest. Canada's Changing Climate Report (Bush and Lemmen, 2019) summarizes information from CMIP5 models, based on RCP2.6, RCP4.5, and RCP8.5, for temperature and precipitation across Canada. The average changes for the Canadian North (ensemble median and 25^{th}-75^{th} percentiles) are provided in tables and maps. Although, CMIP5 and CMIP6 data are available for download for other meteorological variables, such as wind speeds and humidity, the report does not offer information for these variables for Canada because of limited research on the mechanisms and causes of changes in those variables.

The ensemble presented in the report consists of 29 GCM simulations, with a single run per GCM, with each run having equal weighting. How to construct an ensemble of models, how to best separate poorer performing GCMs from better-performing GCMs, is an ongoing research question, and consensus has not yet been achieved on the subject. The present practices are (1) to use as many GCMs and runs as possible to reduce the influence of model uncertainty and natural variability on results or (2) to choose a single run per GCM. The advantage of this last option is that all GCMs have equal weighting and so a single run per GCM means that each GCM has its variability represented on an equal basis; the disadvantage is that it is technically not making use of all information available. Tests were done for the CMIP5 variables analyzed in Canada's Changing Climate Report, by comparing results from the two options, and almost no difference was found. Discussions are still ongoing for the CMIP6 ensemble, which contains many GCMs with a higher climate sensitivity than their CMIP5 versions.

b) Dynamically and Statistically Downscaled Ensembles

Detailed regional climate change impact, vulnerability and/or risk assessments and impact models need climate projections for meteorological variables at a higher spatial resolution than that offered by the CMIP ensembles. Dynamically and statistically downscaled ensembles can be used in those situations. The statistical downscaled ensemble based on BCCAQv2, the CanLEAD ensemble (Cannon *et al*., 2022) and the CORDEX ensembles are the major datasets providing high-resolution climate change projections for meteorological variables for Canada. They take advantage of the most recent generation of international global climate models, the most up-to-date statistical downscaling methods (in BCCAQv2) and the most recent regional climate models (in CORDEX ensembles), as well as the available high-resolution observed gridded datasets over all of Canada (in BCCAQv2). The ensembles provide multiple climate simulations to take into account the spread of model uncertainty (24 members for BCCAQv2 ensemble, 7 RCMs driven by 9 GCMs for CORDEX –NA ensemble, 11 RCMs driven by 4 GCMs for CORDEX-Arctic, and 50 simulations with the Canadian model for the CanLEAD ensemble), and each ensemble has positive and negative points to consider. The following summarizes some of those points.

BCCAQv2:

- The BCCAQv2 ensemble presented on the CCCS webpage and on Climate.Data.ca consists of 24 downscaled runs from the 29 used in Canada's Changing Climate Report and covers GCM uncertainty well.
- The BCCAQv2 ensemble provides bias-corrected projections on a high-resolution grid of 300 arc seconds (1/12° grids, approx. 10 km), for daily minimum temperature, daily maximum temperature and daily total precipitation. Many climate indices were computed based on these two variables and made available for download on several climate portals in formats suitable for a wide variety of applications: the ensemble percentiles for each month and season of the year can be used in simple risk assessments and communication materials, while daily data for each member of the ensemble is needed for more complex risk assessments based on exceedance thresholds.
- Because the BCCAQv2 methodology downscales maximum and minimum temperature and precipitation independently, these downscaled data cannot be used to compute compound indices that require temporal consistence between temperature and precipitation, or other variables.
- Care must be taken when examining multi-day events (such as indices describing consecutive warm/cold/wet/dry events), as the BCCAQv2 methodology can break up multi-day (i.e., persistent) meteorological events.
- Although there are no analyses of BCCAQv2 results specifically for Northern Canada, some theoretical observations must be considered. BCCAQv2 is correcting GCM biases with respect to ANUSPLIN gridded observations. In locations where the underlying observational data in the target dataset are sparse, such as in the Canadian North, the robustness of the gridded observational dataset is questionable. The quality of the BCCAQv2 output is dependent on the quality of the target dataset, so where few observations exist on which to base BCCAQv2 downscaling, the resulting downscaled products may contain higher uncertainty. The BCCAQv2 results in the Arctic, therefore, are not grounded on a strong observational basis.
- The BCCAQv2 ensemble does not provide projections for other meteorological variables, such as wind and humidity, because it is difficult to construct an accurate gridded historical observational dataset to use as a target for wind and humidity from the limited station observations available in Canada.

CORDEX:

- CORDEX raw-data ensembles provide data for all meteorological variables analyzed in this report, but at a coarser spatial resolution than the BCCAQv2 ensemble. The data is available for download just as raw output from models (no ensemble percentiles are available for download) and can be used as input into regional impact models and for computing simple and complex indices (e.g., fire weather index), which need to respect the temporal consistency between variables. Temperature and precipitation projections (and related climate indices) from CORDEX were analyzed in the context of the Canadian climate (see for example Diaconescu *et al*., 2018 for the CORDEX ensemble over the Canadian Arctic and Barrette *et al*. (2020) for the CORDEX ensemble over Nunavik and Nunatsiavut).

Diaconescu *et al.* (2018) showed that most RCMs in the CORDEX-Arctic ensemble were able to simulate climate indices related to mean air temperature and hot extremes well over most of the Canadian Arctic, with the exception of the Yukon region where models displayed biases related to topographic effects. Overall performance was generally poor for indices related to cold extremes, and the Canadian RCMs (CanRCM4 and CRCM5) perform better than reanalyses for precipitation indices. However, there are no studies that have analyzed climate indices based on wind and humidity over the Canadian North. Therefore, the CORDEX performance for those indices is unknown.

- The number of simulations in the CORDEX ensembles is smaller than in CMIP5 or the BCCAQv2 ensembles. According to Andrews *et al*. (2012) and Flato *et al.* (2013), the ECS of CMIP5 GCMs spans a range from 2.1 °C to 4.7 °C. The RCM simulations considered in the CORDEX ensembles were driven by GCMs with ECS values spanning a similar interval of values (2.4°C to 4.6°C; see https://na-cordex.org/simulation-matrix). Consequently, the choice of GCMs used for the CORDEX simulations adequately sampled the CMIP5 interval of ECS values ensuring that the uncertainty related to the global scale is adequately represented. Figure 4.8 shows that at the regional level, over Canada, the CORDEX-NA ensemble covers the CMIP5 range well for annual mean temperature and annual mean precipitation.

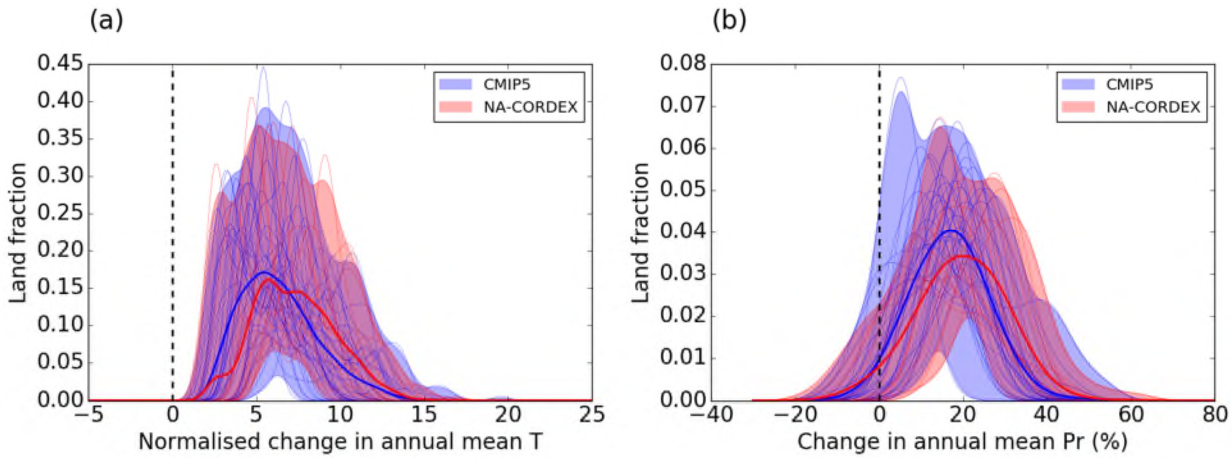

Figure 4.8. Probability Density Function (PDF) showing the land fraction (over Canada) experiencing a given change for the 1976-2100 period (x-axis) with respect to the 1980-2004 period for: (a) annual mean temperature; and (b) annual mean precipitation. Changes in annual mean temperature at each grid point and for each simulation are normalized with respect to the standard deviation of the corresponding simulation over the 1980–2004 period and, for annual mean Pr, as a percentage with respect to the climatological mean of the corresponding simulation over the 1980–2004 period. The light blue/red lines correspond to individual CMIP5/NA-CORDEX simulations, while the blue/red shading shows the range across all CMIP5/NA-CORDEX simulations. The thick blue/red line corresponds to the median PDF of the CMIP5/NA-CORDEX ensemble and was computed by poling together all CMIP5/NA-CORDEX changes. PDFs were computed following the methodology proposed by Fischer *et al*. (2013).

- CORDEX has also developed a bias-corrected ensemble for daily minimum and maximum temperature, precipitation, specific humidity, and incoming solar radiation, using as target a very high-resolution dataset (Daymet at 1 km x 1 km). Users must keep in mind that the enhanced detail provided does not necessarily mean added value, especially in the Canadian North, because the target high-resolution dataset is based on the same sparse network of stations as the ANUSPLIN dataset used by the BCCAQv2 ensemble. There are no studies that have analyzed the CORDEX bias-corrected ensembles over the Canadian North.

CanLEAD:

- The CanLEAD bias-corrected ensemble has statistically downscaled several meteorological variables from the Canadian Earth System Model Large Ensemble (CanESM2 LE) over North America using a multivariate bias adjusted (MBCn method; Cannon, 2016) against two target datasets with 0.5° x 0.5 spatial resolution. The bias correction method preserves the inter-variable consistency and can be employed to develop complex indices like the meteorological fire weather index. The dataset was used in the Climate Resilient Buildings and Core Public infrastructure report (Cannon *et al*., 2020), which provides future-looking climate data, including temperature, precipitation and wind data, based on over 660 locations across Canada to be used in building and infrastructure codes and standards. However, there are no studies using these projections that focus only on the Canadian North.
- Data is available only for the high-emission scenario RCP 8.5, and can be used in the ''Levels of Global Warming'' framework to derive projections for the other emission scenarios for Canada only.
- As for the other statistically downscaled ensembles, results for the Canadian North are not grounded on a strong observational basis.
- Because the ensemble is constructed using only one model, the spread covers in large part, but not completely, the CMIP5 spread (see Figure 4.4).

Although the statistically and dynamically downscaled projections have a higher resolution then CMIP5/CMIP6 models, care must be taken in interpreting the data in areas of complex topography (Diaconescu *et al*. 2018). In such areas, e.g., in Yukon, this resolution may still be too coarse to adequately represent detailed climate gradients. This is particularly apparent when absolute values for threshold-based indices are compared with equivalent values at stations with elevations which are significantly different from the grid-box elevation. Using anomalies, rather than absolute values, is the preferred approach in this case.

A very limited number of analyses were done for climate projections of wind over Canada (e.g., Jeong *et al*., 2020; Cheng *et al*., 2012; Jeong and Sushama, 2019) and even fewer related to humidity (e.g., Jeong and Cannon, 2020).

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4.2.2 Snow and hydrology variables

Lead Authors: Lawrence Mudryk (CRD/ECCC) and Rajesh Shrestha (WHERD/ECCC)

4.2.2.1 Simulated snow data

Snow is a complex climate variable and can be simulated in a variety of model types (e.g., fully coupled atmosphere-ocean/ESM models, offline land surface models, and reanalyses) as a component of the surface which can interact with incoming radiation, and which couples the lowest layer of the atmosphere to the soil both thermodynamically and hydrologically. Snow may exist on land surfaces, ice surfaces or both depending on the model type.

There are three key physical effects related to snow typically simulated within a climate model:

1. Snow cover modifies the absorption of radiation by the surface, since its high albedo reflects more incoming shortwave radiation than most other types of surface cover. This effect depends on location and season since the amount of incoming radiation varies according to these, as well as on the condition of the snow: melt and snow aging processes can reduce snow albedo somewhat, and deposition of black carbon ("soot") or other dark contaminating materials (e.g., organic debris) on the snowpack can alter the albedo more substantially.

2. Snow mediates the exchange of heat between the atmosphere and the soil layer underneath the snow by slowing the transfer of heat between the two. In typical winter conditions the air above the snow pack is colder than the soil layer, such that the snow acts to keep the soil warmer. This effect will depend on the thickness of the snow pack and on internal characteristics that affect its thermal diffusivity such as density, liquid water content, stratigraphy.

3. The snowpack acts as a water reservoir, accumulating frozen precipitation under winter conditions and releasing it during melt. In snow-dominated regions, this stored water typically melts over a reasonably short period and is responsible for springtime surges in runoff and river discharge, as well as seasonal contributions to the soil water levels.

On the land surface, snow is typically modelled as several separate layers (e.g., 1-5, although complex offline snow models may use 10-100) using the same geometry as the atmospheric grid. Sometimes it is considered to be a topmost "soil layer". On sea ice, snow has not typically been modelled explicitly since sea ice is mobile and it has historically been too computationally expensive to model individual ice floes (nor are heuristic parametrizations, for example, a snow depth related to sea ice surface roughness usually employed). More recently snow on sea ice has been modelled in a multi-step way, using ice motion derived from model output in a second implementation that then deposits snow on the moving sea ice.

Snow is treated as a component of the global hydrological cycle within climate models and in general, all snow-related output stems from calculating how much snow mass is contained within a grid cell. This mass of snow is usually expressed as its equivalent height in water spread uniformly across either the entire grid cell or across the land-covered portion of the grid cell ("snow water equivalent"). The mass is calculated by tracking the balance between accumulation and ablative losses (melt, sublimation), and depending on the complexity of the model, various processes related to vertical mass transfer between layers, and horizontal transfer of mass between adjacent cells (very infrequently). From a practical perspective, all other snow output is derived from this key quantity. Estimates of snow depth are computed by also modelling the density of snow layers combined with the information on mass. The proportion of the surface covered by snow is also typically parametrized as a function of the mass of snow within the cell (e.g., as fully covered above some mass threshold and as a decreasing fraction of all land cover below, although a range of formulations exist and in mountainous regions they may include additional dependencies).

Considerations and limitations:

Typical considerations required for model ensemble analysis of other physical climate variables also apply to snow since uncertainty in snow projections stem from a combination of different model biases and internal climate variability. Therefore, the current practice is to use the CMIP or CORDEX ensembles for several emission scenarios to obtain large-scale or regional climate information.

The output frequency of specific variables will differ by model and choice of experiments (e.g., historical vs future scenarios) for both CMIP6 and CMIP5. For CMIP6 snow related variables, the typically provided variables are snow cover fraction (snc) and surface snow amount (snw), followed by snow depth (snd) and snowfall (prsn). For some models, some of the variables will be available at daily frequency.

Information on snow cover from CMIP5 over Canada is summarized in Canada's Changing Climate Report (Bush and Lemmen, 2019) for RCP2.6, RCP4.5, and RCP8.5. Presently, statistically downscaled or bias corrected simulations for snow for the Canadian North are not available. The following is summarizing the current knowledge on models' skill.

Successive generations of climate model ensembles have improved in their ability to represent historical snow extent on average (i.e. the ensemble mean) between CMIP3 through CMIP6, however, there remains a persistent amount of spread in skill among the models (Mudryk *et al*., 2020 and references therein). This spread in historical snow extent continues to cause spread in assessments of simulated snow-albedo feedbacks (Thackeray *et al*., 2021). The ability of climate models to reproduce the historical snow mass climatology is less constrained because estimates of historical snow mass from gridded products have relatively high uncertainty compared to snow extent, especially in mountain regions (Mudryk *et al*. 2015). This stems from the fact that snow observations are sampled at limited spatial and temporal frequency compared to their variability, although recent work has both narrowed the spread (Pulliainen *et al*. 2020) and better assessed the accuracy of gridded snow mass products (Mortimer *et al*. 2020) across Northern Hemisphere nonalpine regions. The uncertainty in the overall mass balance means that climatological rates of melt and sublimation are also uncertain (and it is difficult to isolate biases in one versus the other). The overall uncertainty in the primary snowpack balance related to accumulation and ablation also means that biases stemming from higher-order effects (vegetation-snow interactions, wind redistribution) can be difficult to isolate. Given the above, seasonal and spatial biases in snow water equivalent, snow depth, and snow cover fraction can be expected to reflect not only model-specific biases in temperature and precipitation as they vary by region and season, but also the combination of parametrization uncertainties specific to a particular model.

The ability of climate models to simulate historical trends in snow extent has also improved between CMIP3 and CMIP6, in part due a better understand of trends in historical datasets (Brown and Derksen 2013, Hori *et al*., 2017, Mudryk et al. 2020). For snow mass, despite poor constraints on the seasonal balance of accumulation and ablation, monthly trends in this quantity are better estimated. This is because the trends are controlled by a combination of more slowly evolving boundary forcings (e.g., anthropogenic aerosols, GHGs, volcanic forcing and solar variability), and synoptic scale variability in temperature and precipitation, which models simulate more or less reasonably. Similarly, in offline models or reanalysis, historically observed temperature, precipitation, and other observational data are used to simulate the snowpack, and these variables already contain the time-varying signals related to boundary forcing and synoptic-scale variability, producing snow mass estimates with similar temporal components.

Sensitivity experiments indicate that hemispheric snow extent, like sea ice extent, responds as a fast component of the cryosphere, and therefore, doesn’t depend on the rate of warming (Mudryk *et al*., 2020), or prior snow extent conditions (hysteresis).This fast response suggests that accurate projections of hemispheric snow extent should result from accurate projections of global temperatures. The fidelity of such projections on regional or local scales is less well established since historical evaluation on these scales is limited due to the presences of increased natural variability (Mudryk *et al*., 2017). Sensitivity of snow mass to temperature is also less established.

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4.2.2.2 Simulated streamflow data

Simulated streamflow data are usually obtained from watershed to river basin scale hydrologic models, which are considered suitable for detailed analyses (e.g., seasonal water availability, extreme events). Watershed processes in cold regions are mainly dominated by spring snowmelt, which often lead to the largest annual discharge events. The presence of permafrost, and frozen soils that limit infiltration rates lead to unique challenges in modelling cold regions hydrologic regime. Several models, such as Variable Infiltration Capacity (VIC) (Liang *et al*., 1994; Hamman *et al*., 2018), Modelisation Environmentale Communautaire – Surface and Hydrology (MESH) (Pietroniro *et al*., 2007), the Canadian Hydrological Model (CHM) (Marsh *et al*., 2020), and Soil and Water Assessment Tool (SWAT) (Arnold *et al*., 1998, 2012) among others, were developed to take into account those specific requirements of cold climates. Wang *et al*. (2021) offers a recent review of the work done for modelling watershed and river basin processes in cold climate regions. Along with streamflow, the hydrologic models provide simulations of a range of hydrologic variables, such as evapotranspiration, snow accumulation, snowmelt, infiltration, soil moisture, and surface and subsurface runoff. The hydrologic models are set up at various spatial resolutions (typically ranging from 100 m to 10 km) and calibrated to reproduce watershed/sub-watershed scale streamflow, which may be supplemented by calibration of SWE, evaporation, etc.

Required meteorological forcings for hydrologic models include a range of variables (e.g., minimum and maximum temperature, precipitation, relative humidity, surface pressure, wind speed, incoming shortwave radiation and incoming longwave radiation, etc.), with historical simulations obtained by driving the model with observations or gridded observation products, reanalyses, etc. For GCM driven simulations, it is customary to employ a downscaling technique for a finer spatial-scale representation of climatic variables, which may include statistical and/or dynamical downscaling technique in combination with a bias correction method. This procedure is necessary because the GCMs do not provide sufficient resolution for hydrologic model simulation, as well as representing local-level extremes (e.g., wet and dry conditions), which are the important issues for water resources management.

A number of studies have used downscaled CMIP5 GCMs for simulating historical and future streamflow in northern Canada. These include, climate change impacts on inland waterway transport in the Mackenzie River (Scheepers *et al*., 2018), impacts of 1.5 and 2.0° C warming on river discharge into the Hudson Bay (MacDonald *et al*., 2018), uncertainty of climate change impacts due to hydrologic model components over two Nordic Quebec catchments (Troin *et al*., 2018), climatic controls on future hydrologic changes in the Liard river basin (Shrestha *et al*., 2019), and simulation of 90-year (1981–2070) spatially distributed freshwater fluxes from the Arctic basins (Stadnyk *et al*., 2021). However, modelled streamflow from these studies are not readily accessible. Historical and projected future streamflow and runoff based on CMIP5 GCMs are available for downloading from the Pacific Climate Impacts Consortium data portal (https://www.pacificclimate.org/data/daily-gridded-meteorological-datasets). The dataset is only available for the Peace, Fraser and Columbia basins in western/southern Canada (Schoeneberg and Schnorbus 2021) and further details are given in Tables 3.2 and 3.3.

At Ouranos, PAVICS offers a suite of tools constructed in Python, named Raven, to streamline the analysis of climate change's impacts on hydrology (https://pavics.ouranos.ca/hydrology.html#a). The tool permits to run hydrological model simulations on remote servers or with remote input data as well as to calibrate hydrological models on a remote server. The website presents an example on how to run the GR4J-CemaNeige hydrological model. Other three models can be run in the same way: HBV-E, HMETS, MOHYSE.

Considerations and limitations:

Similar to other hydro-climatic variables, future hydrologic projections are subject to different sources of uncertainties including anthropogenic forcings (emission scenarios), natural variability of the climate system, GCM structure and downscaling methods (e.g., Giuntoli *et al*., 2018; Hattermann *et al*., 2018). Additionally, hydrologic model structure and parameterization, such as the representation of permafrost and glacier affect the streamflow projections (Bring *et al*., 2016). Generally, uncertainties due GCM structure and greenhouse gas concentration and anthropogenic forcings are considered to be the most important sources of uncertainties, and it is a common practice to incorporate multiple RCP or emissions scenarios, and an ensemble of GCMs in projecting hydrologic impacts of climate change (e.g., Shrestha *et al*., 2014; 2019; MacDonald *et al*., 2018).

Besides basin-scale hydrologic models, global/regional hydrology models or land surface models (e.g., Schewe *et al*., 2014; Bring *et al*., 2017; Gädeke *et al*., 2020) provide CMIP5 GCM driven streamflow simulations over historical and future periods in northern Canada. These models are typically of coarser resolution (~0.5°), and unlike basin-scale hydrologic models they are generally not calibrated to reproduce the basin specific streamflow, which can lead to considerable uncertainty. Likewise, for the northern Canada domain, RCM land surface simulations also provide runoff variables, for example, RCMs that participated in the Coordinated Regional Climate Downscaling Experiment (CORDEX) (Giorgi *et al.*, 2009) over North America (NA-CORDEX: na-cordex.org) and Arctic (Arctic-CORDEX: https://climate-cryosphere.org/activities/polar-cordex/arctic). CORDEX has both hindcast (ERA-Interim and GCM-driven historical simulations) and CMIP5 scenarios (RCP4.5, RCP8.5 simulations), with a spatial resolution of 0.22°(~25 km) or 0.44°(~50 km). Some GCMs/RCMs have been coupled with routing schemes to simulated streamflow, for example, projections of 2 °C vs. high warming flood-generating mechanisms across Canada (Teufel and Sushama, 2021), simulation of future changes in flood hazards across Canada (Gaur et al., 2018). However, as in the case of other variables, bias in the RCMs also affects the streamflow simulations. Nevertheless, the simulations from the global/regional hydrology models and RCMs offer useful information regarding the direction of climate change driven streamflow changes over large areas.

Table 4.2. VIC hydrologic model simulated SWE/runoff datasets

Name	Source	Type	Spatial Domain	Spatial Resolution	Temporal Coverage	Time Step	Format	Notes	Link to metadata description
Observation driven gridded VIC hydrologic model output	PCIC	Gridded SWE/ runoff data from VIC hydrologic model	Western Canada (Peace, Fraser and Columbia basins)	1/16° (~5-6 km)	Historical 1945-2012	daily	NetCDF	This dataset is produced by driving the VIC-GL model with PNWNAmet (Werner et al. 2019) gridded climate data. Detailed description is available in Schoeneberg and Schnorbus (2021)	https://www.pacificclimate.org/data/gridded-hydrologic-model-output
GCM driven gridded VIC hydrologic model output	PCIC	Gridded SWE/ runoff data from VIC hydrologic model	Western Canada (Peace, Fraser and Columbia basins)	1/16° (~5-6 km)	Historical 1950-2005; Future 2006-2100 for RCP4.5 and RCP8.5 scenarios	daily	NetCDF	This dataset is produced by driving the VIC-GL model with BCCAQ statistically downscaled GCMs (Cannon *et al.*, 2015). Detailed description is available in Schoeneberg and Schnorbus (2021)	https://www.pacificclimate.org/data/gridded-hydrologic-model-output

Table 4.3. VIC hydrologic model simulated river flow dataset

Name	Source	Type	Spatial Domain	Spatial Resolution	Temporal Coverage	Time Step	Format	Notes	Link to metadata description
Observation driven station VIC hydrologic model output	PCIC	VIC hydrologic model simulated flow data at specific locations	Western Canada (Peace, Fraser and Columbia basins)	1/16° (~5-6 km)	Historical 1945-2012	daily	ASCII	This dataset is produced by driving the VIC-GL model with PNWNAmet (Werner et al. 2019) gridded climate data. Detailed description is available in Schoeneberg and Schnorbus (2021)	https://data.pacificclimate.org/portal/hydro_stn_cmip5/map/
GCM driven station VIC hydrologic model output	PCIC	VIC hydrologic model simulated flow data at specific locations	Western Canada (Peace, Fraser and Columbia basins)	1/16° (~5-6 km)	Historical 1950-2005; Future 2006-2100 for RCP4.5 and RCP8.5 scenarios	daily	ASCII	This dataset is produced by driving the VIC-GL model with statistically downscaled GCMs BCCAQ (Cannon et al. 2015). Detailed description is available in Schoeneberg and Schnorbus (2021)	https://data.pacificclimate.org/portal/hydro_stn_cmip5/map/

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4.2.3 Sea ice

Lead Author: Alex Crawford (University of Manitoba)

Contributors: Stephen Howell (CRD/ECCC), Jennifer Lukovich (University of Manitoba)

As with snow variables, the common practice in simulating sea ice variables over historical period and for creating climate future projections is to use ensembles of physical climate models CMIP5 and CMIP6. In these models, sea ice is simulated within discrete cells of a sea ice model component that is coupled to an atmospheric model and ocean model. Growth and melt of sea ice are driven by heat exchange with the atmosphere and ocean. Sea ice cover can also change by divergence and convergence, which are driven by wind in the atmosphere and currents and waves in the ocean. 'Coupling' of model components means that sea ice can in turn influence the ocean and atmosphere (e.g., higher sea ice concentration means a higher reflectivity and less solar radiation input to the surface).

The amount of data available from CMIP5 (https://esgf-node.llnl.gov/search/cmip5/) and CMIP6 (https://esgf-node.llnl.gov/search/cmip6/) is vast because, in addition to the calculation of multiple sea ice variables from multiple experiments, each modelling group may produce more than one model version, and each model version may be run multiple times for the same experiment (as a measure of model internal variability). Many modelling groups release ocean and sea ice data on variable-resolution grids and/or rotated grids (e.g., with the "north pole" shifted to over Greenland), so spatial resolution is not easily compared. The average cell size per model in CMIP5 and CMIP6 ranges from roughly 25 km to roughly 250 km, with finer resolution more common in CMIP6. Sea ice characteristics are available as monthly averages, which some models providing sea ice concentration, thickness, and velocity as daily averages, as well.

The narrow channels in Canadian Arctic waters are not well represented by the coarse spatial resolution GCMs and the uncertainty in model projections is higher for the Canadian Arctic Archipelago than for the pan-Arctic. In spite of this, the CMIP5/6 multi-model ensemble still provides a quantitative basis for projecting future sea ice conditions for applications in the Canadian North.

The primary application of these coarse resolution, long-term simulations is to make projections about the possible uses and routes for human activities in the Arctic throughout the 21st century and beyond. Shipping lanes into Hudson Bay and through the Canadian Arctic Archipelago (the Northwest Passage) will continue to become more accessible as sea ice cover declines, and CMIP5/6 models allow us to estimate how long these routes will be open in the future (e.g., Smith and Stephenson, 2013; Melia *et al*., 2017; Andrews *et al*., 2018). For example, CMIP5 models showed that nearly ice-free summers are very likely with 2.0°C of global warming above pre-industrial levels but unlikely if global warming is limited to 1.5°C (Jahn, 2018; Sigmond *et al*., 2018). For areas with seasonal sea ice cover, the length of the ice-free season expands by about 1 month with each additional 1°C of global warming in CMIP6 models (Crawford *et al*., 2021). This translates to opening of the Northwest Passage and Hudson Bay to all vessels for at least part of the year with 2°C of global warming above pre-industrial levels (Mudryk *et al*., 2021).

CMIP5

In CMIP5, monthly sea ice concentration is available from up to 41 models (16 modelling groups), depending on the experiment. Daily sea ice concentration is available from up to 32 models (16 modelling groups). Sea ice thickness and motion are also available for most but not all those models. Sea ice motion is reported as a velocity for daily data and a volume transport for monthly data. In both cases, motion is divided into an x-component and y-component based on the model's ocean grid (so they are not necessarily zonal and meridional). Historical experiment simulations run 1850-2005. For these, solar variability, atmospheric composition (including aerosols), and land use are prescribed to the models to reproduce observed climate forcings. Future projections include four "representative concentration pathways" (RCPs), each of which has a different timeline of atmospheric composition and land use change. In RCP2.6, radiative forcing peaks at ~2.6 W m-2 near 2100 before declining. In RCP4.5 and RCP6.0, radiative forcing stabilizes after 2100 at ~4.5 W m-2 and ~6.0 W m-2, respectively. In RCP8.5, radiative forcing reaches ~8.5 W m-2 near 2100 but may continue rising. All RCP simulations are run from 2006-2100, with some extended through 2300. Table 3.4 shows the total number of simulations available for each experiment and temporal resolution.

Table 3.4 Number of CMIP5 simulations with available sea ice data for each combination of temporal resolution and experiment (as of Sep 2021).

	Property (variable)	Historical	RCP2.6	RCP4.5	RCP6.0	RCP8.5
Daily	Concentration (sic)	116	32	63	16	52
	Thickness (sit)	106	32	57	16	48
	Motion (usi, vsi)	75	30	54	15	41
Monthly	Concentration (sic)	195	56	146	36	63
	Thickness (sit)	195	56	146	36	63
	Motion (transix, transiy)	134	40	88	31	86

CMIP6

Although some sea ice models were modified between CMIP5 and CMIP6 (e.g, Bailey *et al*., 2020), the biggest difference between these CMIPs is the larger volume of data available from CMIP6. As of September 2021, available CMIP6 data include simulations of monthly sea ice concentration from up to 57 models (29 modelling groups) and daily sea ice concentration data from up to 40 models (21 modelling groups). Compared to CMIP5, the number of historical simulations more than doubled for daily data and nearly tripled for monthly data (Table 3.5). As with CMIP5, most models also produce output for sea ice thickness and motion, but motion is always reported as a velocity (available as an x-component (siu) and y-component (siv)). Several modelling groups have also released additional variables (e.g., frazil ice growth versus basal growth) to better diagnose model processes and biases (Notz *et al*., 2016; Keen *et al*., 2021). Historical experiments for CMIP6 run from 1850-2014. For future projections (2015-2100 or 2015-2300), radiative forcing targets (like those of CMIP5) were combined with "shared socioeconomic pathways” (SSPs), which account for the possibility that a single policy framework may yield different emissions and land use change, and therefore different radiative forcings.

Table 3.5 Number of CMIP6 simulations with available sea ice data for each combination of temporal resolution and experiment (as of Sep 2021).

	Property (variable)	Historical	SSP1 1.9	SSP1 2.6	SSP4 3.4	SSP2 4.5	SSP4 6.0	SSP3 7.0	SSP5 8.5
Daily	Concentration (siconc)	289	76	89	7	206	15	105	91
	Thickness (sithick)	252	19	51	2	139	10	68	53
	Motion (siu, siv)	271	69	69	7	158	15	87	72
Monthly	Concentration (siconc)	590	151	303	9	414	67	280	285
	Thickness (sithick)	526	55	225	10	339	18	208	207
	Motion (siu, siv)	552	156	313	15	378	73	297	247

Considerations and Limitations

As for the other climate variables, differences amongst historical CMIP5/6 simulations of sea ice variables arise from different model biases and internal climate variability, and a multi-model ensemble of multiple simulations from each model must be used. However, each model submitted to CMIP5/6 has a different number of simulations. As for the other variables, to provide equal weight for each model when calculating multi-model means for sea-ice variables, it is common to select just one simulation from each model.

Errors in the boundary conditions with which the models are forced and biases in the observations can also contribute to differences between observations and historical simulations. Several studies making projections of Arctic sea ice properties into the 21st century use only a subset of CMIP models that best match some historical metric, such as the historical average or trend in September sea ice extent (e.g., Wang and Overland, 2012; Mioduszewski *et al*., 2019; Peng *et al*., 2020). However, discarding models in this way risks introducing more bias Internal variability in Arctic sea ice characteristics is often the largest source of model uncertainty (Notz, 2014, Bonan *et al*., 2021), and the impact of internal variability on recent Arctic sea ice loss has been nonuniform for both region and season (England *et al*., 2019). By using a smaller number of members, the ensemble does not sample enough the model uncertainty. Additionally, the models that best match observed trends in Arctic sea ice loss are often correct for the wrong reason, such as combining sea ice sensitivity to warming that is too weak with global warming that is too strong (Rosenblum and Eisenman, 2017). Therefore, success in projecting past sea ice conditions does not provide a substantial reduction to uncertainty in future projections (Laliberté *et al*., 2015).

Moreover, because many modelling groups share code for certain processes, individual models are not truly independent (Annan and Hargreaves, 2017), which may also bias the ensemble based on a single simulation from each CMIP5/6 model. A more sophisticated approach that attempts to address this issue is to keep all model simulations when making projections but weight them based on a) their ability to match observations of Arctic sea ice and temperature characteristics and b) their degree of dependence (Knutti *et al.*, 2017). Diagnostics chosen for weighting should have a physical justification, such as being an emergent constraint on projected sea ice characteristics (Massonnet *et al*., 2012; Knutti *et al*., 2017). Differential weighting balances the shortcomings of other approaches, but it also requires greater computational power and potentially more data storage space for diagnostic variables.

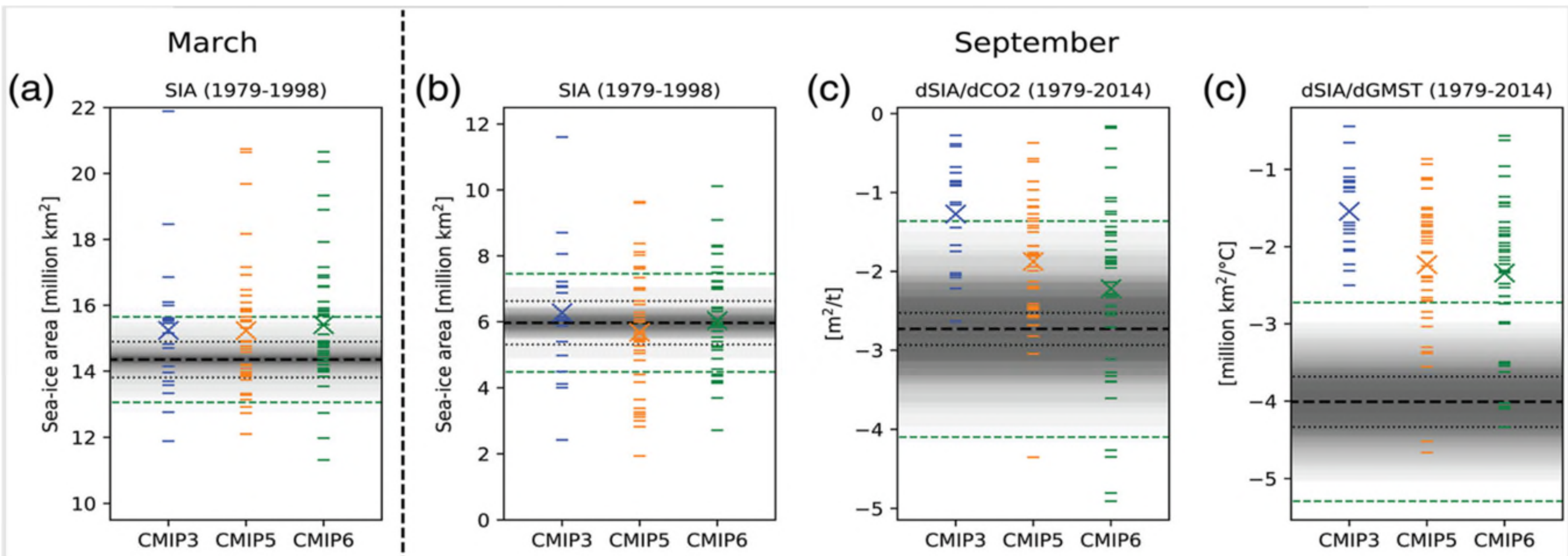

Figure 4.9: (a,b) Comparison of sea-ice area (SIA) in CMIP3, CMIP5, and CMIP6 simulations to the passive microwave record in (a) March 1979-1998 and (b) September 1979-1998. (c) Comparison over 1979-2014 of the sensitivity of the trend in September sea-ice area to the trend in (left) CO_2 emissions

and (right) global mean surface temperature (GMST). Each dash indicates the value for the first ensemble member of each model, and the x's indicate the multi-model mean. The thick black dashed line is the average of three satellite products, and the dotted lines indicate 1 standard deviation of observational uncertainty. Internal variability is calculated as the ensemble standard deviation for any model with at least 3 ensemble members and plotted as overlying gray shading. The green dashed lines show an overall "plausible range" for each property based on both observational uncertainty and internal variability. [Source: SIMIP Community (2020)].

Figure 4.9 summarizes the skill of CMIP3, CMIP5 and CMI6 in simulating sea ice area over the historical period. The March multi-model mean sea-ice area for 1979-1998 CMIP5 and CMIP6 is higher than the observational mean but within a plausible range once observational uncertainty and internal variability are accounted for (Figure 1; SIMIP Community 2020). In September, the multi-model means match observations well. CMIP5 models tend to underestimate the historical downward trend in September sea ice (Stroeve *et al*., 2012; Wang and Overland, 2012) because they underestimate the sensitivity of sea-ice area to global warming (Figure 1c). The trends in CMIP6 models have better alignment with observations (Shu *et al*., 2020), but this does not represent a major improvement to the sea ice model components. Rather, the CMIP6 multi-model mean demonstrates greater sensitivity of temperature to CO_2 emissions than does CMIP5 but has the same bias in the sensitivity of sea-ice area to temperature (SIMIP Community 2020, Fyfe *et al*., 2021). Therefore, CMIP6 represents only slight improvement over CMIP5, and any projections of future sea ice change using either CMIP must be considered with the caveat that the rate of change is likely underestimated.

Biases in CMIP simulations vary significantly by region and by season (Crawford *et al*., 2021; Watts *et al*., 2021). For example, the number of days with sea ice cover is overestimated in Hudson Bay by almost every CMIP6 model, but this parameter is well estimated in the Central Arctic Ocean. In the Beaufort Sea, the August retreat of sea ice below 15% concentration is better aligned between CMIP6 simulations and observations than the October advance above 15% concentration (Crawford *et al*., 2021). Problematically, biases are often opposite in different seasons or regions and so compensate for each other (Smith *et al*., 2020, Crawford *et al*., 2021; Watts *et al*., 2021). Therefore, it is common for pan-Arctic annual metrics to exhibit less bias than regional or seasonal metrics.

Fewer validation studies have been conducted for simulated sea ice thickness and sea ice motion. About half of the CMIP6 models examined by Watts *et al*. (2021) produced spatial patterns of sea ice thickness that matched results from the PIOMAS reanalysis (1979-2014). Pattern correlations were lower but still positive and significant when compared to CryoSat-2 (2011-2014). Sea ice volume, which depends on both sea-ice extent and thickness, has smaller biases in CMIP6 than CMIP5 when compared to PIOMAS, as well as a smaller model spread (Davy and Outten, 2020). This improvement results in part from thicker (and therefore more accurate) sea ice in Hudson Bay and north of the Canadian Arctic Archipelago in CMIP6. An assessment of sea ice drift from CMIP5 models demonstrated their ability to capture the observed increasing trend in sea ice drift speed in winter associated with an increasingly thinner sea ice cover (Tandon *et al*., 2018). Observed increasing trends in summer are, however, not captured by CMIP5 models, which the authors attribute to what is referred to as a sea ice extent effect associated with a transition to a partial ice cover, with implications for ice-ice and ice-coast interactions captured by deformation.

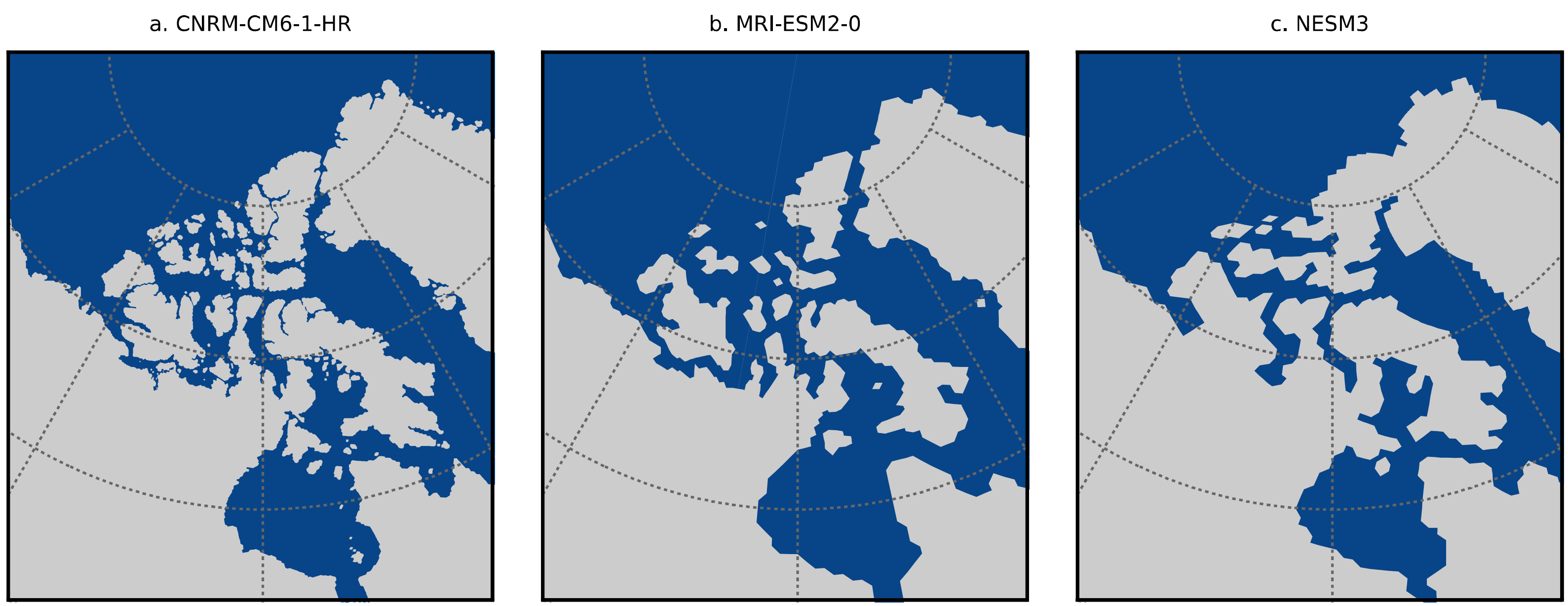

Figure 4.10: Example of land/ocean masks used in three CMIP6 models selected to show the range of detail resolved. Gray represents land and blue represents ocean (and therefore the grid cells capable of having sea ice cover).

The coarse resolution of CMIP5/6 models (Figure 4.10) limits their ability to capture local-scale sea-ice processes. The complexity of Canadian Arctic Archipelago is severely reduced in all but the highest-resolution models. For example, CNRM-CM6-1-HR (Figure 4.10a; nominal resolution of 25 km) resolves the Belcher Islands, differentiates Axel Heiberg from Ellesmere Island, and differentiates Bylot Island from Baffin Island. However, neither MRI-ESM2-0 or NESM3 (nominal resolution of 100 km) are so precise. MRI-ESM2-0 preserves water bodies while shrinking or eliminating land masses (e.g., Southampton Island, Devon Island). NESM3 expands and combines islands together while eliminating many straits (e.g., Victoria Strait and Nares Strait). Dynamically downscaled model output may therefore improve accuracy, but there are currently too few examples of dynamically downscaled sea ice data for proper assessment. For example, sea ice concentration is available for the 25-km North America CORDEX domain from only one model.

Although some CMIP5 models provide reasonable estimates of landfast ice thickness in the Canadian Arctic Archipelago compared to observations, many simulate landfast ice that is too thick and downward trends are excessively strong (Howell *et al*., 2016). Additionally, only models that provide a good match to historical observations of landfast ice thickness typically maintain seasonal landfast ice throughout the 21st century, showing that overall projections of sea ice extent are sensitive to the representation of landfast ice in CMIP simulations (Laliberté *et al*., 2018).

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4.2.4 Permafrost

Lead Authors: Stephan Gruber (Carleton University)

Even though variables related to ground temperature are available from climate projections, their application for informing decision-making related to future permafrost thaw is limited. This is a gap for which the development of new knowledge, methods and capacity is urgently needed in Canada. In the absence of established practice, this section outlines important considerations for using permafrost relevant projected model output in applications to inform adaptation or mitigation decisions.

Context: Climate change drives permafrost thaw globally and in the long term. The climate models used to estimate likely spatial and temporal patterns of climate changes employ grids with about 100–300 km horizontal resolution and the feedback of permafrost thaw to climate change is included only in some, and only partially, with physical processes sometimes represented [e.g., *Burke et al*., 2020] and permafrost carbon dynamics only rarely [e.g., Natali *et al*., 2021]. The timing and magnitude of permafrost thaw resulting from climate change, however, are determined by surface (vegetation, snow, drainage) and subsurface (ice content and other geotechnical variables) characteristics that vary strongly over distances of tens to hundreds of metres, and by processes that predominantly occur at these scales. The challenges for supporting decisions with climate model output that result from this mismatch of scales vary with the type of decision.

Mitigation: The magnitude and timing of permafrost carbon feedback are usually estimated with offline [e.g., de Vrese and Brovkin, 2021] or coupled [Burke *et al*., 2020, CMIP5/6] land-surface models. These are subject to significant shortcomings in representing permafrost carbon processes and feedbacks related to water and thermokarst. The scaling conflict here is a matter of how well model results can be compared with observations [Melton *et al*., 2019] and how well coarse grids can represent nonlinear processes in the sub-grid [Giorgi and Avissar, 1997; Gruber, 2012]. As the variable of interest here is the global amount of greenhouse gasses emitted from thawing permafrost, the scaling conflict can severely affect simulation quality, but it likely does not fundamentally challenge the usefulness of results. Regional warm and cold biases may balance to some degree.

Adaptation: To support adaptation, model output needs to inform decisions related to specific locations and specific ground conditions, usually involving variables such as temperature, ice content, and subsidence of the ground surface. These simulations are required at a resolution fine enough (grid or subgrid) that can represent landscape-scale processes [O'Neill *et al*., 2020, Cao *et al*., 2019, Schneider *et al*., 2021]. The models used for this need permafrost-specific capabilities [Endrizzi *et al*., 2014, Tubini *et al*., 2021] and require input on subsurface characteristics such as ice content, that are rarely available outside local applications. For driving such permafrost simulations, climate model output needs to be downscaled and/or debiased, for example using re-analysis. Debiasing permafrost variables such as ground temperatures or active-layer thickness directly is unsuitable due to the prominence of transient effects related to phase change near 0ºC.

Additional considerations: Permafrost is not readily observed remotely, and in-situ observations are sparse and biased to particular regions and terrain types [Biskaborn *et al*., 2015]. Almost no data is available for climatological periods (e.g., 30 years), for example, a recent global analysis only had about one hundred locations with one decade of observations [Biskaborn *et al*., 2019]. Consequently, testing the representation of permafrost in land-surface models needs to rely strongly on simulations driven by re- reanalysis [Cao *et al*., 2019, Fiddes *et al*., 2015].

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5 Key Recommendations and Conclusions

Lead Author: Emilia Diaconescu (CCCS/ECCC)

Contributors: Silvie Harder (CCCS/ECCC), Elaine Barrow (CCCS/ECCC), Jennifer Lukovich (University of Manitoba), Lawrence Mudryk (CRD/ECCC), Rajesh Shrestha (WHERD/ECCC), Alex Crawford (University of Manitoba), Stephen Déry (University of Northern British Columbia), Brian Horton (Yukon University Research Centre), Paul Kushner (University of Toronto), Michael Allchin (University of Calgary)

Datasets for several variables, inventoried into five categories (meteorological, snow, hydrology, sea ice, and permafrost), were examined with a view to their future use in the development of climate products and tools for various regional and local applications related to climate-change adaptation decision-making in the Canadian North. Present understanding of datasets and the best practices on using them were also provided.

This brief section considers the report's findings across chapters, and draws out the recommendations for the use of datasets and for future actions.

Recommendations for the use of datasets

The selection of a specific historical dataset depends on the application and the spatial scale of interest.

- The best approach for describing local climate, trends and evolution of meteorological variables (near-surface temperature, precipitation, humidity and wind) over a long historical period is to use the adjusted and/or homogenized data from stations as provided in AHCCD datasets, if available for the location of interest. In situ or site-specific measurements of snow depth or snow water equivalent (SWE) should be used only for local applications as they may not capture the average characteristics of the surrounding snow conditions.
- Because station measurements are, in general, sparse and situated at low elevation locations in the Canadian North, meteorological and snow datasets obtained by gridding methods are not recommended for regional applications over areas with important topographic variations. For regions with few stations, merged or hybrid products that make use of assimilation of observations and model output (e.g., reforecasts, high-resolution reanalyses or satellite-derived products), could be a good alternative to gridded observations. However, it is difficult to recommend one particular dataset for those applications as many of the new datasets have not yet been evaluated in a rigorous manner over the Canadian North. The results of continental-scale evaluations of these datasets could be biased by the much larger number of stations in regions outside of the Canadian North. Several studies recommend a multi-dataset approach for temperature, precipitation and SWE to compensate for the differences found in the various products. However, this is untested on smaller regional scales (e.g., the Canadian North) and may or may not apply to other variables.
- The recommendation for river discharge for historical periods is to give preference to in situ river discharge from hydrometric stations, where and when available, given they generally have extended and homogeneous records. When discharge data is insufficient or simply

unavailable, other sources including experimental watersheds maintained by academic institutions and government agencies, and reconstructed streamflow data through remote sensing or models may be employed.

- For historical sea-ice variables (sea ice concentration, thickness and drift), it is recommended that users consider and account for differences in algorithms and methods used to combine sources into long-term sea ice datasets. For long-term and large-scale scientific research, the passive microwave record of sea ice (using the NOAA/NSIDC Climate Data Record version) is recommended because it covers a broader area and yields all three key sea ice variables from one product. For applications in the Canadian North, sea ice charts have been shown to provide more accurate estimates of sea ice concentration in Canadian waters compared to satellite passive microwave estimates. It is recommended that local sea ice information be supplemented with in situ measurements that can be found through the Polar Data Catalogue (PDC), SIKU, and Smart-ICE initiatives. Indigenous knowledge can also inform and address specific questions and applications.
- Developing datasets for climate analyses and climate services for permafrost constitutes a new active field of interest in Canada. While ground temperature and ground ice data exist for different locations in the Canadian North, they are not systematically collected or available in a standardized format. An emerging programme that is working to improve permafrost data standards and interoperability for Canada is PermafrostNet. Another programme of interest for ground temperature data is the Global Terrestrial Network for Permafrost (GTN-P). The Circum-Arctic Map of Permafrost and Ground-Ice Conditions represents the most widely used product for permafrost extent. The Circumpolar Active Layer Monitoring (CALM) program is the primary programme for long-term active-layer measurements (the layer above permafrost that freezes and thaws annually). Data on active layer thickness and ground subsidence in Canada are currently rare and not organized into a central, accessible repository.

There is an increasing amount of climate model data available for download that can be used in risk assessments and adaptation to climate change. The present practice is to use multiple GCMs/ESMs/RCMs, or statistically downscaled GCMs as well as multiple RCPs/SSPs in any given analysis to account for model and emission uncertainties or to opt for the levels of global warming approach. Methodology or model selection depends on the application and the climate variable.

- Bias-corrected and statistically downscaled simulations exist for temperature and precipitation for all of Canada (e.g., BCCAQv2, bias-corrected CORDEX, CanLEAD). The quality of those products is dependent on the quality of the target dataset, which, in most cases, is a gridded observational dataset. Because observations in the Canadian North are sparse, the results of the bias-corrected products are not grounded on a strong observational base. The uncertainty is greater for projections of products developed using daily values and extremes. The use of a large ensemble of RCM raw data could be a solution for the Canadian North. Research analyses have shown that most RCMs in the CORDEX-Arctic ensemble were able to simulate climate indices related to mean air temperature and hot extremes well over most of the Canadian Arctic. The Canadian RCMs (CanRCM4 and CRCM5) perform better over the historical period than reanalyses for precipitation indices.

- Climate projections exist for humidity and wind but there is a very limited number of analyses done for those variables even at the national level.
- Data products based on applying statistical downscaling directly to snow variables are generally not available. It is possible to obtain dynamically downscaled snow data by running high-resolution models with downscaled/bias-corrected meteorological forcings, but at present, these are in the research stage.
- Basin-scale hydrologic models, global/regional hydrology models and land surface models can be used to provide GCM-driven streamflow simulations over historical and future periods in the Canadian North. The simulations from the basin-scale hydrologic models are generally considered suitable for detailed analyses (e.g., seasonal water availability, extreme events), while those from the global/regional hydrology models and RCMs can be used to obtain large-scale general information (e.g., the direction of changes in streamflow over large areas).
- There are no downscaled or bias-corrected products for sea ice. While uncertainty in model projections is higher for the Canadian Arctic Archipelago than for the pan-Arctic, the CMIP5/6 multi-model ensemble still provides a quantitative basis for projecting future sea ice conditions. However, the narrow channels in Canadian Arctic waters are not well represented by the coarse spatial-resolution GCMs.

Recommendations for future actions

The inventory and the analyses realised in this project show that there is a limited number of climate change research projects which focus on the Canadian North. Also, the information from continental or Canada-wide analyses are difficult to extrapolate to the north. Therefore, there is a pressing need for transdisciplinary research to augment current understanding of climate change in northern Canada. There is also a growing demand for the development of strategies that link transdisciplinary applied research programs with local needs and policy making about climate change through iterative interactions between researchers, climate services providers and stakeholders.

This project should be considered as a first step in a long approching process of scientific and user needs in the Canadian North. Next steps consist of translating this information into tools and forms that are easy to use and apply in risk analyses and climate change adaptation plans. It is recommended to share the present report with climate services providers in the Canadian North as well as with CIRNAC. The primary goal will be to verify if the information in this report can be useful for regional Inuit climate change strategies that are presently in development and to find ways to align it with other Inuit or northern Canadian climate data needs analysis. It is recommended that the new phase of the project be focused on answering feedback received from those institutions to better integrate it in the context of regional Inuit knowledge and perspectives on the changing climate and its impacts. If climate services providers and northern institutions consider this process to be useful, the report could be integrated on a web platform using an interactive form that will facilitate access to the information for specific variables as well as the addition of updates as new datasets and methods emerge. Regular reviews and updates of the data sources and methodologies listed in the report will ensure that existing content remains current.

6 List of Working Group Members (December 31, 2021)

			Subgroup			
Name	**Organization**	**Role**	**Meteorology**	**Snow and hydrology**	**Sea ice**	**Permafrost**
Alex Crawford	University of Manitoba	Member			Yes	
Brian Horton	Yukon University Research Centre	Member		Yes		Yes
Brian Sieben	Government of Northwest Territories	Member	Yes			
Elaine Barrow	CCCS/ECCC	Member				
Emilia Diaconescu	CCCS/ECCC	Member	Yes	Yes	Yes	
David Atkinson	University of Victoria	Member	Yes			
Jennifer Lukovich	University of Manitoba	Leader of sea-ice subgroup	Yes		Yes	
Lawrence Mudryk	CRD/ECCC	Member		Yes		

			Subgroup			
Name	**Organization**	**Role**	**Meteorology**	**Snow and hydrology**	**Sea ice**	**Permafrost**
Lindsay Matthews	CCCS/ECCC	Member			Yes	
Marco Braun	Ouranos	Member	Yes	Yes		
Paul Kushner	University of Toronto	Scientific chair of the working group and leader of the meteorology subgroup	Yes		Yes	
Paul Steenhof	CSA Group	Secretariat of the group				
Ryan Hennessey	CCCS/ECCC	Member			Yes	Yes
Silvie Harder	CCCS/ECCC	Member				Yes
Stephan Gruber	Carleton University	Leader of the permafrost subgroup				Yes
Stephen Déry	University of Northern British Columbia	Leader of the snow and hydrology subgroup		Yes		
Stephen Howell	CRD/ECCC	Member			Yes	

Contributors:

Name	**Organization**	**Subgroup**
Aleksandra Elias Chereque	University of Toronto	Meteorology

Name	Organization	Subgroup
Ashley Rudy	Government of Northwest Territories	Permafrost
Carrington Pomeroy	CCCS/ECCC	Meteorology
Fereshteh Ghiami	Carleton University	Permafrost
Galina Jonat	Carleton University	Permafrost
Hannah Macdonell	Carleton University	Permafrost
Heather Macdonald	CFS/NRCan	Meteorology; Snow and hydrology
Housseyni Sankare	CCCS/ECCC	Meteorology
Hugh Brendan O'Neill	GSCNC/NRCan	Permafrost
Kenneth Chow	CCCS/ECCC	Meteorology
Jack Landy	Bristol University	Sea ice
Michael Allchin	University of Calgary	Meteorology; Snow and hydrology
Rajesh Shrestha	WHERD/ECCC	Snow and hydrology
Tricia Stadnyk	University of Calgary	Snow and hydrology

7 Annexes (datasets descriptions)

7.1 Temperature

7.1.1 Dataset: Observations from MSC weather stations – temperature

Overview

This dataset provides in-situ surface observations archived by the Meteorological Service of Canada (MSC). It containes data from the MSC operational observation system as well as from their parteners. Therefore, not all stations are QC or maintained by MSC. The network of stations containes stations with only automatic instruments, and human observing (or manual) stations.

Provider's contact information

Environment and Climate Change Canada

donneesclimatiquesenligne-climatedataonline@ec.gc.ca

Licensing

Open Government Licence - Canada.

Variable name and units:

Hourly temperature in degrees Celsius (°C)

Maximum daily temperature in degrees Celsius (°C);

Minimum daily temperature in degrees Celsius (°C);

Mean daily temperature in degrees Celsius (°C);

Monthly Mean Temperature (°C) and Days with Valid Mean Temperature

Highest Monthly Maximum Temperature (°C) and Days with Valid Maximum Temperature

Lowest Monthly Minimum Temperature (°C) and Days with Valid Minimum Temperature

Spatial coverage and resolution:

Canada, point locations.

Temporal coverage and resolution:

Time period varies per station with data for in the North starting in 1940's or 1950's until present.

The data is available at the hourly, daily and monthly time steps.

The data will continue to be updated regularly.

Information about observations (number, homogeneity)

The number of active stations changed over time. The following figure from Mekis et al. (2018) is presenting the locations of the surface weather stations across Canada with a Needs Index map in the background as of September 2016.

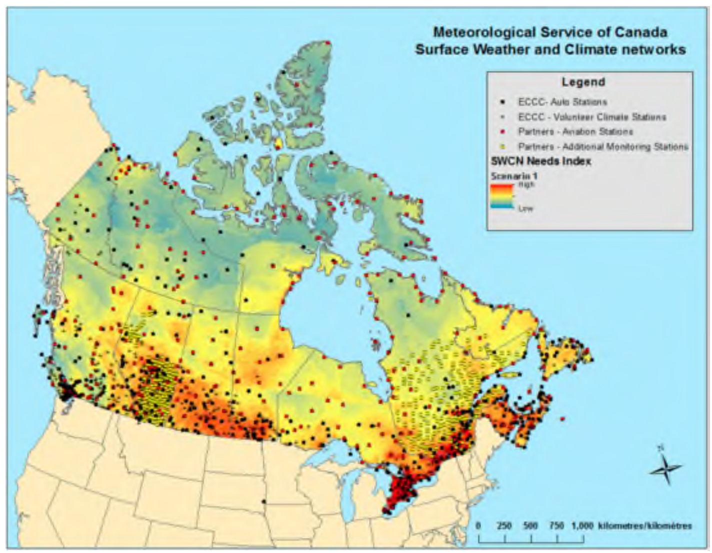


Figure 1. Surface weather stations across Canada, as of September 2016, with a Needs Index map in the background. For further details on station network evolution see Mekis et al. 2018. [Source: Mekis et al., 2018].

Most of the stations over Northern Canda are ECCC atomatic stations, stations from the Cooperative Climate Network of ECCC (a network of volunteer climate observers using high quality sensors provided and maintained by MSC), and stations from the Aviation Monitoring

Station network (which include automated and staffed weather stations) operated by NAV CANADA and the Department of National Defence (DND).

Methodology

Raw and quality-controlled station observations are archived and managed by the MSC's Archive Operations and Climate Services. Observations from different instruments are stored in different formats in the national archive. The methodology, the instruments and the location of instruments have changed in time. The following is summarising some information that should be considered when using historic station data.

For climate stations operating on a 24 hour basis, before June 1, 1957, the climatological day for precipitation and maximum temperature ends at 12 00Z of the following day, and the climatological day for minimum temperatures ends at 00 00Z of the following day; from June 1, 1957 to June 30, 1961, the climatological day for precipitation and maximum temperature ends at 12 00Z of the following day and the climatological day for minimum temperatures ends at 00 00Z of the following day; since July 1, 1961, the climatological day for temperature and precipitation ends at 06 00Z of the following day.

At locations with no hourly observations, observation times are generally morning and evening. In general, the climatological day for precipitation and maximum temperature ends at the morning observation of the following day. The climatological day for minimum temperatures ends at the afternoon observation of the current day. In cases where knowing time-of-observation is critical, the best approach is to check the historical inspection reports for the climate station.

Daily temperature values are derived from: (1) the Daily Climate Stations (that are producing two observations per day: daily minimum temperature and daily maximum temperature) or Synop stations that provided daily measures separately from hourly measurements, and more resently (2) from hourly stations (that typically measure instantaneous data at each hour). For the first type of stations, temperature measurements are made from self-registering maximum and minimum thermometers set in a louvered, wooden shelter. The shelter is mounted on a stand so that the thermometers are approximately 1.5 m above ground, which is usually a level, grassy surface. For hourly stations, maximum temperature is the highest temperature recorded in a 24-hour period ending in the morning of the next day. The minimum values are for a period of the same length, beginning in the evening of the previous day. Mean temperature is the average of the two.

Monthly temperature values include monthly averages and extremes (mean, maximum and minimum temperatures). This data is available from stations that have daily data.

Information about the technical and scientific quality

This dataset represents Environment and Climate Change Canada's official station observations. Data are subject to change on an on-going basis as MSC is constantly QCing the data from ECCC stations. Not all data has the same level of QA/QC (i.e. aviation dat is not QA/QC by MSC but by NAV CANADA).

Limitations and strengths for application in North Canada

It is a challenge to sustain a cost-effective observing system over Norther Canada because of a large part of the teritory is constituted by remote areas (it is hard for technicians to fly to the site for maintenance, and they often have to wait for the thaw) and the cliamtic conditions produce a large risk of instruments to freese, and for power and telecommunication outages. Concequently, observations in Nortehrn Canada are sparse and records are often incomplete.

References to documents describing the methodology or/and the dataset

The manual specific for aviation observations/reports (MANOBS):

http://publications.gc.ca/collections/collection_2019/eccc/En56-238-2-2018-eng.pdf

The manual of Climatological Observations used by the Cooperative Climate Network of ECCC (MANCLIM): https://publications.gc.ca/collections/collection_2012/ec/En56-238-3-2012-eng.pdf

https://climate.weather.gc.ca/doc/Technical_Documentation.pdf

Link to download the data and format of data:

Hourly, Daily and Monthly

Database searchable by location for CSV via CDO/MSC/ECCC: https://climate.weather.gc.ca/historical_data/search_historic_data_e.html

Only Hourly:

Map based extraction tool for GeoJSON and CSV on CCCS/ECCC: https://climate-change.canada.ca/climate-data/#/hourly-climate-data

Note: Only a subset of the total stations is shown due to size limitations. The priorities for inclusion are as follows: (1) Station is currently operational, (2) Stations with long periods of record, (3) Stations that are co-located with the categories above and supplement the period of record. For additional stations not included, go to CDO/MSC/ECCC.

Only Daily

Map based extraction tool for GeoJSON and CSV on CCCS/ECCC: https://climate-change.canada.ca/climate-data/#/daily-climate-data

CSV via MSC/ECCC: https://dd.weather.gc.ca/climate/observations/daily/

Note: Only a subset of the total stations is shown due to size limitations. The priorities for inclusion are as follows: (1) Station is currently operational, (2) Stations with long periods of record, (3) Stations that are co-located with the categories above and supplement the period of record. For additional stations not included, go to CDO/MSC/ECCC.

Only Monthly

Map based extraction tool for GeoJSON and CSV on CCCS/ECCC: https://climate-change.canada.ca/climate-data/#/monthly-climate-summaries

CSV via MSC/ECCC: https://dd.weather.gc.ca/climate/observations/monthly/

Provincial and territory observation summaries in XML format for the last month are available on the MSC Datamart

Publications including dataset evaluation or comparison with other data in northern Canada

There are no publications that evaluate station data specifically on northern Canada. The following papers are providing general discussions on the issues with station data in Canada, with focus on temperature data.

Vincent, L.A., X.L. Wang, E.J. Milewska, H. Wan, F. Yang, and V. Swail, 2012: A second generation of homogenized Canadian monthly surface air temperature for climate trend analysis, Journal of Geophysical Research: Atmospheres, 117(D18), doi:10.1029/2012JD017859.

Vincent, L.A., M.M. Hartwell, and W.L. Wang, 2020: A third generation of homogenized temperature for trend analysis and monitoring changes in Canada’s climate. Atmosphere-Ocean, 58(3), 173-191, doi:10.1080/07055900.2020.1765728.

7.1.2 *Dataset: MSC Climate Normals – temperature*

Overview

This dataset provides Climate Normals at the in-situ surface observations archived by the Meteorological Service of Canada (MSC), which containes data from the MSC operational observation system as well as from theirparteners. The Climate Normals summarize or describe the average climatic conditions of a particular location over a period of 30 years, and they are based on Canadian climate stations with at least 15 years of data in the 30-year period. At the completion of each decade, Environment and Climate Change Canada updates its Climate Normals for as many locations and as many climatic characteristics as possible. MSC is QC the Normals but the QC of the data used in the Normal computation is done by the owers of the sites.

Provider's contact information

Environment and Climate Change Canada

donneesclimatiquesenligne-climatedataonline@ec.gc.ca

Licensing

Open Government Licence - Canada.

Variable name and units:

Mean Temperature in degrees Celsius (°C)

Mean daily maximum temperature (°C)

Mean daily minimum temperature (°C)

Days with Maximum Temperature

≤ 0°C

> 0°C

> 10°C

> 20°C

> 30°C

> 35°C

Days with Minimum Temperature

> 0°C

≤ 2°C

≤ 0°C

< -2°C

< -10°C

< -20°C

< -30°C

Extreme values and degree days are also available.

Spatial coverage and resolution:

Canada, point locations.

Temporal coverage and resolution:

The data is presented as 30-year average and has a decadal time step: 1941-1970, 1951-1980, 1961-1990, 1971-2000 and 1981-2010 periods.

The data will continue to be updated every decade.

Information about observations (number, homogeneity)

The number of active stations changed over time. The following figure from Mekis et al. (2018) is presenting the locations of the surface weather stations across Canada with a Needs Index map in the background as of September 2016.

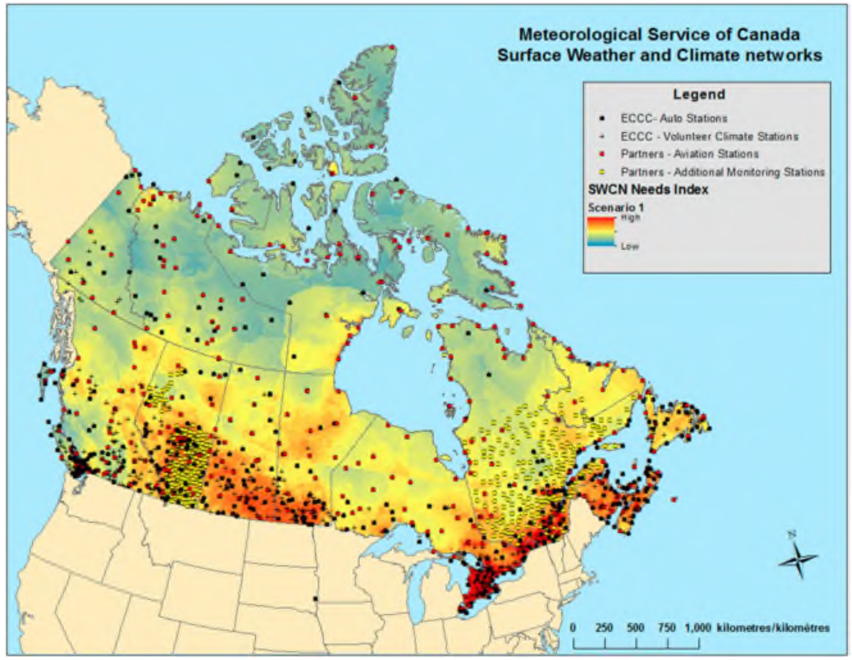


Figure 1. Surface weather stations across Canada, as of September 2016, with a Needs Index map in the background. For further details on station network evolution see Mekis et al. 2018. [Source: Mekis et al., 2018].

Stations over Northern Canda with temperature measurements are the ECCC atomatic stations, the ECCC Volunteer Climate Stations and stations from the Aviation Monitoring Station network (which include automated and staffed weather stations) operated by NAV CANADA and the Department of National Defence (DND).

The following table presents the number of stations per region in the Northen Canada for the 1981-2010 normals (the number varies with the period of the record).

Region	No. stations 1981-2010
Yukon	19 (BEAVER CREEK A; BLANCHARD RIVER; BURWASH A; CARCROSS; DAWSON A; DRURY CREEK; FARO A; MAYO A; MAYO ROAD; MCQUESTEN; OLD CROW A; OTTER

	FALLS NCPC; PELLY RANCH; STEWART CROSSING; TAKHINI RIVER RANCH; TESLIN A; WATSON LAKE A; WHITEHORSE A; WHITEHORSE RIVERDALE)
NWT	11 (FORT LIARD A; FORT MCPHERSON A; FORT SIMPSON A; FORT SMITH A; HAY RIVER A; INUVIK A; NORMAN WELLS A; SACHS HARBOUR A; TUKTOYAKTUK A; ULUKHAKTOK A; YELLOWKNIFE A)
Nunavut	24 (ALERT; ARVIAT A; BAKER LAKE A; CAMBRIDGE BAY A; CAPE DORSET A; CHESTERFIELD INLET A; CLYDE A; CORAL HARBOUR A; EUREKA A; GJOA HAVEN A; HALL BEACH A; IGLOOLIK; IGLOOLIK A; IQALUIT A; KUGAARUK A; KUGLUKTUK A; LUPIN A; NANISIVIK A; POND INLET A; RANKIN INLET A; REPULSE BAY A; RESOLUTE CARS; TALOYOAK A; WHALE COVE A)
North Quebec	3 (LA GRANDE RIVIERE A; KUUJJUARAPIK A; KUUJJUAQ A)
Labrador	4 (CARTWRIGHT; GOOSE A; MAKKOVIK A; NAIN A; WABUSH LAKE A)

Methodology

The MSC computation of normal follows WMO standard procedure, which has evolved with the time. For temperatue, (1) the normal are computed over a 30 year period of consecutive records, starting January 1st and ending December 31st, (2) they are arithmetic means calculated for each month of the year from daily data with a limited number of allowable missing values, (3) a month was not used if more than 3 consecutive days or more than a total of 5 days were missing (its corresponding year-month mean is not computed and it is considered missing). Normal values were calculated as the mean for each month from all the individual months in the period of 30 years that sufficiently fulfilled the requirement. The calculation method for the variables that counts the days has changed in new WMO standards:

(a) The count of values for each individual month is calculated, and converted to a percentage of days with available observations. (For example, if there were 25 days with observations in February 1991 and there were 22 days with temperatures ≥ 30 °C, the value for February 1991 is calculated as 88%).

(b) The average percentage count for each month with sufficient available data within the 1991–2020 period is calculated.

(c) This average is then reconverted to an average number of days for the month by multiplying the average percentage by the number of days in the month. February percentages should be multiplied by 28.25.

(d) The sum of the monthly normals as per above instructions constitutes the annual normal.

Information about the technical and scientific quality

This dataset is produced following the standard WMO procedure. MSC is QC the Normals but the QC of the data used in the Normal computation is done by the owers of the sites.

Limitations and strengths for application in North Canada

It is a challenge to sustain a cost-effective observing system over Norther Canada because of a large part of the teritory is constituted by remote areas (it is hard for technicians to fly to the site for maintenance, and they often have to wait for the thaw). The special climatic conditions produce a large risk of power and telecommunication outages. Concequently, observations in Nortehrn Canada are sparse and records are often incomplete. Therefore, apart from any uncertainty due to site, instrument, or observing program changes, or general representativeness of the observing site with the surrounding region, the normals for most locations will have some uncertainty due to the fact that the observations are not complete for the 30-year period.

References to documents describing the methodology or/and the dataset

https://climate.weather.gc.ca/doc/Canadian_Climate_Normals_1981_2010_Calculation_Information.pdf

https://climate.weather.gc.ca/doc/Canadian_Climate_Normals_1971_2000_Calculation_Information.pdf

https://climate.weather.gc.ca/doc/Canadian_Climate_Normals_1961_1990_Calculation_Information.pdf

https://drive.google.com/open?id=1M2W8t7bG1JmseLEgm90G8O7hAc718RBD

https://drive.google.com/open?id=1OLqRySaAdJSpajkEGmOAHd7zKR2FW72s

Link to download the data and format of data:

Most recent Normals (1981-2010):

GeoJSON and CSV on CCCS/ECCC: https://climate-change.canada.ca/climate-data/#/climate-normals

CSV via MSC: https://dd.weather.gc.ca/climate/observations/normals/

CSV via ClimateData.ca: https://climatedata.ca/explore/variable/?var=weather-stations

Note: A smaller number of stations qualify for Normals compared to earlier Normals decadal publications.

For all Normals periods:

CSV via CDO/MSC/ECCC: https://climate.weather.gc.ca/climate_normals/index_e.html

Publications including dataset evaluation or comparison with other data in northern Canada

Information not available.

7.1.3 *Dataset: MSC Daily Climate Records (LTCE, Long Term Climate Extremes) – temperature*

Overview

The daily climate records database, also known as Long Term Climate Extremes, was developed to address the fragmentation of climate information due to station changes (opening, closing, relocation, etc.) over time. For approximately 750 locations in Canada, "virtual" climate stations have been developed by joining (threading) climate data for an urban location, from nearby stations to make long-term records. For each long-term record, the extremes (record values) of daily maximum/minimum temperatures, total precipitation and snow for each day of the year were identified. This dataset identifies, for example, the highest temperature over the record for each day of the year for the selected area (e.g., the highest daily maximum temperature recorded in the Tuktoyaktuk area for May 31st was 20.9°C and was reached in 1985).

Provider's contact information

Environment and Climate Change Canada

climatatlantique-climateatlantic@ec.gc.ca

Licensing

Open Government Licence - Canada.

Variable name and units:

Highest Maximum temperature (°C) and the year when the record was reached

Highest Minimum temperature (°C) and the year when the record was reached

Lowest Maximum temperature (°C) and the year when the record was reached

Lowest Minimum temperature (°C) and the year when the record was reached

Spatial coverage and resolution:

Canada, point locations.

Temporal coverage and resolution:

The data is available for each day of the year. The record value over the entire recorded period and the year when the record was reached are provided. The data will continue to be updated regularly.

Information about observations (number, homogeneity)

The following table presents the number of stations per region and variable

Region	Temperature
Yukon	14
NWT	23
Nunavut	28
North Quebec	7
Labrador	10

Methodology

The dataset was developed using daily values from MSC stations. For climate stations operating on a 24-hour basis, since July 1, 1961, the climatological day for temperature and precipitation ends at 0600Z of the next day. From June 1, 1957, to June 30, 1961, the climatological day for precipitation and maximum temperature ended at 1200Z of the next day. The climatological day for minimum temperatures ended at 0000Z of the next day. Before June 1, 1957, the climatological day for precipitation and maximum temperature ended at 1200Z of the next day. The climatological day for minimum temperatures ended at 0000Z of the next day.

At locations with no hourly observations, observation times are generally morning and evening local time. In general, the climatological day for precipitation and maximum temperature ends at the morning observation of the next day. The climatological day for minimum temperatures ends at the afternoon observation of the current day. For sites reporting only once per day, the calendar day rather than climatological day applies.

Each of the City Page locations of weather.gc.ca has a Virtual climate station. A virtual climate station is the result of threading (joining) together climate data from nearby current and historical stations to build a long-term dataset. All available data within a 20 km radius of each urban center was searched and catalogued (some latitude was permitted to include data which was close to the 20 km cut-off during the subjective review stage). The starting point is a representative, currently active station in the area of the urban center. These data were followed backward in time until it was no longer available or until it was replaced by a higher quality dataset from the same station. When the earliest or end point of a thread fragment was reached, an alternate from the catalogue was chosen, keeping in mind data quality, proximity to the prior station and any gaps in data length. This process was repeated until the thread extended back in time as far as possible.

In a small percentage of cases where there is no currently active climate station within 20 km of the urban center, an alternate station may have been chosen from representative stations at a maximum radius of 35 km**.**

Information about the technical and scientific quality

This dataset represents summaries of Environment and Climate Change Canada's official station observations.

Limitations and strengths for application in North Canada

Observations are sparse in the northern Canada and the records have missing data.

References to documents describing the methodology or/and the dataset

Technical documentation

Frequently asked questions about long term climate extremes for Canada

Link to download the data and format of data:

GeoJSON and CSV on CCCS/ECCC: https://climate-change.canada.ca/climate-data/#/daily-climate-records

Publications including dataset evaluation or comparison with other data in northern Canada

There are no publications that evaluate this dataset in northern Canada.

7.1.4 *Dataset: ECMWF 5th Generation Atmospheric Reanalysis (ERA5) - temperature*

Overview

This document provides an overview of the surface temperature products (T2m) of ERA5, in the context of the larger ERA5 dataset. As background, ERA5 is the 5th generation of the global atmospheric reanalysis (the latest – it replaces the ERA-Interim reanalysis) produced by the Copernicus Climate Change Service at ECMWF, covering the period from January 1950 to present. It provides hourly data on many atmospheric, land-surface and sea-state parameters together with estimates of uncertainty.

Provider's contact information

ERA5 is produced by the Copernicus Climate Change Service (C3S) at ECMWF.

Copernicus User support (copernicus-support@ecmwf.int (external to C3S)).

Licensing

Licence: Copernicus (Licence agreement information can be found here or here).

Dataset citable as: Copernicus Climate Change Service (C3S) (2017): ERA5: Fifth generation of ECMWF atmospheric reanalyses of the global climate . Copernicus Climate Change Service Climate Data Store (CDS), date of access. https://cds.climate.copernicus.eu/cdsapp#!/home

Variable name and units:

The 2 m temperature product (K) of ERA5 over Northern Canada is the main focus of this document. This parameter has units of kelvin (K). Temperature measured in kelvin can be converted to degrees Celsius (°C) by subtracting 273.15. **Hourly** and **monthly** subsets are available.

The ERA5 2 m temperature product can be found as follows:

- Select 2 m temperature from hourly data on single levels from 1950 to 1978,
- Select 2 m temperature hourly data on single levels from 1979 to present,
- Select 2 m temperature monthly averaged data on single levels from 1950 to 1978,
- Select 2 m temperature monthly averaged data on single levels from 1979 to present,

In ERA5, hourly "2 m temperature" is an instantaneous parameter provided at hourly time step from the analyses. Monthly data is pre-calculated as monthly-mean averages from hourly data.

"Minimum and maximum temperature at 2 metres since previous post-processing" are the maximum and minimum in the last hour (computed from 5 time steps of 12 minutes), and are available from the forecasts only. However, ERA5 forecast model has a cold bias in the lower regions of the troposphere over most parts over the globe, which is at least partially corrected by the analysis system. It is therefore recommended to use the instantaneous hourly (analyzed) "2 m temperature" to construct the minimum and maximum over longer periods, such as a day. ERA5 also offers hourly and monthly for 2 m dew point temperature and skin temperature (follow the links provided for 2 m temperature if interested in those variables). The following table summarizes the single-level temperature data available in ERA5.

Name	Units	Description
2 m temperature	K	Temperature of air at 2 m above the surface of land, sea or inland waters. 2 m temperature is calculated by interpolating between the lowest model level and the Earth's surface, taking account of the atmospheric conditions. Temperature measured in kelvin can be converted to degrees Celsius (°C) by subtracting 273.15.
Maximum 2 m temperature since previous post-processing	K	This parameter is the highest temperature of air at 2 m above the surface of land, sea or inland water since the parameter was last archived in a particular forecast. 2 m temperature is calculated by interpolating between the lowest model level and the Earth's surface, taking account of the atmospheric conditions. This parameter has units of kelvin (K). Temperature measured in kelvin can be converted to degrees Celsius (°C) by subtracting 273.15.
Minimum 2 m temperature since previous post-processing	K	This parameter is the lowest temperature of air at 2 m above the surface of land, sea or inland waters since the parameter was last archived in a particular forecast. 2 m temperature is calculated by interpolating between the lowest model level and the Earth's surface, taking account of the atmospheric conditions. See further information. This parameter has units of kelvin (K). Temperature measured in kelvin can be converted to degrees Celsius (°C) by subtracting 273.15.
2 m dew point temperature	K	Temperature to which the air, at 2 m above the surface of the Earth, would have to be cooled for saturation to occur. It is a measure of the humidity of the air. Combined with temperature and pressure, it can be used to calculate the relative humidity. 2 m dew point temperature is calculated by

		interpolating between the lowest model level and the Earth's surface, taking account of the atmospheric conditions. Temperature measured in kelvin can be converted to degrees Celsius (°C) by subtracting 273.15.
Skin temperature	K	Temperature of the surface of the Earth. The skin temperature is the theoretical temperature that is required to satisfy the surface energy balance. It represents the temperature of the uppermost surface layer, which has no heat capacity and so can respond instantaneously to changes in surface fluxes. Skin temperature is calculated differently over land and sea. Temperature measured in kelvin can be converted to degrees Celsius (°C) by subtracting 273.15.

More broadly, ERA5 provides four main subsets available: with **hourly** and **monthly** sampling on **pressure levels** (upper air fields) and **single levels** (atmospheric, ocean-wave and land surface quantities.

Spatial coverage and resolution:

ERA5 2 m temperature, like all ERA5 data, is a global dataset. The atmospheric data is available on a regular latitude-longitude grid at 0.25° x 0.25° resolution (converted from native reduced-Gaussian grid resolution of approximately 31 km x 31 km), and on 37 pressure levels.

Temporal coverage and resolution:

ERA5 2 m temperature data, like all ERA5 data, is available from 1950 to present (split into two entries: primary from 1979 onwards and a back extension from 1950-1978). The back extension is a preliminary version that has been released in 2020, and an updated version (that corrects some issues in the tropics) will appear around the end of 2021.

The data is available at hourly and monthly sampling (see above).

ERA5 2 m temperature, like all ERA5 data, is updated daily with a latency of about 5 days in an early product and with a final release 2 to 3 months later.

Information about observations (number, homogeneity)

Like any other climate variable from a reanalysis product, 2 m temperature is potentially influenced by all observations assimilated into the product. ERA5's data assimilation uses observations for all geophysical quantities from about 0.75 million observations per day in 1979 and about 24 Million in 2018. The 2D-OI uses surface observations at 'screen level'. The online technical documentation provides tables with the satellite and in-situ observations used as input into ERA5.

The satellite measurements used in ERA5 are: temperature, humidity, ozone, column water vapour, cloud liquid water, precipitation, ocean surface wind speed, wind vector, soil moisture, and wave height.

The in-situ data is provided by WMO WIS and consists in measurements for: surface pressure, temperature, humidity, wind, wind profiles and snow depth. Figure 4 from Hersbach *et al*., (2020) presents the conventional observations assimilated per day in ERA5 during the period 1979–2018.

ERA5 assimilates rain rates from ground-based radar–gauge composite observations from 2009, and snow cover (NH only) from NOAA/NESDIS IMS.

The time evolving nature of the assimilated observations means that caution should be employed when using ERA5 to evaluate long-term variability and trends in 2 m temperature over regions such as Northern Canada.

Methodology

Like any other climate variable from a reanalysis product, ERA5 2 m temperature is strongly influenced by the data assimilation methodology. ERA5 is produced using 4D-Var data assimilation with the ECMWF's Integrated Forecast System (IFS) model (CY41R2). The forecast model has 137 hybrid sigma/pressure (model) levels in the vertical, with the top level at 0.01 hPa. The IFS is coupled to a land-surface model and an ocean wave model. The model uses as boundary conditions the sea surface temperature, the sea ice cover, the greenhouse gases, the aerosols, and the total solar irradiance. Climate variables are offered from the atmospheric model, the surface model and the wave model.

The ERA5 dataset contains one (31 km) high resolution realization (HRES) and a reduced resolution 10-member ensemble (EDA). The model time step is 12 minutes for the HRES and 20 minutes for the Ensemble Data Assimilation (EDA), though occasionally these numbers are adjusted to cope with instabilities. Climate variables result from analyses and short (18 hours) forecasts, initialized twice daily from analyses at 06 and 18 UTC. Most of climate variables from the analyses are also available from the forecasts. However, there are several climate variables from forecast, e.g., mean rates and accumulations that are not available from the analyses. More information on the differences between analysis, forecast, instantaneous, accumulated and mean rate parameters are provided on:

https://confluence.ecmwf.int/pages/viewpage.action?pageId=85402030.

The ERA5 atmospheric analysis is based on a hybrid incremental 4-dimensional variational data assimilation (4D-Var) system including variational bias correction (VarBias). The method finds the best estimate of the state of the atmosphere/land/surface ocean within an assimilation time window, given a background forecast valid at the start of the window and observations falling within that window. The 4D-Var data assimilation uses 12 hour windows from 09 UTC to 21 UTC and 21 UTC to 09 UTC (the following day).

Uncertainty estimate: An uncertainty estimate is sampled by a 10-member lower-resolution Ensemble Data Assimilation (EDA) which provides background-error estimates for the deterministic HRES 4D-Var Data Assimilation system. The analysis method is the same for each EDA member and follows that of the HRES. Each member (except the control) is run with different random perturbations added to the observations. Likewise, the model physical tendencies are perturbed in the short forecasts that link subsequent analysis windows. Ensemble mean and spread have been pre-computed for convenience. Such uncertainty estimates are closely related to the information content of the available observing system which has evolved considerably over time. They also indicate flow-dependent sensitive areas. To facilitate many climate applications, monthly-mean averages have been pre-calculated too, though monthly means are not available for the ensemble mean and spread.

2 m temperature is the temperature of air at 2 m above the surface of land, sea or inland waters, and it is calculated by interpolating between the lowest model level and the Earth's surface, taking account of the atmospheric conditions.

A strength of reanalysis for analysis of ERA5 2 m temperature and other variables is the use of a consistent assimilation/forecast methodology throughout the analysis cycle. Thus, even though the observations assimilated are evolving in time (see above), the data assimilation approach can be considered fixed throughout the products analysis period, which adds to the homogeneity of the dataset.

Information about the technical and scientific quality

ERA5 2 m temperature represents one of the products of the latest global atmospheric reanalysis produced by Copernicus Climate Change Service at ECMWF. It is archived at a shorter (hourly) time step, has a finer spatial resolution, uses a more advanced assimilation system and includes more sources of data than previous versions. It is accompanied by extensive technical documentation and two principal scientific documentation papers. A list of 'known issues' is maintained at the online documentation (https://confluence.ecmwf.int/display/CKB/ERA5%3A+data+documentation#ERA5:datadocumentation-Knownissues).

A prerelease quality control revealed some problems affecting the performance in the tropics (tropical cyclones are too intense) and that the deep soil moisture tends to be too dry for the 1950-1978 dataset. A new version of the data should gradually become available by late 2021. This issue will be of little direct relevance to ERA5 2 m temperature in Canada's north, but the user should be aware of the reason for this update.

Information on model improvement: The forecast model of the ERA5 is the IFS Cycle 41r2. In the ten-year period between ERA-Interim (Cy31r2) and ERA5 (Cy41r2), many significant improvements have been made to the representation of atmospheric physical processes (see Section 4 of Hersbach *et al*., (2020)). ERA5 2 m temperature will be influenced by several changes to ERA5's land-surface model and parameterization schemes. ERA5's HTESSEL land surface scheme (Balsamo et al., 2015) accounts for seasonally varying monthly vegetation maps specified from a MODIS-based satellite dataset. In addition, an enhanced snowpack parameterization allows a more realistic timing of runoff and terrestrial water storage variations and a better match of the albedo to satellite products. The chosen parameterization for lakes (FLake), allows consideration of both subgrid and resolved water bodies, which is potentially relevant for the lake-enriched Canadian sub-Arctic. This series of changes contributes to significant improvements in the soil moisture and land surface fluxes consistency, which allowed for the usage of satellite data in ERA5 to analyze soil moisture. This will influence the surface energy budget and hence ERA5 2 m temperature in Canada's north. Some important improvements in the wave model include: an updated model bathymetry with a more recent version of ETOPO2 and a revised unresolved bathymetry scheme. Some of these changes will also affect ERA5 2 m temperature in coastal regions as well as better accounting for wave propagation along coastlines and better modelling of the impact of previously unresolved features like islands and narrow embayments.

Limitations and strengths for application in North Canada

ERA5 is a new atmospheric reanalysis and there are not available scientific evaluations of the dataset dedicated specifically to North Canada. However, it should be noted that in North Canada, there are currently no sub-daily records over a long historical period for many weather stations. Reanalyses data with hourly output cover this gap and, with suitable investigation and calibration (downscaling), could be valuable particularly for hydrological models and sub-daily extremes analyses. Such a comparison could be assisted by the fact that unlike other reanalysis ERA5 assimilate directly surface temperature from stations.

As for all gridded data, observed values of 2 m temperature at local scales can differ from the values provided by the gridded dataset, which represent a statistical summary of the area surrounding a grid point. Also, as mentioned above, changes in the amounts and types of observational data that are assimilated may produce artificial trends or variability in 2 m temperature and other reanalysis variables. For ERA5 this has been observed for wind in the boundary layer (Hersbach *et al*., 2020).

Some general observed issues:

- Up to once or twice per year, the analyzed near-surface (e.g., 10 m) winds in ERA5 suffer from a problem of extremely large wind speeds; the largest speeds seen so far are of order 300 ms $^{-1}$. The effect of this on 2 m temperature has not been investigated.
- In mountainous regions above about 1,500 m, the snow depth is unrealistically large. The effect of this on 2 m temperature has not been investigated.

References to documents describing the methodology or/and the dataset

Hersbach, H., B. Bell, P. Berrisford, G. Biavati, A. Horányi, J. Muñoz Sabater, J. Nicolas, C. Peubey, R. Radu, I. Rozum, D. Schepers, A. Simmons, C. Soci, D. Dee, J-N. Thépaut, 2018: ERA5 hourly data on single levels from 1979 to present. Copernicus Climate Change Service (C3S) Climate Data Store (CDS). (Accessed on < 29-Apr-2019 >), https://doi.org/10.24381/cds.adbb2d47

Hersbach, H., B .Bell, P. Berrisford, S. Hirahara, A. Horányi, J. Muñoz-Sabater, J. Nicolas, C. Peubey, R. Radu, D. Schepers, A. Simmons, C. Soci, S. Abdalla, X. Abellan, G. Balsamo, P. Bechtold, G. Biavati, J. Bidlot, M. Bonavita, G. Chiara, P. Dahlgren, D. Dee, M. Diamantakis, R. Dragani, J. Flemming, R. Forbes, M. Fuentes, A. Geer, L. Haimberger, S. Healy, R.J. Hogan, E. Hólm, M. Janisková, S. Keeley, P. Laloyaux, P. Lopez, C. Lupu, G. Radnoti, P. Rosnay, I. Rozum, F. Vamborg, S. Villaume, and J.-N. Thépaut, 2020: The ERA5 global reanalysis. Quarterly Journal of the Royal Meteorological Society, 146(730), 1999–2049. https://doi.org/10.1002/qj.3803.

Online technical documentation: **https://confluence.ecmwf.int/display/CKB/ERA5%3A+data+documentation**

Link to download the data and format of data:

Data Access: Copernicus | NCAR | ECMWF

ERA5 is available in GRIB1 and NetCDF formats

Link to download hourly and monthly data on Copernicus:

- hourly data on single levels from 1950 to 1978,
- hourly data on single levels from 1979 to present,
- hourly data on pressure levels from 1950 to 1978,
- hourly data on pressure levels from 1979 to present,
- monthly averaged data on single levels from 1950 to 1978,
- monthly averaged data on single levels from 1979 to present,
- monthly averaged data on pressure levels from 1950 to 1978,
- monthly averaged data on pressure levels from 1979 to present.

Publications including dataset evaluation or comparison with other data in Canada

Tarek, M., F.P. Brissette, and R. Arsenault, 2020: Evaluation of the ERA5 reanalysis as a potential reference dataset for hydrological modelling over North America. *Hydrology and Earth System Sciences,* 24(5), 2527-2544. (It *compares ERA5 and ERA-Interim with stations in US and Canada south of 60º latitude*).

Sheridan, S.C., C.C. Lee, and E.T. Smith, 2019: A comparison between station observations and reanalysis data in the identification of extreme temperature events. *Geophysical Research Letters,* 47(15), e2020GL088120. (*It compares observations, ERA5, ERA5-LAND, and NARR, in the United States and Canada- only a very small number of stations are in North Canada*).

Betts, A.K., D.Z. Chan, and R.L. Desjardins, 2019: Near-surface biases in ERA5 over the Canadian Prairies. Frontiers in Environmental Science, 7 (129). (*ERA5 is compared with hourly data for 4 stations in Saskatchewan, Canada*).

Cao, B., X. Quan, N. Brown, E. Stewart-Jone, and S. Gruber, 2019: GlobSim (v1.0): deriving meteorological time series for point locations from multiple global reanalyses. Geosci. Model Dev., 12, 4661–4679, https://doi.org/10.5194/gmd-12-4661-2019 (*2 m temperature from ERA5 is compared with ERA-Interim, JRA-55 and MERRA-2 at a site located near the north shore of Lac de Gras in the Northwest Territories, Canada*)

7.1.5 *Dataset: Adjusted and homogenized Canadian climate data (AHCCD) – 3rd Generation of Temperature data*

Overview

Adjusted and homogenized Canadian climate data (AHCCD) consist of daily, monthly, seasonal and annual means of homogenized daily maximum, minimum and mean surface air temperatures for more than 330 locations in Canada. The data at stations incorporate adjustments (derived from statistical procedures) to the original historical station data to account for discontinuities from non-climatic factors, such as instrument changes or station relocation. Daily observations from nearby sites were often merged into a single record to create a long-time series. AHCCD was developed for use in climate research, including climate change studies.

Provider's contact information

Environment and Climate Change Canada

Contact cccs-ccsc@ec.gc.ca for information related to monthly, seasonal and annual data.

Contact ahccd@ec.gc.ca for information relate do daily data.

Licensing

Open Government Licence - Canada.

The end-user licence for Environment and Climate Change Canada's data servers specifies the conditions of use of this data.

Variable name and units:

Maximum temperature in degree Celsius (°C);

Minimum temperature in degree Celsius (°C);

Mean temperature in degree Celsius (°C);

Spatial coverage and resolution:

Canada, point location.

Temporal coverage and resolution:

Time period varies per station with data for most stations in the North starting in 40’s or 50’s and ending in 2017.

The data is available at **daily, monthly, seasonal, annual** time steps.

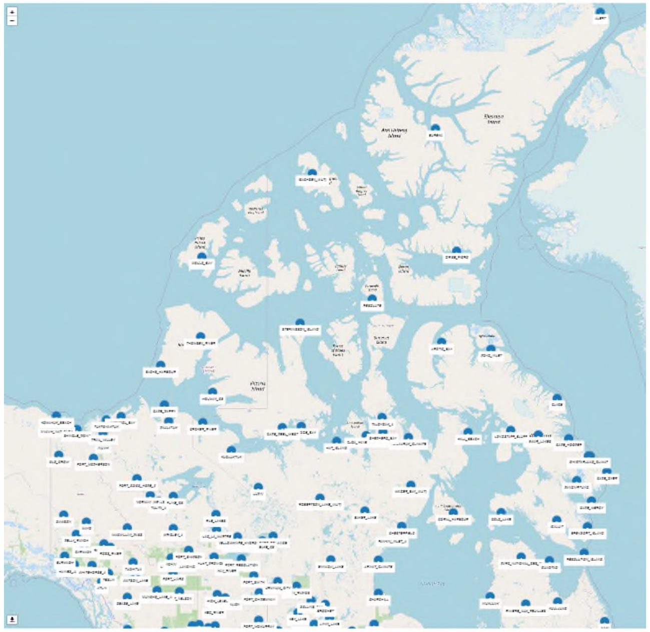
The data will continue to be updated regularly.

Information about observations (number, homogeneity)

This new dataset includes the observations taken at Reference Climate Stations and from some of the NavCan sites, which are used to extend past climate observations into recent times. The following table presents the number of stations per region and variable:

Region	Temperature
Yukon	18
NWT	31
Nunavut	40
North Quebec	15
Labrador	8

The figure below show the position of the stations for northern Canada.



Methodology

The daily AHCCD station data are derived from observations made at the weather stations from the Meteorological Service of Canada (MSC) and use the same ID as MSC stations; this allows users to compare the raw station data to homogenized and adjusted data. The AHCCD dataset was developed for use in climate research, including climate change studies that needs long-term data records. Over long periods, meteorological records are subject of changes (e.g., site exposure, location, instrumentation, observer, and observing procedures) that are not related to climate. These non-climatic changes were detected and removed in AHCCD using statistical procedures.

The daily data were developed first for daily maximum temperature and daily minimum temperature using MSC daily observations. The MSC daily data are derived from two sources depending on if the station has an automatic hourly sensor (most do now):

- hourly (temperatures are reported every hour and then the maximum temperature of the day and minimum temperature of the day are reported as daily max/min values), and
- daily (using a thermometer just for maximum temperature and a thermometer just for minimum temperature that are reported twice a day).

In AHCCD data, the daily minimum temperatures were adjusted for the change in observing time in 1961 at principal stations. Parallel daily data were used to detect non-climatic shifts when the observations of nearby sites were merged together. Daily temperatures were adjusted using a Quantile-Matching procedure to remove inhomogeneities if needed. The procedures are described in Vincent *et al*., (2020).

Daily mean temperatures were calculated as the average of daily minimum and maximum temperatures. The monthly values for maximum (or minimum) temperature were computed as the average of daily values over the month and were set to missing if more than eight random or five consecutive daily values in the month were missing. Annual and seasonal means were calculated from the monthly values and retained if all related monthly values are non missing. The seasons are defined as winter (December of the previous year to February of the current year), spring (March–May), summer (June–August), and autumn (September–November):

Series of annual and seasonal mean temperatures were tested separately for homogeneity using neighbour observations as a reference series.

Information about the technical and scientific quality

The data were quality controlled (information is provided in Vincent *et al*., (2020)) and use up-to-date methods. For temperature, the third version was released in December 2020. The data will continue to be updated periodically.

The dataset is accompanied by a technical documentation and a scientific paper.

Limitations and strengths for application in North Canada

The data constitute the longest records at stations that were adjusted to eliminate non-climatic shifts and take into account the change in observing time. Data availability over most of the Canadian Arctic is restricted to the mid-1940s to 2017. This dataset is usually used to validate other historical datasets estimated using various models or methodologies.

The major limitation for applications in the North is the number restrained of locations with a record. As any data at stations, it has missing values, which may vary by variable, station and time. The missing values in daily records were taken into account when monthly, seasonal and annual data was developed (see methodology section).

References to documents describing the methodology or/and the dataset

Vincent, L.A., M.M. Hartwell, and W. L. Wang, 2020: A Third Generation of Homogenized Temperature for Trend Analysis and Monitoring Changes in Canada's Climate. Atmosphere-Ocean. https://doi.org/10.1080/07055900.2020.1765728.

Technical documentation: http://crd-data-donnees-rdc.ec.gc.ca/CDAS/products/AHCCD/Temperature_Documentation_Gen3.doc

Link to download the data and format of data:

For daily data:

http://crd-data-donnees-rdc.ec.gc.ca/CDAS/products/AHCCD_daily/ (.txt on CRD/ECCC webpage)

https://climatedata.ca/download/#ahccd-download (this will be available in the following months)

For monthly, seasonal and annual data:

https://climate-change.canada.ca/climate-data/#/adjusted-station-data (GeoJSON and CSV on CCCS/ECCC webpage)

http://crd-data-donnees-rdc.ec.gc.ca/CDAS/products/AHCCD/ (.txt on CRD/ECCC webpage)

On MSC Datamart at https://dd.weather.gc.ca/climate/ahccd/geojson/historical/ (GeoJSON)

Publications including dataset evaluation or comparison with other data in northern Canada.

This dataset is usually used as reference in the evaluation of climate variables from other datasets.

7.1.6 *__Dataset__: Canadian Gridded Temperature Anomalies (CANGRD)*

Overview

This document focuses on temperature data from Canadian gridded anomalies (CANGRD) dataset. The dataset provides historical gridded temperature and precipitation anomalies, interpolated from adjusted and/or homogenized climate station data at a 50 km resolution across Canada. The anomalies are computed as the departure from a mean reference period (1961-1990) and are used to produce the Climate Trends and Variations Bulletin (CTVB).

Provider's contact information

Environment and Climate Change Canada (Contact the Climate Services Support Desk)

Electronic Mail Address at CRD: f.ccds.info-info.dscc.f@ec.gc.ca

Licensing

Open Government Licence - Canada.

The end-user licence for Environment and Climate Change Canada's data servers specifies the conditions of use of this data.

Variable name and units:

Maximum daily temperature anomaly in degree Celsius (°C);

Minimum daily temperature anomaly in degree Celsius (°C);

Mean daily temperature anomaly in degree Celsius (°C);

Spatial coverage and resolution:

Canada, 50 km spatial resolution, polar stereographic grid.

Temporal coverage and resolution:

Temperature anomalies: 1948 - 2020

Data is available at monthly, seasonal, and annual time steps.

Information about observations (number, homogeneity)

CANGRD is based on AHCCD for historical climate observations from 1948 for all of Canada until 2020 for temperature (based on the 3rd generation temperature AHCCD). AHCCD has a small number of stations in North Canada, and the distance between stations is large.

Methodology

The monthly, seasonal, annual mean daily maximum temperature, and annual mean daily minimum temperature anomalies are computed at each station by subtracting the relevant baseline average (defined as average over 1961-1990 reference period) from the relevant monthly, seasonal, and annual values. The anomalies are interpolated to the evenly spaced (50 km) grid using the Gandin's Optimal Interpolation. The grid box values of mean temperature departures are the average of those for daily minimum and maximum.

Information about the technical and scientific quality

A positive aspect of this dataset is the use of adjusted and/or homogenized data from the AHCCD (homogenized temperature data). This station-based datasets have undergone rigorous quality control, and have been adjusted for identified inhomogeneities caused by station relocation, changes in instrumentation and in observing practices.

The dataset uses classical methods for the interpolation. In general, results from the interpolation of anomalies are better than those from actual values because anomalies vary less in space. Another positive aspect of interpolating anomalies instead of actual values is related to temperature inversions in Yukon. Gandin Optimal Interpolation is a classical interpolation method that is also used in other reanalyses. This method does not take into consideration the elevation, which is indicated when interpolating temperature. Generally, interpolation of absolute temperature values in Yukon region is challenging because of the presence of semi-permanent temperature inversions in that region. Inversions make the temperature to be colder in valleys than at elevation, which is opposite to normal situations; consequently, the temperature lapse rate cannot be used uniformly over the domain. However, interpolation of anomalies is less affected, and it offers a good option for such complex regions. The correlation coefficients for anomalies in maximum temperature at the nearest grid and station are generally larger than 0.85 in the northern part of the country. However, it is expected that the errors increase with the distance from the station.

Data is available in .grd format on the CRD webpage. This format is not a standard format. Less advanced users should use the CCCS webpage to download GeoTIFF format. CCCS webpage offers the possibility to download the data in NetCDF format as well.

The dataset is accompanied by a technical report.

Limitations and strengths for application in North Canada

The data was constructed to describe large-scale climate change over Canada and for national-scale assessments. Interpolation errors are expected to rise with the increase in the distance between stations. Because there is a small number of stations available in North Canada (most of them in coastal and valley locations), interpolation errors in inland regions and in Yukon high elevation regions can be significant. Consequently, the result should be interpreted as a mean change over a large region (e.g., the mean change over the North or a territory), and it is not recommended to be used for local applications.

Because it provides anomalies, not actual temperature values, it cannot be used to compute other climate indices.

Some users can find the data in .grd difficult to use because of its custom projection and format.

References to documents describing the methodology or/and the dataset

Environment and Climate Change Canada (2018). Canadian Gridded Temperature Anomalies CANGRD. Accessed August 16 2018.

Vincent, L.A., M.M. Hartwell, and X.L. Wang, 2020. A third generation of homogenized temperature for trend analysis and monitoring changes in Canada's climate, Atmosphere-Ocean., 58:3, 173-191, doi:10.1080/07055900.2020.1765728.

Link to download the data and format of data:

https://climate-change.canada.ca/climate-data/#/historical-gridded-data (GeoTIFF and NetCDF on CCCS/ECCC webpage)

GeoTIFF data available on the MSC Datamart

http://crd-data-donnees-rdc.ec.gc.ca/CDAS/products/EC_data/CANGRD/ (gridded data .grd on CRD/ECCC webpage)

Publications including dataset evaluation or comparison with other data in northern Canada

Rapaić, M., R. Brown, M. Markovic, and D. Chaumont, 2015: An Evaluation of Temperature and Precipitation Surface-Based and Reanalysis Datasets for the Canadian Arctic 1950–2010. Atmos. Ocean, 53(3), 283-303, 10.1080/07055900.2015.1045825. (*The paper compares CANGRD to several other gridded datasets and other coarse-resolution reanalysis*)

7.1.7 ***<u>Dataset</u>: The NOAA NCEP Climate Forecast System Reanalysis (CFSR) and Climate Forecast System Version 2 (CFSv2) - temperature***

Overview

This document provides an overview of the 2 m temperature products from the Climate Forecast system reanalysis (CFSR) and its operational extension CFSv2. The CFSR is a third-generation reanalysis product, developed by the National Oceanic and Atmospheric Administration's (NOAA) National Center for Environmental Prediction (NCEP), and it is using a global, high resolution, coupled atmosphere-ocean-land surface-sea ice system. The spatial resolution of the global atmospheric data is ~ 38 km (T382) and many atmospheric variables are provided at hourly and monthly temporal resolution.

Provider's contact information

CFSR is developed by the National Oceanic and Atmospheric Administration's (NOAA) National Center for Environmental Prediction (NCEP).

Contact name: DOC/NOAA/NESDIS/NCEI > National Centers for Environmental Information, NESDIS, NOAA, U.S. Department of Commerce

Contact email: Contact: cfs@noaa.gov

Licensing and citation

Please reference the following article when using the CFS Reanalysis (CFSR) data:

Saha, S., S. Moorthi, H. Pan, X. Wu, J. Wang, and Coauthors, 2010: The NCEP Climate Forecast System Reanalysis. Bulletin of the American Meteorological Society, 91, 1015–1057, doi:10.1175/2010BAMS3001.1.

For hourly data downloaded from UCAR RDA: **Saha**, S., et al. 2010. NCEP Climate Forecast System Reanalysis (CFSR) Selected Hourly Time-Series Products, January 1979 to December 2010. Research Data Archive at the National Center for Atmospheric Research, Computational and Information Systems Laboratory. https://doi.org/10.5065/D6513W89. Accessed dd mmm yyyy.

For monthly data downloaded from UCAR RDA: **Saha**, S., et al. 2010. NCEP Climate Forecast System Reanalysis (CFSR) Monthly Products, January 1979 to December 2010. Research Data Archive at the National Center for Atmospheric Research, Computational and Information Systems Laboratory. https://doi.org/10.5065/D6DN438J. Accessed dd mmm yyyy.

Please reference the following article when using the CFS Reforecast model or data:

Saha, S., S. Moorthi, X. Wu, J. Wang, S. Nadiga, P. Tripp, D. Behringer, Y. Hou, H. Chuang, M. Iredell, M.Ek, J. Meng, R. Yang, M.P. Mendez, H. van den Dool, Q. Zhang, W. Wang, M. Chen, and E. Becker, 2014: The NCEP Climate Forecast System Version 2, Journal of Climate, 27(6), 2185-2208, doi:10.1175/JCLI-D-12-00823.1.

For hourly data downloaded from UCAR RDA: **Saha**, S., et al. 2011, updated monthly. NCEP Climate Forecast System Version 2 (CFSv2) Selected Hourly Time-Series Products. Research Data Archive at the National Center for Atmospheric Research, Computational and Information Systems Laboratory. https://doi.org/10.5065/D6N877VB. Accessed dd mmm yyyy.

For monthly data downloaded from UCAR RDA: **Saha**, S., et al. 2012. NCEP Climate Forecast System Version 2 (CFSv2) Monthly Products. Research Data Archive at the National Center for Atmospheric Research, Computational and Information Systems Laboratory. https://doi.org/10.5065/D69021ZF. Accessed dd mmm yyyy.

Variable name and units:

The following table summarizes the name of the variables available at NCAR RDA as hourly time series.

Notation (name)	Units
TMP2M (2 m air temperature; instantaneous)	K
TMIN (2 m Minimum air temperature)	K
TMAX (2 m Maximum air temperature)	K
DPT (Dewpoint temperature)	K
TMPSFC (surface temperature; instantaneous)	K

Note: The forecast at the first time step (f00) of 3 minutes constitutes a spin up of the model physics, and IT IS NOT THE ANALYSIS.

Spatial coverage and resolution:

CFSR data, is a global dataset. All atmospheric variables are provided on the same horizontal regular latitude-longitude grid with a spatial resolution of ~38 km (T382).

Temporal coverage and resolution:

CFSR is covering the 01 Jan 1979 – 31 Mar 2011 period. The product was extended beyond 2011 as an operational real-time product, using the new version of the forecast system: NCEP's Climate Forecast System Version 2 (CFSv2). CFSR temperature data are available at an hourly time resolution and as monthly means.

Information about observations (number, homogeneity)

All available conventional and satellite observations were included in the CFSR. Satellite observations were used in radiance form and were bias corrected with "spin up" runs at full resolution, taking into account variable CO2 concentrations. This procedure enabled smooth transitions of the climate record due to evolutionary changes in the satellite observing system.

It is extremely difficult to assimilate 2 m temperature over land in systems like the CFSR. Therefore, surface temperature from stations is not assimilated in CFSR.

The CFSR uses the NCEP operational observation quality control procedures.

Methodology

The CFSR is a third generation reanalysis product, and it using global, high resolution, coupled atmosphere-ocean-land surface-sea ice system. It includes (1) coupling of atmosphere and ocean during the generation of the 6 hour guess field, (2) an interactive sea-ice model, and (3) assimilation of satellite radiances. The CFSR global atmosphere resolution is ~38 km (T382) with 64 levels. The global ocean is 0.25° at the equator, extending to a global 0.5° beyond the tropics, with 40 levels. The global land surface model has 4 soil levels and the global sea ice model has 3 levels. The CFSR atmospheric model contains observed variations in carbon dioxide (CO2), together with changes in aerosols and other trace gases and solar variations.

Information about the technical and scientific quality

The CSFR products are superior to previous NCEP reanalyses with respect to: improved model, finer resolution, advanced assimilation schemes, atmosphere-land-ocean-sea ice coupling, assimilates satellite radiances rather than retrievals, and accounts for changing CO2 and other trace gasses, aerosols, and solar variations.

Known CFSR data issues are explained in the August 2011 CFSRR Known Issues Technical Document.

Limitations and strengths for application in North Canada

GENERAL KEY STRENGTHS: Approaches the horizontal resolution of regional reanalyses like the NARR and Arctic System Reanalysis
GENERAL KEY LIMITATIONS: Ocean-atmosphere interactions are not used directly. Rather the information is used for background information. The actual reanalysis is uncoupled.

References to documents describing the methodology or/and the dataset

Saha, S., S. Moorthi, H. Pan, X. Wu, J. Wang, and Coauthors, 2010: The NCEP Climate Forecast System Reanalysis. Bulletin of the American Meteorological Society, 91, 1015–1057, doi:10.1175/2010BAMS3001.1.

Saha, S., S. Moorthi, X. Wu, J. Wang, S. Nadiga, P. Tripp, D. Behringer, Y. Hou, H. Chuang, M. Iredell, M.Ek, J. Meng, R. Yang, M.P. Mendez, H. van den Dool, Q. Zhang, W. Wang, M. Chen, and E. Becker, 2014: The NCEP Climate Forecast System Version 2, Journal of Climate, 27(6), 2185-2208, doi:10.1175/JCLI-D-12-00823.1**.**

Link to download the data and format of data:

The CFSR data (1979 to 2011) are available in GRIB-2 format and can be accessed in multiple ways.

NCEI NOMADS THREDDS Data Server: URL: https://nomads.ncdc.noaa.gov/thredds/cfsr.html

NOAA NOMADS FTP access: URL: ftp://nomads.ncdc.noaa.gov/CFSR/

At UCAR RDA data is grouped as follows:

NCEP Climate Forecast System Version 2 (CFSv2) Monthly Products (ds094.2)

NCEP Climate Forecast System Version 2 (CFSv2) Selected Hourly Time-Series Products (ds094.1)

NCEP Climate Forecast System Reanalysis (CFSR) Monthly Products, January 1979 to December 2010 (ds093.2)

NCEP Climate Forecast System Reanalysis (CFSR) Selected Hourly Time-Series Products, January 1979 to December 2010 (ds093.1)

Publications including dataset evaluation or comparison with other data in Canada

7.1.8 *Dataset: Modern-Era Retrospective analysis for Research and Applications, Version 2 (MERRA-2) - temperature*

Overview

This document provides an overview of the temperature data from the Modern-Era Retrospective analysis for Research and Applications, Version 2 (MERRA-2). MERRA-2 represents a third generation atmospheric global reanalysis produced by the Global Modeling and Assimilation Office (GMAO) at NASA. It begins in 1980 and it replaces the original MERRA reanalysis (Rienecker *et al*., 2011) using an upgraded version of the Goddard Earth Observing System Model, Version 5 (GEOS-5) data assimilation system. Alongside the meteorological data assimilation using a modern satellite database, MERRA-2 includes an interactive analysis of aerosols that feed back into the circulation, uses NASA's observations of stratospheric ozone and temperature, and takes steps towards representing cryogenic processes by including a representation of ice sheets over Greenland and Antarctica.

Provider's contact information

MERRA-2 is developed by the Global Modeling and Assimilation Office (GMAO) and produced through NASA's Modeling, Analysis and Prediction (MAP) program.

Data Download questions should go to the GES DISC help email: gsfc-help-disc@lists.nasa.gov

Science questions regarding MERRA-2 data be emailed to: merra-questions@lists.nasa.gov

When contacting these emails, provide specific information and links to where you have attempted the data downloads. They also ask you to familiarize yourself with the existing documentation first (MERRA-2: http://gmao.gsfc.nasa.gov/reanalysis/MERRA-2/docs/)

Licensing and citation

MERRA-2 data is freely available from the Goddard Earth Sciences (GES) Data Information Services center (DISC). Note that each MERRA-2 data collection has a citable DOI that should be used in peer-reviewed publications.

Citing MERRA-2 data has 2 steps for a full citation:

(1) First pick the correct variable here.
(2) When you click on the correct variable, it will take you to a second webpage with tabs that you can click that include: (1) documentation papers you need to cite, and (2) the correct variable citation information. You need both types of citation.

Variable name and units:

2 m temperature is available as instantaneous values for every hour. Monthly means of instantaneous diagnostics have also been computed.

inst1_2d_asm_Nx collection of data contains basic assimilated fields from IAU corrector provided on a single level as hourly instantaneous values.

instM_2d_asm_Nx collection of data contains basic assimilated fields from IAU corrector provided on a single level as monthly means of the instantaneous values.

In MERRA-2, a new collection is included for certain daily statistics computed from the model time step integration. **Daily maximum and minimum temperatures** are saved from the time step in which they occur and saved as a daily value, alongside the **daily mean temperature** (all at 2 m above the surface). Those values can be found in **statD_2d_slv_Nx** collection of data.

Name	Description	Units	Collection of data
T2M	2 m air temperature	K	inst1_2d_asm_Nx; instM_2d_asm_Nx
TS	Surface skin temperature	K	inst1_2d_asm_Nx; instM_2d_asm_Nx
T2MDEW	Dewpoint temperature at 2 m	K	tavg1_2d_slv_Nx
T2MMAX	Daily maximum temperatures at 2 m	K	statD_2d_slv_Nx
T2MMIN	Daily minimum temperatures at 2 m	K	statD_2d_slv_Nx
T2MMEAN	Daily mean temperature at 2 m	K	statD_2d_slv_Nx

More broadly, **MERRA-2 File Specification** document has a comprehensive list of datasets available, as well as description of the horizontal and vertical grids.

Spatial coverage and resolution:

MERRA-2 is a global dataset. All variables are provided on the same horizontal regular latitude-longitude grid that has 576 points in the longitudinal direction and 361 points in the latitudinal direction, corresponding to a resolution of 0.625° × 0.5°.

Temporal coverage and resolution:

MERRA-2 data, is available from 1980 to present.

2 m temperature data is available at hourly and monthly time step as instantaneous value.

MERRA-2 data, is updated on a monthly base (each new month is available approximately between the 15th and 20th of the next month.).

Information about observations (number, homogeneity)

Like any other climate variable from a reanalysis product, temperature is potentially influenced by all observations assimilated into the product. MERRA-2 assimilates conventional and satellite-based observations.

Conventional observations include surface, upper air, and aircraft measurements. **From land based surface meteorology stations, only surface pressure is assimilated in MERRA and MERRA-2**. 2 m temperature from surface observations is not assimilated in MERRA-2. Radiosonde stations may contribute to the lower level analysis (T, Qv, U, V). Likewise, commercial aircraft can provide lower level data on the ascent and descent (T, U, V). There are also wind profilers (U,V). Over ocean, ships and buoys may provide PS, T, Qv, U and V.

Spaceborne observations include satellite radiances and retrieved measurements of the temperature and moisture fields, and satellite observations of wind (derived retrievals of surface and upper-air wind). Spaceborne observations represent the majority of the global observing system, and the percentage of the global observing system that is measured from space increases from 62% in Jan 1980 to 88% in Dec 2014. Modern hyperspectral radiance and microwave observations, along with GPS-Radio Occultation and NASA ozone datasets are now assimilated in MERRA-2.

See the MERRA-2 Observations Tech Memo for more details.

Methodology

Like any other reanalysis, MERRA-2 data is strongly influenced by the data assimilation methodology. MERRA-2 is currently being produced with the GMAO/GEOS-5 Data Assimilation System Version 5.12.4, which incorporates the Global Statistical Interpolation (GSI) analysis scheme of Wu *et al*., (2002). The system utilizes a revised version of the GEOS global atmospheric model (Molod *et al*., 2014). MERRA-2 is intended to replace the MERRA reanalysis product (which was created with GEOS-5.2.0). Details of the MERRA-2 system, including the major changes from the MERRA system, are summarized in the companion GMAO Office Note No. 10. The major motivation for replacing MERRA with MERRA-2 is the fact that the MERRA data assimilation system was frozen in 2008 and is not capable of ingesting several important new data types such as the newer microwave sounders and hyperspectral infrared radiance instruments. The GEOS-5 system actively assimilates roughly 2×10^6 observations for each analysis, including about 7.5×10^5 AIRS radiance data. The input stream is roughly twice this volume, but because of the large volume, the data are thinned commensurate with the analysis grid to reduce the computational burden. Data are also rejected from the analysis through quality control procedures.

There is a fundamental change between MERRA and MERRA-2 over land surfaces. Soil moisture in MERRA-2 is initialized using a separate observation-based precipitation product (variable PRECTOTCORR in "flx" collections). This approach improves the representation of land surface properties and runoff, and is similar to the soil moisture initialization scheme developed for MERRA-Land (Reichle *et al*., 2011; Reichle, 2012; Reichle and Liu, 2014). The forcing precipitation is primarily based on gauge observations at low and midlatitudes, and gradually tapers to the MERRA-2 modelled precipitation over a zonal range from 42.5° to 62.5° latitude. The forcing precipitation is entirely composed of the MERRA-2 modelled precipitation poleward of 62.5°.

MERRA-2 is produced as four production Streams, each of the first three covering approximately a third of the MERRA-2 period, with the fourth stream starting within a couple years of real time. Initial conditions for the four MERRA-2 streams were derived from MERRA with a subsequent single year spin-up period, which has not been released in MERRA-2.

Information about the technical and scientific quality

MERRA-2 replaces the original NASA MERRA reanalysis (Rienecker *et al*., 2011) using an upgraded version of the data assimilation system, and of the forecast model. It is accompanied by extensive technical documentation (see section below on reference to s describing the methodology or/and the dataset). It incorporates observations from the more recent satellite instruments, uses observation-corrected precipitation forcing for the land surface, includes stratospheric ozone products and assimilates interactive aerosols and observed time varying emissions.

A webpage is provided with FAQ answers here: https://gmao.gsfc.nasa.gov/reanalysis/MERRA-2/FAQ/#

Limitations and strengths for application in North Canada

Key general limitations:

- Discontinuities occur in the sea ice and SST boundary condition fields that affect certain time series analysis
- Discontinuities associated with major observing system variations do occur

References to documents describing the methodology or/and the dataset

MERRA-2 Overview:

Gelaro, R., W. McCarty, M. J. Suárez, R. Todling, A. Molod, L. Takacs, C. A. Randles, A. Darmenov, M. G. Bosilovich, R. Reichle, K. Wargan, L. Coy, R. Cullather, C. Draper, S. Akella, V. Buchard, A. Conaty, A. M. da Silva, W. Gu, G. Kim, R. Koster, R., Lucchesi, D. Merkova, J. E. Nielsen, G. Partyka, S. Pawson, W. Putman, M. Rienecker, S. D. Schubert, M. Sienkiewicz, and B. Zhao, 2017: The Modern-Era Retrospective Analysis for Research and Applications, Version 2 (MERRA-2), Journal of Climate, 30(14), 5419-5454. doi: 10.1175/JCLI-D-16-0758.1

The American Meteorological Society has a special collection of articles relevant to MERRA-2. This collection, coordinated by Mike Bosilovich, is available at http://journals.ametsoc.org/collection/MERRA2.

There are several MAO Technical Memoranda that document and evaluate different aspects of the MERRA-2 system aspects of the MERRA-2 system:

#43, Bosilovich et al. – MERRA-2: Initial Evaluation of the Climate

#45, Randles et al. – The MERRA-2 Aerosol Assimilation

#46, McCarty et al. – MERRA-2 Input Observations: Summary and Assessment

Description of the observation corrected precipitation process used in MERRA-2:
Reichle, R., Q. Liu, R. Koster, C. Draper, S. Mahanama, and G. Partyka, 2017. Land Surface Precipitation in MERRA-2. *J. Clim.*, doi:10.1175/JCLI-D-16-0570.1 Link.

Description of the GEOS-5 model changes between the MERRA and MERRA-2 systems:

Molod, A., L. Takacs, M. Suarez, and J. Bacmeister, 2015: Development of the GEOS-5 atmospheric general circulation model: evolution from MERRA to MERRA-2, *Geosci. Model Dev.*, 8, 1339-1356, doi:10.5194/gmd-8-1339-2015. Link.

Description of the mass constraint used in MERRA-2:

Takacs, L. L., M. Suarez, and R. Todling, 2015: Maintaining Atmospheric Mass and Water Balance Within Reanalysis. *NASA/TM–2014-104606*, Vol. 37 Document.

Link to download the data and format of data:

The MERRA-2 data are available online through the Goddard Earth Sciences (GES) Data and Information Services Center (DISC) (http://disc.sci.gsfc.nasa.gov/mdisc/). All MERRA-2 data are organized into file collections that contain fields with common characteristics. 2 m temperature and skin temperature can be found in the following collections:

MERRA-2 inst1_2d_asm_Nx: contains basic assimilated fields from IAU corrector provided on a single level as hourly instantaneous values.

MERRA-2 instM_2d_asm_Nx: contains basic assimilated fields from IAU corrector provided on a single level as monthly means of the instantaneous values.

MERRA-2 statD_2d_slv_Nx: contains daily minimum, mean and maximum 2 m saved from the time step in which they occur as a daily value.

MERRA-2 data files are provided in netCDF-4 format. Due to the size of the MERRA-2 archive, most product collections are compressed with a GRIB like method that is invisible to the user. This method does degrade the precision of the data, but every effort has been made to ensure that differences between the product and the original, non-degraded data are not scientifically meaningful.

Publications including dataset evaluation or comparison with other data in Canada

7.1.9 *Dataset: The Japanese 55-year Reanalysis (JRA-55) - temperature*

Overview

This document provides an overview of the 2 m temperature data from JRA-55. JRA-55 is a third-generation reanalysis developed by the Japanese Meteorological Agency (JMA). It spans from1958 to the present period and represents an update of the previous Japanese 25-year Reanalysis (JRA-25). The analysis period starts in 1958, when regular radiosonde observation began on a global basis. Many of the deficiencies of JRA-25 are alleviated in JRA-55 because the Data Assimilation (DA) system used for the project featured a variety of improvements.

Provider's contact information

JRA-55 is developed by the Japanese Meteorological Agency (JMA). Contact JMA at the email address below with any questions on JRA-55:

Climate Prediction Division, Global Environment and Marine Department,
Japan Meteorological Agency,
Email: jra@met.kishou.go.jp
Contact DIAS Office at the email address below with any questions on JRA-55 stored at DIAS:
DIAS Office
Japan Agency for Marine-Earth Science and Technology
Email: dias-office@diasjp.net

Licensing and citation

The intellectual property rights of the datasets belong exclusively to JMA.

JRA-55 data are provided by collaborative organizations that are separate entities from JMA. User registration and agreement to terms and conditions of data service usage are required individually for each organization. Data at NCAR RDA is licensed under a Creative Commons Attribution 4.0 International Licence.

Individual users should provide JMA (jra@met.kishou.go.jp) with a copy of their scientific or technical papers, publications, press releases or other communications regarding these datasets. The source of the products should be duly acknowledged in scientific or technical

papers, publications, press releases or other communications regarding the products. This includes information on the provider of data and of the collaborative organizations from where the data was downloaded.

Example for data downloaded from DIAS Office:

"In this study, the Japanese 55-year Reanalysis (JRA-55) provided by the Japan Meteorological Agency (JMA) was utilized. This dataset was also collected and provided under the Data Integration and Analysis System (DIAS), which was developed and operated by a project supported by the Ministry of Education, Culture, Sports, Science and Technology. "

Example for downloaded from NCAR RDA:

Japan Meteorological Agency/Japan. 2013, updated monthly. JRA-55: Japanese 55-year Reanalysis, Daily 3-Hourly and 6-Hourly Data. Research Data Archive at the National Center for Atmospheric Research, Computational and Information Systems Laboratory. https://doi.org/10.5065/D6HH6H41. Accessed† dd mmm yyyy.

†Please fill in the "Accessed" date with the day, month, and year (e.g., 5 Aug 2011) you last accessed the data from the RDA.

Spatial coverage and resolution:

JRA-55 data, is a global dataset. Data is available at two spatial resolutions: (1) data on pressure levels at 1.25 degree spatial resolution and (2) data on model TL319L60 grid (~55 km) that was processed to a regular latitude-longitude Gaussian grid (320 latitudes by 640 longitudes, nominally 0.5625 degrees) and is available on NCAR RDA.

Variable name and units:

The following table summarizes the 2 m temperature data available at NCAR RDA a regular latitude-longitude Gaussian grid (320 latitudes by 640 longitudes, nominally 0.5625 degrees).

Notation (name)	Units	Dataset product
2 m Maximum temperature	K	JRA-55 **3-Hourly** Model Resolution 2-Dimensional **Minimum-Maximum Diagnostic Fields (minmax_surf)**
2 m Minimum temperature	K	JRA-55 **3-Hourly** Model Resolution 2-Dimensional **Minimum-Maximum Diagnostic Fields (minmax_surf)**

2 m Temperature	K	JRA-55 **3-Hourly** Model Resolution 2-Dimensional **Instantaneous Diagnostic Fields (fcst_surf)** JRA-55 **6-Hourly** Model Resolution **Surface Analysis Fields (anl_surf)**

Two-dimensional extreme fields (minmax_surf) are produced every three hours and they are computed from the beginning of forecasts up to three hours for 00 - 03, 06 - 09, 12 - 15 and 18 - 21 UTC, and from three to six hours for 03 - 06, 09 - 12, 15 - 18 and 21 - 24 UTC. They are produced for daily data, but not for monthly statistics.

Temporal coverage and resolution:

JRA-55 is covering 1958 to the present period. The Instantaneous Diagnostic fields are available at 3h time steps, while the Surface Analysis Fields are available just at 6h time steps.

Monthly statistics are computed as averages and variances for the whole month using only six-hourly data for analyzed and instantaneous forecast fields.

The data is updated on a monthly base.

Information about observations (number, homogeneity)

Most of the observational data employed in JRA-55 are those used in JRA-25. Additionally, newly reprocessed METEOSAT and GMS data were supplied by EUMETSAT and MSC/JMA respectively. The table below summarizes the conventional data assimilated in JRA-55. From 1958 to 2002, JRA-55 is using the same conventional data as ECMWF ERA-40 reanalysis.

Table 1. Conventional data assimilated in JRA-55

Obs type	Parameter	Level
SYNOP	P	surface
SHIP	P	surface
BUOY	P	surface
Upper-level	T	~100 hPa
Upper-level	T	100~1000 hPa
Upper-level	u	~100 hPa
Upper-level	u	100~1000 hPa
Upper-level	Rh	100~1000 hPa
Aircraft	u	100~1000 hPa
Profiler (US)	u	100~1000 hPa

Temperatures from aircraft are not used in JRA-55. JRA-55 performed bias correction for radiosonde temperature. For satellite radiances, tropospheric temperature, and humidity channels are only used in clear sky condition and channels sensitive to the ground are excluded over land and sea ice because surface temperature and emissivity estimates over those regions are not very reliable.

Quality control of conventional data is basically the same as the one used for JRA-25, and it includes a climatological check, track check, removal of duplicates, consistency check and gross error check.

The analysis of screen-level variables (2 m temperatures, 2 m relative humidities and 10 m winds) is performed separately from the atmospheric analysis component. These variables are analyzed with a univariate 2-dimensional optimal interpolation (2D-OI). Temperature and wind observations from islands are not used because they are not necessarily representative at the grid scale of JRA-55. Determining whether an observation is from an island is based on the 0.25-degree resolution land cover data; consequently, observations from the coast are also excluded.

Methodology

JRA-55 has been produced with the TL319 version of the Japan Meteorological Agency (JMA) operational data assimilation system (as of December 2009), which features numerous improvements made since the Japanese 25-year Reanalysis (JRA-25). These include a revised longwave radiation scheme, 4D-Var and variational bias correction for satellite radiances. It also incorporates several newly available observational datasets produced as a result of ongoing efforts to improve quality of past observations, including homogenization of radiosonde temperature observations (Haimberger *et al*., 2008, 2012) and reprocessing of satellite data at major meteorological satellite centers.

The analysis of screen-level variables (2 m temperatures, 2 m relative humidities and 10 m winds) is performed separately with a univariate 2-dimensional optimal interpolation (2D-OI). Land surface analysis fields are generated by driving an offline version of the JMA Simple Biosphere (SiB) model with forcing fields from the atmospheric model. Snow depth analysis fields are generated once a day with 2D-OI using SYNOP snow depth observations. First-guess fields are derived for each grid point using (A) snow depth of the land surface analysis and (B) satellite snow covers. Satellite snow covers are retrieved in the 0.25° × 0.25° latitude/longitude grid from microwave imager radiances.

The forecast model used for JRA-55 is based on the TL319 spectral resolution version of the JMA global spectral model (GSM) as of December 2009 (JMA 2007, 2013b), which has been extensively improved since JRA-25.

The reanalysis period was divided into two streams (A002, B002) which have been producing three discontinuities: at 00 UTC on 1 July 1958, 00 UTC on 1 September 1980, and 00 UTC on 1 October 1992. JRA-55 is presently operated on a near-real-time basis and provides monthly updates for the data.

Information about the technical and scientific quality

One important advance in JRA-55 is the increase in the model resolution (T319L60 vs T106L40 in JRA-25). Among the improvements in the product are reduced biases in stratospheric temperature and Amazonian rainfall, and greater temporal consistency of the temperature analysis. Some notable biases persist, including a dry bias in the upper and middle troposphere, and a warm bias in the upper troposphere. The impacts of changes in the observing system on the forecast error are generally more evident in the Southern Hemisphere than the Northern Hemisphere.

The data is updated on a monthly base. JMA provide a webpage where the issues with JRA-55 are described: JRA-55 Quality Issues

Limitations and strengths for application in North Canada.

GENERAL KEY STRENGTHS:

- Longest-running full observing system reanalysis with 4DVar

GENERAL KEY LIMITATIONS:

- Time-varying warm bias in the upper troposphere.
- Excessive precipitation is observed over the tropics.
- Dry bias in upper and middle troposphere and in regions of deep convection

- Tropical cyclone strength analyzed in JRA-55 exhibits unrealistic trends.
- The impact of changes in observing systems is particularly apparent for July 2006, when Global Navigation Satellite System-Radio Occultation (GNSS-RO) refractivity data were introduced into JRA-55.

References to documents describing the methodology or/and the dataset

Kobayashi, S., Y. Ota, Y. Harada, A. Ebita, M. Moriya, H. Onoda, K. Onogi, H. Kamahori, C. Kobayashi, H. Endo, K. Miyaoka, and K. Takahashi, 2015: The JRA-55 Reanalysis: General specifications and basic characteristics. Journal of the Meteorological Society of Japan. Ser. II, 93(1), 5-48, doi:10.2151/jmsj.2015-001.

Harada, Y., H. Kamahori, C. Kobayashi, H. Endo, S. Kobayashi, Y. Ota, H. Onoda, K. Onogi, K. Miyaoka, and K. Takahashi, 2016: The JRA-55 Reanalysis: Representation of atmospheric circulation and climate variability, J. Meteor. Soc. Japan, 94, 269-302, doi:10.2151/jmsj.2016-015.

Link to download the data and format of data:

The JRA-55 data are available in GRIB-2 format and can be accessed from the following organizations:

DIAS: Data Integration & Analysis System (data from 1958 to 2012, on a grid of approx. 1.25 deg.):

http://search.diasjp.net/en/dataset/JRA55

NCAR: National Center for Atmospheric Research (USA) (data from 1958 to present, on both spatial grids):

- Daily, 3-Hourly and 6-Hourly Data http://rda.ucar.edu/datasets/ds628.0/
- Monthly Means and Variances http://rda.ucar.edu/datasets/ds628.1/
- Near Real-Time Data http://rda.ucar.edu/datasets/ds628.8/
- Near Real-Time Data -- Monthly Means and Variances http://rda.ucar.edu/datasets/ds628.9/

Publications including dataset evaluation or comparison with other data in Canada

7.1.10 *Dataset: The NCAR Arctic System Reanalysis (ASRv2) - temperature*

Overview

This document provides an overview of the surface temperature products (T2m) of ASRv2. ASRv2 is a multi-agency, university-led regional reanalysis product that covers the Arctic. It is produced using high-resolution versions of the Polar Weather Forecast Model (PWRF) and the WRF-VAR and High Resolution Land Data Assimilation (HRLDAS) systems that have been optimized for the Arctic. The final version, which has 15 km horizontal resolution and spans 2000-2016 period, is available online through the NCAR's RDA.

Provider's contact information

ASRv2 is produced by Polar Meteorology Group, Byrd Polar & Climate Research Center, the Ohio State University and is available at **NCAR CISL RDA.**

RDA NCAR user support manager : schuster@ucar.edu

Licensing and citation

Licence: licensed under Creative Commons Attribution 4.0 International Licence (Licence agreement information can be found here)

Dataset citable as:

National Center for Atmospheric Research/University Corporation for Atmospheric Research, and Polar Meterology Group/Byrd Polar and Climate Research Center/The Ohio State University. 2017. Arctic System Reanalysis version 2. Research Data Archive at the National Center for Atmospheric Research, Computational and Information Systems Laboratory. https://doi.org/10.5065/D6X9291B , https://rda.ucar.edu/datasets/ds631.1/

Bromwich, D., L. Bai, K. Hines, S. Wang, Z. Liu, H. Lin, Y. Kuo, and M. Barlage. 2012: Arctic System Reanalysis (ASR) Project. Research Data Archive at the National Center for Atmospheric Research, Computational and Information Systems Laboratory.

Variable name and units:

The 2 m temperature of ASRv2 is the main focus of this annex. This parameter has units of kelvin (K). Temperature measured in kelvin can be converted to degrees Celsius (°C) by subtracting 273.15.

The parameter is noted 2 m temperature and it is available from the ‘’2D surface analysis’’ as well as from the ‘’2D surface forecast’’ datasets. Many other variables are provided in those two groups.

Spatial coverage and resolution:

Geographical Coverage: 15 km x 15 km (at 60 N) oriented 175 W (720 x 720 North Polar Stereographic).

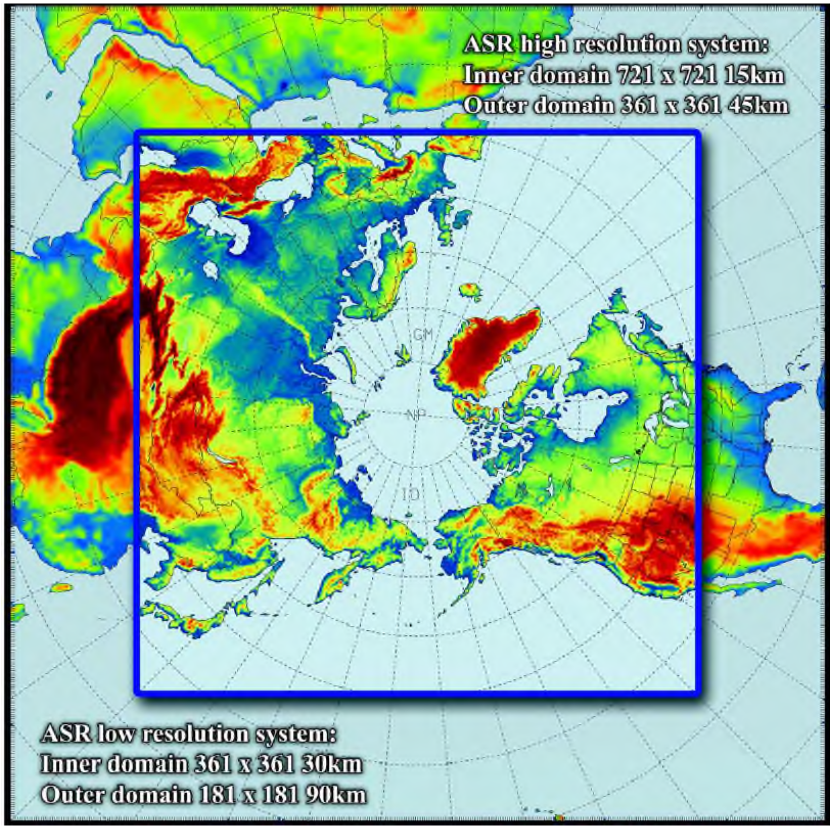


Figure 1. ASR domain (from http://polarmet.osu.edu/ASR/)

Temporal coverage and resolution:

ASRv2 "2 m temperature" is available from 2000 to 2016 as an instantaneous parameter provided at **3 hourly** time step and as **monthly means**.

Methodology

ASRv2 provides a high resolution description of the atmosphere-sea ice-land surface system of the Arctic. It is using the polar version of the Weather Research and Forecasting (WRF) model version 3.6.0. It uses the 3DVAR technique and the High Resolution Land Data Assimilation (HRLDAS) data assimilation systems that have been optimized for the Arctic.

A full description of ASRv2 is presented in the Bulletin of the American Meteorological Society (PDF).

Observations data in ASRv2

The observations data used in ASRv2 (Figure 2) includes synoptic surface observations (black dots), METARs (purple plus signs), ship observations (royal blue dots), buoys (navy-blue dots), radiosondes (purple asterisks), global positioning system refractivity observations (red dots), wind profiler (yellow dots), aviation in-flight weather reports (green dots), QuikSCAT sea surface winds (orange dots), and satellite atmospheric motion vectors (aqua dots).

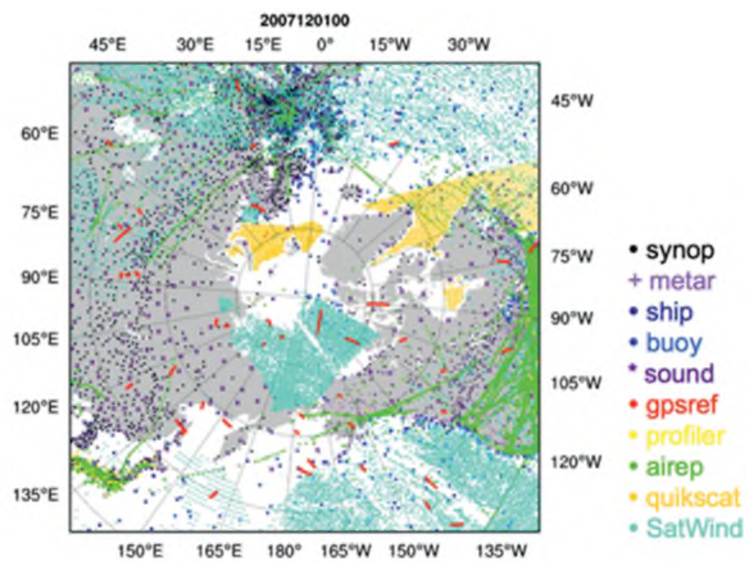


Figure 2. Distribution of observations

Information about the technical and scientific quality

New features in ASRv2 compared to ASRv1 are higher horizontal resolution, updated model physics including sub-grid scale cloud fraction interaction with radiation, and a dual outer loop routine for more accurate data assimilation.

The following document compares near-surface variables from ASRv1, ASRv2, and ERAI to observations from ~4500 surface stations provided by the National Centers for Environmental Information (https://www.ncdc.noaa.gov/) for the period December 2006-November 2007: **http://polarmet.osu.edu/ASR/asr_v2_table.pdf.** For 2 m temperature it is mentioned: ''Analysis reveals that ERAI and ASR products have small annual mean biases, with the smallest biases represented by ASRv2. However, ASRv2 is colder than both ASRv1 and ERAI with negative biases from February through October. Decreasing annual mean RMSE values from ERAI to ASRv2 indicate that ASRv2 is an excellent fit to observations and the standard deviation of the unexplained variance is small. This is further supported by increasing skill indicated by higher correlation.''

Presently there are plans to update ASRv2. The updated version will use the latest version of WRF and WRFDA, a more advanced data assimilation procedure, implement Morrison microphysics with a specified variable aerosol concentration, change to Noah-MP land surface model, incorporate a thermodynamic sea ice model, and increase the horizontal resolution to at least 10 km with ~ 100 vertical levels. This version will be known as ASRv3. Plans are to conduct a reanalysis of the MOSAiC drift period (fall 2019 - fall 2020) and it will be available through NCAR.

Limitations and strengths for application in North Canada

The following notes are general observations provided at https://climatedataguide.ucar.edu/climate-data/arctic-system-reanalysis-asr

Key Strengths: Excellent reproduction of near-surface and tropospheric variables

Key Limitations: A dry bias is still present during the cooler months in ASRv2.

References to documents describing the methodology or/and the dataset

Bromwich, D., Y.-H. Kuo, M. Serreze, J. Walsh, L.S. Bai, M. Barlage, K. Hines, and A, Slater, 2010: Arctic System Reanalysis: Call for community involvement. EOS Trans. AGU, 91, 13-14. https://doi.org/10.1029/2010EO020001

Online technical description:

https://rda.ucar.edu/datasets/ds631.0/#!docs

Link to download the data and format of data:

Data Access: NCAR/RDA

ASRv2 is available in NetCDF format.

Link to download 3 hourly and monthly data on RDA:

ASR 15 km 2D surface analysis

ASR 15 km 2D surface forecast

ASR 15 km monthly means of analysis products

ASR 15 km monthly means of forecast products

Publications including dataset evaluation or comparison with other data in Canada

Bromwich, D.H., A.B. Wilson, L. Bai, G.W.K. Moore, and P. Bauer, 2016: A comparison of the regional Arctic System Reanalysis and the global ERA-Interim Reanalysis for the Arctic. Q. J. R. Meteorol. Soc., 142, 644-658. https://doi.org/10.1002/qj.2527

Bromwich, D.H., K.M. Hines, and L.-S. Bai, 2009: Development and testing of Polar WRF: 2. Arctic Ocean. J. Geophys. Res., 114, D08122. https://doi.org/10.1029/2008JD010300

Smirnova, J., and P. Golubkin, 2017: Comparing polar lows in atmospheric reanalyses: Arctic System Reanalysis versus ERA-Interim. Mon. Wea. Rev., 145, 2375-2383, https://doi.org/10.1175/MWR-D-16-0333.1

Avila-Diaz, A., D.H. Bromwich, A.B. Wilson, F. Justino, S.-H. Wang, 2021: Climate extremes across the North American Arctic in modern reanalyses. J. Climate, , 34, 2385–2410, https://doi.org/10.1175/JCLI-D-20-0093.1

Chanona, M., and S. Waterman, 2020: Temporal Variability of Internal Wave-Driven Mixing in Two Distinct Regions of the Arctic Ocean. J. Geophys. Res. Oceans, 125, https://doi.org/10.1029/2020JC016181

Edel, L., C. Claud, C. Genthon, C. Palerme, N. Wood, T. L'Ecuyer, and D. Bromwich, 2020: Arctic snowfall from CloudSat observations and reanalyses. J. Clim., 33, 2093-2109, https://doi.org/10.1175/JCLI-D-19-0105.1

Kaiser-Weiss, A.K., M. Borsche, D. Niermann, F. Kaspar, C. Lussana, F.A. Isotta, E. van den Besselaar, G. van der Schrier, and P. Undén, 2019: Added value of regional reanalyses for climatological applications. Environ. Res. Commun., 1, https://doi.org/10.1088/2515-7620/ab2ec3

Gutjahr, O., and G. Heinemann, 2018: A model-based comparison of extreme winds in the Arctic and around Greenland. Int. J. Clmatol., 38, 5272-5292, https://doi.org/10.1002/joc.5729

Rabatel, M., P. Rampal, A. Carrassi, L. Bertino, and C. K. Jones, 2018: Impact of rheology on probabilistic forecasts of sea ice trajectories: Application for search and rescue operations in the Arctic. Cryosphere, 12, 935-953, https://doi.org/10.5194/tc-12-935-2018

Kohnemann, S.H., G. Heinemann, D.H. Bromwich, and O. Gutjahr, 2017: Extreme warming in the Kara Sea and Barents Sea during the winter period 2000-16. J. Clim., 30, 8913-8927, https://doi.org/10.1175/JCLI-D-16-0693.1

Kolstad, E.W., 2017: Higher ocean wind speeds during marine cold air outbreaks. Quarterly J. Roy. Meteor. Soc., 143, 2084-2092, https://doi.org/10.1002/qj.3068

Rampal, P., S. Bouillon, E. Ólason, and M. Morlighem, 2016: neXtSIM: a new Lagrangian sea ice model. The Cryosphere, 10, 1055-1073, https://doi.org/10.5194/tc-10-1055-2016

Wang, F., W. Li, and S. Wang, 2016: Polar cyclone identification from 4D climate data in a knowledge-driven visualization system. Climate, 4, https://doi.org/10.3390/cli4030043

7.1.11 ***Dataset*: NCEP North American Regional Reanalysis (NARR) - temperature**

Overview

This document focuses on temperature data from NARR. NARR is a regional reanalysis covering the North America using a Northern Lambert Conformal Conic grid with an approximately 0.3 degrees (32 km) spatial resolution at the lowest latitude. Dataset was originally produced at NOAA's National Center for Atmospheric Prediction (NCEP), and detailed description is provided at https://psl.noaa.gov/data/gridded/data.narr.html#detail with online Analysis and Plotting Tools at https://psl.noaa.gov/cgi-bin/data/getpage.pl.

Provider's contact information

Physical Sciences Laboratory: Data Management

NOAA/ESRL/PSL

325 Broadway

Boulder, CO 80305-3328

psl.data@noaa.gov.

Licensing and citation

If the data are taken from PSD, the providers ask that the data is acknowledged by including text such as NCEP Reanalysis data provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, from their Web site at http://www.esrl.noaa.gov/psd/ in any documents or publications using these data.

If the data are taken from NCAR, the citation should include the following: National Centers for Environmental Prediction/National Weather Service/NOAA/U.S. Department of Commerce. 2005, updated monthly. NCEP North American Regional Reanalysis (NARR). Research Data Archive at the National Center for Atmospheric Research, Computational and Information Systems Laboratory. https://rda.ucar.edu/datasets/ds608.0/. Accessed dd mmm yyyy.

Variable name and units:

The variables are divided into three sections: Pressure level, Monolevel (surface and others) and Subsurface. **2 m temperature** [**K]** and **2 m Dew Point Temperature** data are available in the list of Monolevel variables and they are the output of the analysis and first guess forecast:

Table with snow variables available in NetCDF format at NOAA

Variable	**Statistic**	**Level**	**Download File**
Air Temperature at 2 m	3-hourly value	2 m	air.2m.yyyy.nc
Air Temperature at 2 m	Daily Mean	2 m	air.2m.yyyy.nc
Air Temperature at 2 m	Long-term Daily Mean	2 m	air.2m.day.ltm.nc
Air Temperature at 2 m	Monthly Mean	2 m	air.2m.mon.mean.nc
Dew Point Temperature at 2 m	3-hourly value	2 m	dpt.2m.yyyy.nc
Dew Point Temperature at 2 m	Daily Mean	2 m	dpt.2m.yyyy.nc
Dew Point Temperature at 2 m	Monthly Mean	2 m	dpt.2m.mon.mean.nc
Dew Point Temperature at 2 m	Long-term Monthly Mean	2 m	dpt.2m.mon.mltmnc

Values labelled 3 hourly values are output at that exact time (no averaging).

For a complete list of model output variables, see NCEP's variable list. Details for Monolevel variables are provided on https://psl.noaa.gov/data/gridded/data.narr.monolevel.html .

NARR is also offering a variable named Surface temperature. This variable is the "skin" temperature. Over water, it is the SST. Over land, it would be the "radiative" temperature of the surface. The skin temperature is generated from the land surface model. Note, the skin temperature is not the top layer soil temperature. During the day, the surface temperature is typically higher than the soil and 2 m air temperature.

Spatial coverage and resolution:

The data is available for all of North America at an approximate 0.3 degrees (32 km) spatial resolution at the lowest latitude, on a Northern Lambert Conformal Conic grid. Corners of this grid are 1.000001 N, 145.5 W; 0.897945 N, 68.32005 W; 46.3544 N, 2.569891 W; 46.63433 N, 148.6418 E. A page describing the coverage along with information on reading the projection is available.

Temporal coverage and resolution:

Data is available as 3h values, Daily and Monthly means, for the period 1979/01/01 to 2021/05/31.

Information about observations

The data that are assimilated in order to initialize the model are temperatures, winds, and moisture from radiosondes as well as pressure data from surface observations. Also included in this dataset are dropsondes, pibals, aircraft temperatures and winds, satellite radiance (a measure of heat) from polar (orbiting Earth) satellites, and cloud-drift winds from geostationary (fixed at one location viewing Earth) satellites. The sources of observations are summarized in the table below.

Dataset	Details	Source
Precipitation	Continental United States: comes from a 1/8-degree gauge dataset analyzed using PRISM and a least-squares distance-weighting algorithm. Canada and Mexico: comes from 1-degree gauge datasets and is disaggregated using NCEP R2 hourly precipitation weighting factors. Over oceans (< 42.5°N): comes from the Climate Prediction Center (CPC) CMAP (CPC Merged Analysis of Precipitation), a merged combination of satellite and gauge precipitation. It is using a 15-degree “blending belt” between 27.5 and 42.5 N, with no CMAP north of 42.5 N.	NCEP/CPC,Canada, Mexico
TOVS-1B radiances	Temperature, precipitable water over ocean	NESDIS

NCEP Surface	Wind, moisture	GR
TDL Surface	Pressure, wind, moisture	NCAR
COADS (ships/buoys)	Pressure, wind, moisture	NCEP/EMC
Air Force Snow	Snow depth	COLA and NCEP/EMC
SST	1-degree Reynolds, with Great Lakes SSTs	NCEP/EMC, GLERL
Sea and lake ice	Contains data on Canadian lakes, Great Lakes	NCEP/EMC, GLERL, Ice Services Canada
Tropical cyclones	Locations used for blocking of CMAP Precipitation	Lawrence Livermore National Laboratory

Previous tests on assimilation of 2 m land surface station air temperatures, in NARR proved to be harmful in the sense of making the first guess considerably worse, throughout the troposphere. **Consequently, 2 m land surface station air temperatures are not assimilated by NARR**.

The following figure presents the distributions of surface assimilated data for 1 January 1988.

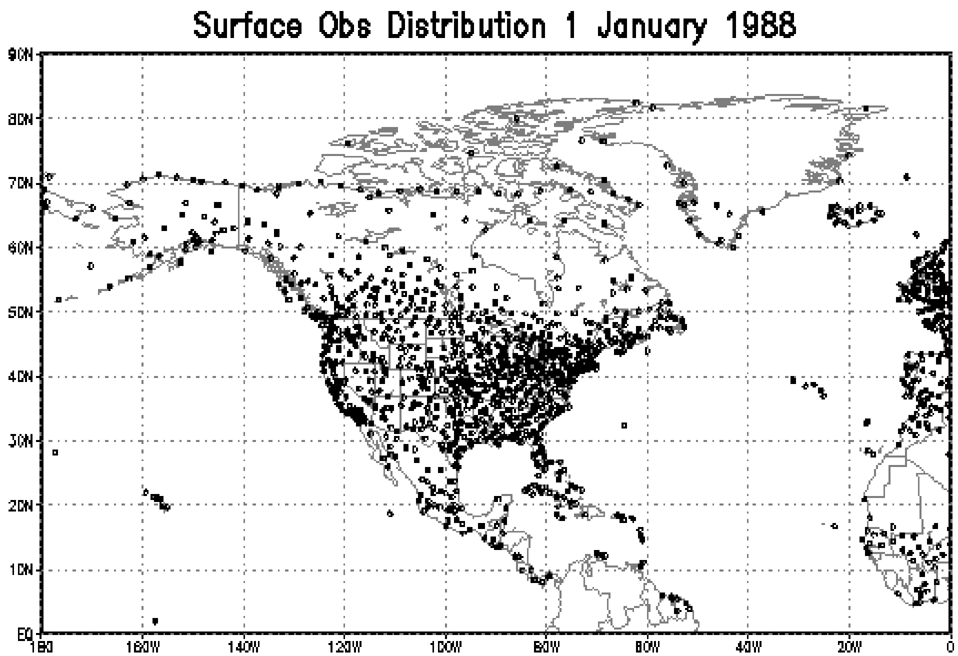


Figure 1. Distribution of surface observations

Methodology

The NARR project is an extension of the NCEP Global Reanalysis which is run over the North American Region. The NARR model uses a high-resolution NCEP Eta Model (32 km/45 layer) together with the Regional Data Assimilation System (RDAS) using 3DVAR method, and it is one of the few reanalysis that assimilates precipitation along with other variables, also over Canada this feature is much reduced comparable to US. It is using the ETA / NOAH land surface model and it is assimilating snow depths from US Air Force daily snow depth analysis.

For more information, please refer to the publication in the references section below.

Information about the technical and scientific quality

The improvements in the model/assimilation have resulted in a dataset with substantial improvements in the accuracy of temperature, winds and precipitation compared to the NCEP-DOE Global Reanalysis 2 (the parent global reanalysis). Wind improvement is especially greatest in the upper troposphere in winter. The 10 m winds improved greatly in winter, a little bit in summer. Relative humidity also improved in both analysis and first guess forecast.

Precipitation over Canada: the number of gauge observations is insufficient to do better than the model is doing.

Tests on assimilation of 2 m land surface station air temperatures, in NARR proved to be harmful in the sense of making the first guess considerably worse, throughout the troposphere. Consequently, 2 m land surface station air temperatures are not assimilated by NARR.

Useful information can be found at NCEP's NARR FAQ page: http://www.emc.ncep.noaa.gov/mmb/rreanl/faq.html .

Data is updated on a monthly base.

Limitations and strengths for application in North Canada

A very small amount of surface data is assimilated over North Canada.

References to documents describing the methodology or/and the dataset

Mesinger, F., G. DiMego, E. Kalnay, K. Mitchell, and Coauthors, 2006: North American Regional Reanalysis. Bulletin of the American Meteorological Society, 87, 343–360, doi:10.1175/BAMS-87-3-343.

Link to download the data and format of data:

NARR is available through NOAA ftp page, UCAR and from NCDC page.

NOAA: ftp://ftp.cdc.noaa.gov/Datasets/NARR/ (NetCDF standard format; the data are divided by variable and year and month into separate files; Missing data is flagged with a value of 9.96921e+36f.)

NCDC: https://www.ncdc.noaa.gov/data-access/model-data/model-datasets/north-american-regional-reanalysis-narr (GRIB format)

UCAR: https://rda.ucar.edu/datasets/ds608.0/ (GRIB format)

Publications including dataset evaluation or comparison with other data in northern Canada.

7.1.12 *Dataset: North American Precipitation and Land Surface Reanalysis - Regional Deterministic Reforecast System, Version 2 (RDRSv2) - temperature*

Overview

This document focuses on temperature data from RDRSv2 (designated as version 2 to differentiate it from the previous iteration). RDRSv2 is a precipitation and surface reanalysis developed at the Canadian Centre for Meteorological and Environmental Prediction (CCMEP) of Environment and Climate Change Canada (ECCC). It provides various forecasted meteorological variables obtained with the Regional Deterministic Reforecast System (RDRS) two-way coupled with the Canadian Land Data Assimilation System (CaLDAS) and Precipitation Analysis (CaPA), and is initialized and driven by ERA-Interim reanalysis. Results are provided at a spatial resolution of 10 km across North America. Data is currently available for the period of 1980 - 2017.

Provider's contact information

Data developed by the Canadian Centre for Meteorological and Environmental Prediction (CCMEP) of Environment and Climate Change Canada (ECCC)

Electronic Mail Address of the provider: The Canadian Surface Prediction Archive (caspar.data@uwaterloo.ca)

Licensing

The end-user licence for Environment and Climate Change Canada's data servers specifies the conditions of use of this data.

The Canadian Surface Prediction Archive Terms of Service

Variable name and units:

The following temperature data are available:

RDRS_P_TT_1.5m	Air temperature [degrees C] at 1.5 m
RDRS_P_TT_09944	Air temperature [degrees C] at approx. 40 m
RDRS_P_TD_1.5m	Dew point temperature [degree C] at 1.5 m
RDRS_P_TD_09944	Dew point temperature [degree C] at approx. 40 m

Temperature data is available as **instantaneous predicted values** at hourly time steps. The near-surface air temperature is temperature at 1.5 m and the units are (°C);

Maximum daily temperature and Minimum daily temperature are not available from the forecast. They can be computed by users using the hourly near-surface air temperature. This will be an approximation as the hourly near-surface air temperature is an instantaneous predicted value.

Information about other variables available for download can be found on CaSPAr data portal. Those variables are available at various levels – surface, 1.5 metres, and/or ~40 metres in elevation.

Spatial coverage and resolution:

The data is available for all of North America at an approximate 10 km x 10 km spatial resolution on a rotated pole grid.

Temporal coverage and resolution:

RDRSv2 is available for the period of 1980 - 2017. Data for. Data is available at **hourly time** steps.

Information about observations (number, homogeneity)

RDRSv2 is initialized and driven by ERA-Interim reanalysis and rely only on surface observations and no remote sensing observations, such as satellite or radar data. Observations were taken from ECCC's operational and climate data archives and include temperature and dew point temperature. The Integrated Surface Data (ISD, DS463.3) is used in the version v2.1 for the years prior to 2000. Table 3 from Gasset *et al*., (2021) summarizes the surface observation datasets used in the assimilation processes.

Table 3. Surface networks and variables used by CaLDAS and CaPA.

Network	Domain covered	Availability at CCMEP	Variables used by CaLDAS	Variables used by CaPA-6h	Variables used by CaPA-24h
METAR	North America	1992-present	T, T_d	P, T, $\|\|U\|\|$	P, T, $\|\|U\|\|$
SWOB	North America	2013-present	T, T_d, S_d	Not used	P, T, $\|\|U\|\|$
SYNOP	North America	1992-present	T, T_d, S_d	P, T, $\|\|U\|\|$	P, T, $\|\|U\|\|$
AdjDlyRS	Canada	1980-present	Not used	Not used	P
RMCQ	Province of Quebec	2011-present	Not used	Not used	P, T, $\|\|U\|\|$
SHEF	USA	1998-present	Not used	Not used	P, T, $\|\|U\|\|$

T: temperature, T_d: dew point temperature, S_d: snow depth, P: total precipitation, $||U||$: wind speed

Figure 1 from Lespinas *et al*., (2010) is presenting the spatial distribution of the meteorological stations assimilated by CaPA and geographical limits of the Canadian terrestrial ecozones.

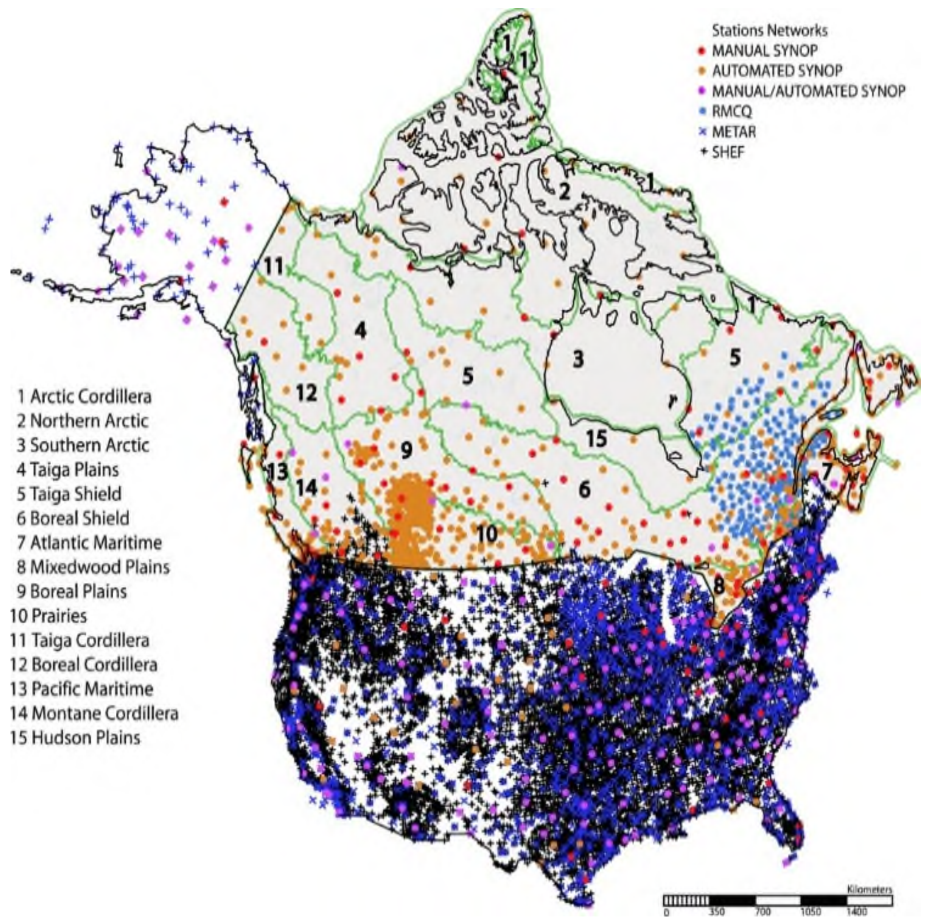


Figure 1. Spatial distribution of the meteorological stations assimilated by CaPA. Source: Journal of Hydrometeorology 16, 5; 10.1175/JHM-D-14-0191.1)

Supplementary information relevant for precipitation, soil moisture and snow: The 24 h a posteriori precipitation analysis, CaPA-24, is also using the Adjusted Daily Rain and Snow (AdjDlyRS) observations dataset (Wang *et al*., 2017). AdjDlyRS data features 3346 stations that are mainly manual stations from the Canadian synoptic network, and are known as the most reliable observations (they were adjusted for systematic errors, and in particular undercatch and evaporation caused by wind effects, gauge-specific wetting loss, as well as for trace precipitation amounts.).

Methodology

ERA-Interim reanalysis is first used to initialize the atmospheric conditions of the Global Deterministic Reforecast System (GDRS) at a spatial resolution of 39 km. Additional surface conditions are input via the GEM-Surf model, which is also initialized by ERA-Interim. The GDRS output is then dynamically downscaled to 10 km using the RDRS. These finer resolution outputs are two-way coupled with the Canadian Land Data Assimilation System (CaLDAS) and Precipitation Analysis (CaPA) system (this means that outputs from RDRS is used to drive both the CaLDAS and CaPA system, and these results are then fed back into RDRS). This coupling results in significantly improved near-surface atmospheric and land-surface predictions.

Both GDRS and RDRS are based on the latest stable version of the Global Environment Multiscale (GEM v4.8-LTS) model and they are both using the same geophysical fields (i.e. orography, vegetation characteristics, soil thermal and hydraulic coefficients, glaciers fraction) as the corresponding forecast operational versions. The coupling with CaLDAs and CaPA allows for combining surface observations of temperature, humidity, snow depth and precipitation with the first guess provided by the RDRS. CaLDAS uses a one-dimensional Ensemble Kalman Filter (EnKF) to estimate soil moisture and soil temperature, and an optimal interpolation (OI) scheme to estimate snow depth. CaPA combines precipitation observations with a background field obtained from the short-term reforecast provided by the RDRS through an OI method. CaPA also serves to provide CaLDAS with 6-h precipitation analysis.

For more information, please refer to the publication in the references section below.

Information about the technical and scientific quality

Version 2 was evaluated and compared to the operational numerical weather prediction system (RDPS) over the period of 2010 - 2017. Gasset et al. (2021) mentions that the RDRS-10 improves upon RDPS in most regions and for most variables, notably for Alaska and the Canadian Arctic, as well as Western USA. Absolute and dew point temperatures forecasts are improved for all seasons and all areas, with the sole exception of absolute temperature in spring and summer for the Eastern Canada.

In general, reanalyses often do not assimilate any observations of precipitation and of the land-surface state, but instead only provide short-term forecasts of these variables. RDRS do assimilate precipitation observations through the coupling with CaPA. Gasset *et al*., (2021) mentions that the coupling approach of the GDRS, RDRS, CaLDAS, and CaPA demonstrates significant improvements in the surface layer compared to the results obtained without coupling.

Strict quality control procedures are in place in CaPA to avoid the assimilation of biased observations, and in particular wind-induced undercatch of solid precipitation (based on a temperature analysis, different wind speed thresholds are used depending on the network, the type of gauge and whether the station is manned or automated).

In Gasset *et al*., (2021), short-term absolute temperature, dew point temperature, and wind speed forecasts from RDRSv2 were compared to observations from synoptic stations across North America. Results indicate that these data may be suitable in driving other environmental models. Likewise, a preliminary streamflow modelling study has also demonstrated that the RDRSv2 has some skill in driving hydrological models to predict runoff into Lake Erie, suggesting that the RDRSv2 may be useful for hydrological purposes.

Data is available in netCDF format on CaSPAr data portal. Two scientific papers accompany the dataset, one detailing CaSPAr and the other detailing the RDRSv2 dataset. It is expected that the data will be updated regularly.

Limitations and strengths for application in North Canada

RDRSv2 is initialized and driven by ERA-Interim, a reanalysis dataset that has been since superseded by ERA5. The pending data for the years 1980 - 1999 and 2018 will continue to use ERA-Interim, and tests are currently being conducted to determine the suitability and impacts of switching to another dataset. Furthermore, a bug that was identified during the development of the 2000 - 2017 reanalysis data: snow depth was expressed in metres in the code whereas it is supposed to be expressed in centimetres. It was verified that while biases and other errors for snow depth itself wasn't heavily impacted, snow density and snow water equivalent demonstrated significant differences. As such, these two fields are not distributed for 2000 - 2017 in version 2 release. The error is corrected in version 2.1 and will be available for download soon.

References to documents describing the methodology or/and the dataset

Gasset, N., V. Fortin, M. Dimitrijevic, M. Carrera, B. Bilodeau, R. Muncaster, É.,Gaborit, G. Roy, N. Pentcheva, M. Bulat, X. Wang, R. Pavlovic, F. Lespinas, and D. Khedhaouiria, 2021: A 10 km North American Precipitation and Land Surface Reanalysis Based on the GEM Atmospheric Model. *Hydrology and Earth System Sciences*, *25*(9), 4917-4945, https://doi.org/10.5194/hess-25-4917-2021

Link to download the data and format of data:

The data can be accessed through the CaSPAr data catalogue as well as directly from their data portal:

Data catalogue: **https://github.com/julemai/CaSPAr/wiki/Available-products**

Data portal: **https://caspar-data.ca/caspar** **(NetCDF)**

Publications including dataset evaluation or comparison with other data

Mai, J., B.A. Tolson, H. Shen, É. Gaborit, V. Fortin, N. Gasset, H. Awoye, T. A. Stadnyk, L. M. Fry, E. A. Bradley, F. Seglenieks, A. G. T. Temgoua, D. G. Princz, S. Gharari, A. Haghnegahdar, M. E. Elshamy, S. Razavi, M. Gauch, J. Lin, X. Ni, Y. Yuan, M. McLeod, N. B. Basu, R. Kumar, O. Rakovec, L. Samaniego, S. Attinger, N. K. Shrestha, P. Daggupati, T. Roy, S. Wi, T. Hunter, J. R. Craig, and A. Pietroniro, 2021: Great Lakes Runoff Intercomparison Project Phase 3: Lake Erie (GRIP-E), Journal of Hydrologic Engineering, 26(9), 05021020-1-19. https://doi.org/10.1061/(ASCE)HE.1943-5584.0002097

Reference for CaPA:

Mahfouf, J.-F., B. Brasnett, and S. Gagnon, 2007: A Canadian precipitation analysis (CaPA) project: Description and preliminary results, Atmosphere-Ocean, 45(1), 1-17, DOI: 10.3137/ao.v450101.

Fortin, V., G. Roy, T. Stadnyk, K. Koenig, N. Gasset, and A. Mahidjiba, 2018: Ten Years of Science Based on the Canadian Precipitation Analysis: A CaPA System Overview and Literature Review, Atmosphere-Ocean, 56(3), 178-196, DOI: 10.1080/07055900.2018.1474728.

Lespinas, F., V. Fortin, G. Roy, P. Rasmussen, and T. Stadnyk, 2015: Performance Evaluation of the Canadian Precipitation Analysis (CaPA), Journal of Hydrometeorology, 16(5), 2045-2064. Retrieved May 26, 2021, from

https://journals.ametsoc.org/view/journals/hydr/16/5/jhm-d-14-0191_1.xml

7.1.13 *Dataset: NOAA-CIRES-DOE Twentieth Century Reanalysis, Version 3 (20CRv3) - temperature*

Overview

This document provides an overview of the 2 m temperature data from Twentieth Century Reanalysis (20CRv3). The 20th Century Reanalysis Project is an effort led by NOAA's Physical Sciences Laboratory (PSL) and CIRES at the University of Colorado, supported by the Department of Energy (DOE), to produce reanalysis datasets spanning the entire 20th century and much of the 19th century. These reanalyses assimilate only surface observations of synoptic pressure into NOAA's Global Forecast System, and prescribed sea surface temperature and sea ice distribution in order to estimate atmospheric variables, from the surface to the top of the atmosphere, throughout the 19th and 20th centuries. 20CRv3 is version 3 of the project. For version 3, the ensemble mean and standard deviation for each value were calculated over a set of 80 analyses and short-term forecasts.

Provider's contact information

20CRv3 is developed by the NOAA's Physical Sciences Laboratory (PSL) and CIRES at the University of Colorado, supported by the Department of Energy (DOE).

Contact information for help with the dataset:

Gilbert P. Compo

CIRES, University of Colorado at Boulder, and Physical Sciences Laboratory, National Oceanic and Atmospheric Administration

gilbert.p.compo at noaa.gov

Laura C. Slivinski

CIRES, University of Colorado at Boulder, and Physical Sciences Laboratory, National Oceanic and Atmospheric Administration

laura.slivinski at noaa.gov

Licensing and citation

20CRv3 data are provided by several collaborative organizations. User registration and agreement to terms and conditions of data service usage are required individually for each organization.

Data at NCAR RDA is licensed under a Creative Commons Attribution 4.0 International Licence.

The following citation should be used for data downloaded from NCAR RDA:

" **Slivinski**, L. C., et al. 2019. NOAA-CIRES-DOE Twentieth Century Reanalysis Version 3. Research Data Archive at the National Center for Atmospheric Research, Computational and Information Systems Laboratory. https://doi.org/10.5065/H93G-WS83. Accessed† dd mmm yyyy.

†Please fill in the "Accessed" date with the day, month, and year (e.g., - 5 Aug 2011) you last accessed the data from the RDA. "

The following citation should be used for data downloaded from Physical Sciences Laboratory (PSL) or from National Energy Research Scientific Computing Center (NERSC):

Papers using the NOAA-CIRES-DOE Twentieth Century Reanalysis Project version 3 dataset are requested to include the following text in their acknowledgments: "Support for the Twentieth Century Reanalysis Project version 3 dataset is provided by the U.S. Department of Energy, Office of Science Biological and Environmental Research (BER), by the National Oceanic and Atmospheric Administration Climate Program Office, and by the NOAA Physical Sciences Laboratory."

If you acquire 20th Century Reanalysis V3 data products from PSL, we are asked to acknowledge PSL by including also a text such as *20th Century Reanalysis V3 data provided by the NOAA/OAR/ESRL PSL, Boulder, Colorado, USA, from their Web site at /* in any documents or publications using these data and send a copy of the relevant publications to:

Physical Sciences Laboratory: Data Management

NOAA/ESRL/PSL

325 Broadway

Boulder, CO 80305-3328

psl.data@noaa.gov

Spatial coverage and resolution:

20CRv3 data, is a global dataset. 20CRv3 has a Gaussian T-254 grid (approximately 75 km at the equator).

Variable name and units:

The following table summarizes the 2 m temperature data.

Notation (name)	Units	Organisation (type)

TMIN (Minimum Temperature at 2 m)	K	PSL; NCAR (Analysis Fields)
TMAX (Maximum Temperature at 2 m)	K	PSL; NCAR (Analysis Fields)
TMP2m at NERSC and AIR at PSL (Air temperature at 2 m)	K	PSL; NERSC; NCAR (Analysis Fields and First Guess Forecast Fields)

Temporal coverage and resolution:

On PSL website, 20CRv3.SI is available for years 1836 - 1980 and 20CRv3.MO is available for years 1981 - 2015 (the only differences between these two versions are the prescribed sea surface temperatures and dates of availability):

- 3-hourly values for 1836/01/01 0Z to 2015/12/31 21Z.
- Daily average values for 1836/01/01 to 2015/12/31.
- Monthly values for 1836/01 to 2015/12 (Combined SI-MO).

At NCAR RDA, 20CRv3 is available from:

- 1835/12/31 18Z to 2016/01/01 0Z (Yearly Time Series 3-Hourly Analysis Fields (Gaussian T-254))
- 1806/12/31 18Z to 2015/12/31 12Z (Yearly Time Series 3-Hourly First Guess Forecast Fields (Gaussian T-254))
- 1806/12/31 21Z to 2015/12/31 15Z (Yearly Time Series 6-Hourly Analysis Fields (Gaussian T-254))

The data is updated on an irregular basis.

Information about observations (number, homogeneity)

These reanalyses assimilate only surface observations of synoptic pressure. Boundary conditions of pentad sea surface temperature and monthly sea ice concentration and time-varying solar, volcanic, and carbon dioxide radiative forcings are prescribed.

The surface pressure observations: ISPD version 4.7, made available through international cooperation facilitated by the Atmospheric Circulation Reconstructions over the Earth (ACRE) initiative and working groups of the Global Climate Observing System and World Climate Research Program.

Sea Ice Concentration Boundary Condition: monthly HadISST2.3 sea ice (Slivinski *et al*., 2019; Titchner & Rayner 2014; Walsh *et al*., 2015)

Sea Surface Temperature Boundary Condition: prior to 1981 (20CRv3.SI): 8 members of pentad interpolated to daily Simple Ocean Data Assimilation with Sparse Input (SODAsi) version 3 (SODAsi.3, Giese *et al*., 2016) seasonally adjusted to the 1981 - 2010 HadISST2.2 climatology. Regions where sea ice was ever indicated in HadISST2.3 are filled with: HadISST2.2 daily (1963+); HadISST2.1 monthly interpolated to daily (1850 - 1962); or the 1861–1891 HadISST2.1 climatology (1849 and earlier)**; 1981 and later (20CRv3.MO)**: 8 members of pentad interpolated to daily HadISST2.2 sea surface temperatures.

Methodology

20CRv3 assimilates only surface observations of synoptic pressure into an 80-member the coupled Global Forecast System land-atmospheric model with prescribed sea surface temperatures and sea ice concentration. A coupled one-dimensional thermodynamic sea-ice model is also used. Boundary conditions of pentad sea surface temperature and monthly sea ice concentration and time-varying solar, volcanic, and carbon dioxide radiative forcings are prescribed.

Forecast model: 20CRv3 uses the atmospheric model from the NCEP Global Forecast System v14.0.1 coupled with the Noah land surface model and 2.5-layer thermodynamic sea ice model (Compo *et al*., (2011). The forecast system is run at a resolution of T254 (approximately 75 km at the equator) with 64 vertical levels up to .3 mb and it has 80 individual ensemble members.

Assimilation model: The data assimilation algorithm is the Ensemble Square Root Filter (Whitaker and Hamill 2002) with 4D Incremental Analysis Update (4D-IAU; Bloom *et al*., 1996, Lei & Whitaker 2016). The snow relaxes to a monthly climatology (Saha *et al*., 2010) over 60 days.

Streams: Every 5th year a stream is produced for a continuous 5 year period. Stream years are 1835, 1840, ... , 2005, 2010. Stream year 2010 will be extended beyond 2015.

Information about the technical and scientific quality

There are three previous versions of the reanalysis: V1, V2, and V2c. Several adjustments were made to the model prior to implementation in the 20CRv3 system. Updates to the parameterizations are described in Saha *et al*., (2010) and include revised solar radiation transfer, boundary layer vertical diffusion, cumulus convection, and gravity wave drag parameterizations. In addition, the cloud liquid water is a prognostic quantity with a simple cloud microphysics parameterization. Another important improvement is in the resolution and ensemble size. Previous 20CR versions were using a 56-member ensemble with a coarser spatial resolution (T62 28 levels), while the 20CRv3 is using 80 ensemble members with a finer spatial resolution (T254 64 levels). 20CRv3 also assimilates a larger set of observations, and includes an improved data assimilation system relative to its predecessor 20CRv2c.

Observations are first grossly tested for quality control: if the observation is outside the range 850 and 1090 hPa, or if the absolute difference between the observation and the first guess value is greater than 3.2 times the square root of the sum of the forecast ensemble variance and the observation error variance, the observation is rejected. (Slivinski *et al*., 2018). They are then subject to adaptive quality control and adaptive localization control.

Limitations and strengths for application in North Canada

Key Strengths: Length of record and estimates of uncertainty

Key Limitations: As with all reanalyses, users should take care in interpreting long-term trends - inconsistencies between 20CR and other data have been reported, especially on a regional scale.

References to documents describing the methodology or/and the dataset

Compo, G.P., J.S. Whitaker, P.D. Sardeshmukh, N. Matsui, R.J. Allan, X. Yin, B.E. Gleason, R.S. Vose, G. Rutledge, P. Bessemoulin, S. Brönnimann, M. Brunet, R.I. Crouthamel, A.N. Grant, P.Y. Groisman, P.D. Jones, M. Kruk, A.C. Kruger, G.J. Marshall, M. Maugeri, H.Y. Mok, Ø. Nordli, T.F. Ross, R.M. Trigo, X.L. Wang, S.D. Woodruff, and S.J. Worley, 2011: The Twentieth Century Reanalysis Project. Quarterly Journal of the Royal Meteorological Society, 137(654), 1-28, DOI: 10.1002/qj.776.

Slivinski, L.C., G.P. Compo, J.S. Whitaker, P.D. Sardeshmukh, B.S. Giese, C. McColl, R. Allan, X. Yin, R. Vose, H. Titchner, J. Kennedy, L. J. Spencer, L. Ashcroft, S. Brönnimann, M. Brunet, D. Camuffo, R. Cornes, T. A. Cram, R. Crouthamel, F. Domínguez-Castro, J. E. Freeman, J. Gergis, E. Hawkins, P. D. Jones, S. Jourdain, A. Kaplan, H. Kubota, F. Le Blancq, T.-C. Lee, A. Lorrey, J. Luterbacher, M. Maugeri, C. J. Mock, G.W. K. Moore, R. Przybylak, C. Pudmenzky, C. Reason, V. C. Slonosky, C. A. Smith, B. Tinz, B. Trewin, M. A. Valente, X. L. Wang, C. Wilkinson, K. Wood, and P. Wyszyński, 2019: Towards a more reliable historical reanalysis: Improvements for version 3 of the Twentieth Century Reanalysis system. Quarterly J. Roy. Meteorol. Soc., in press. DOI: 10.1002/qj.3598.

Link to download the data and format of data:

20CRv3 data are available at several organizations.

At NOAA/PSL, the ensemble mean and the ensemble uncertainty files are available in netCDF4 format: https://psl.noaa.gov/data/gridded/data.20thC_ReanV3.monolevel.html

At National Center for Atmospheric Research (NCAR), the ensemble mean and the ensemble uncertainty files are available in netCDF4 format: https://rda.ucar.edu/datasets/ds131.3/

At NERSC Science Gateway, data for every member of 20CRv3 are available in netCDF4 format: https://portal.nersc.gov/project/20C_Reanalysis/

Publications including dataset evaluation or comparison with other data in Canada

7.1.14 ***Dataset*: The ECMWF 5th Generation Land Reanalysis (ERA5-Land) - temperature**

Overview

This document provides an overview of the near-surface temperature products (T2m) of ERA5-Land, in the context of the larger ERA5-Land dataset. ERA5-Land is a replay of the land component of the ERA5 atmospheric global reanalysis using a finer spatial resolution and including a series of improvements making it more accurate for all types of land applications. ERA5-Land is produced by ECMWF framed within the Copernicus Climate Change Service (C3S) of the European Commission. The data covers a period from January 1950 to the present. It provides hourly data for many near-surface atmospheric and land-surface parameters.

Provider's contact information

ERA5-Land is produced by the Copernicus Climate Change Service (C3S) at ECMWF.

Copernicus User support (copernicus-support@ecmwf.int (external to C3S)).

Licensing

Licence: Copernicus (Licence agreement information can be found here or here).

Dataset citable as: **Muñoz Sabater**, J., (2019): ERA5-Land hourly data from 1981 to present. Copernicus Climate Change Service (C3S) Climate Data Store (CDS). (Accessed on < DD-MMM-YYYY >), 10.24381/cds.e2161bac

Variable name and units:

The 2 m temperature product (K) of ERA5-Land over northern Canada is the main focus of this document. 2 m temperature is calculated by interpolating between the lowest model level and the Earth's surface, taking account of the atmospheric conditions. This parameter has units of kelvin (K). Temperature measured in kelvin can be converted to degrees Celsius (°C) by subtracting 273.15. **Hourly** and **monthly** subsets are available.

The ERA5-Land 2 m temperature product can be found as follows:

- Select 2 m temperature hourly data from 1950 to present,
- Select 2 m temperature monthly averaged data from 1981 to present,

In ERA5-Land, hourly "2 m temperature" is an instantaneous parameter provided at hourly time step from the analyses. Monthly data is pre-calculated as monthly-mean averages from hourly data.

ERA5-Land also provides values for 2 m dew point temperature and skin temperature. The following table describes the single-level temperature data available in ERA5-Land.

Name	Units	Description
2 m temperature	K	Temperature of air at 2 m above the surface of land, sea or inland waters. 2 m temperature is calculated by interpolating between the lowest model level and the Earth's surface, taking account of the atmospheric conditions. Temperature measured in kelvin can be converted to degrees Celsius (°C) by subtracting 273.15.
2 m dew point temperature	K	Temperature to which the air, at 2 m above the surface of the Earth, would have to be cooled for saturation to occur. It is a measure of the humidity of the air. Combined with temperature and pressure, it can be used to calculate the relative humidity. 2 m dew point temperature is calculated by interpolating between the lowest model level and the Earth's surface, taking account of the atmospheric conditions. Temperature measured in kelvin can be converted to degrees Celsius (°C) by subtracting 273.15.
Skin temperature	K	Temperature of the surface of the Earth. The skin temperature is the theoretical temperature that is required to satisfy the surface energy balance. It represents the temperature of the uppermost surface layer, which has no heat capacity and so can respond instantaneously to changes in surface fluxes. Skin temperature is calculated differently over land and sea. Temperature measured in kelvin can be converted to degrees Celsius (°C) by subtracting 273.15.

Spatial coverage and resolution:

ERA5-Land is a global land-surface dataset. The atmospheric data is available on a regular latitude-longitude grid at 0.1° x 0.1° resolution (converted from native reduced-Gaussian grid resolution of approximately 9 km x 9 km), and on 4 surface layers. Oceans have been masked out with data available over landmasses and inland lakes.

Temporal coverage and resolution:

ERA5-Land 2 m temperature data is available from 1950 to present. The data is available at hourly and monthly sampling (see above).

ERA5-Land 2 m temperature data updates are made synchronously with ERA5 updates, approximately 2-3 months behind real time.

Information about observations (number, homogeneity)

ERA5-Land is not directly influenced by observations, but rather, indirectly influenced through the ERA5 atmospheric forcings. ERA5's data assimilation uses observations for all geophysical quantities from about 0.75 million observations per day in 1979 and about 24 million in 2018. The 2D-OI uses surface observations at 'screen level'. The online technical documentation provides tables with the satellite and in-situ observations used as input into ERA5. Further details can also be found in the ERA5 document previously prepared by the CCCS.

Methodology

ERA5-Land is produced under a single simulation of the land component of the ERA5 climate reanalysis, without coupling to the atmospheric module of the ECMWF's Integrated Forecasting System (IFS) and without data assimilation. The low atmospheric forcing is provided by the ERA5 reanalysis, with additional lapse-rate correction. The core of ERA5-Land is the Tiled ECMWF Scheme for Surface Exchanges over Land incorporating land surface hydrology (H-TESSEL). Because it runs without data assimilation, it makes it computationally affordable for relatively quick updates. For example, if significant improvements of the land surface model are implemented, the whole or part of the dataset can be reprocessed in a relatively short period. Updates are possible in case improved auxiliary datasets are used as input for the production.

Production of ERA5-Land is not produced as a single continuous segment, but instead as three segments: Stream-1 (2001 onwards), Stream-2 (1981-2000), and Stream-3 (1950-1980). This is because it allows parallel production of data enabling sooner public access to the data, and because the atmospheric forcings used by ERA5-Land is derived from ERA5, thus needing corresponding completed ERA5 segment. Each stream is initialized with various meteorological fields from ERA5 (temperature, precipitation, humidity, radiation, etc.). While ERA5-Land does not assimilate observations directly, they are introduced via the ERA5 atmospheric forcings. These forcings are adjusted using ERA5 derived lapse rates before being integrated with the ECMWF Carbon Hydrology-Tiled ECMWF Scheme for Surface Exchanges over Land (CHTESSEL) land surface model. This is done in 24-hour cycles, generating hourly outputs and the evolution of the land surface state and water and energy fluxes. For further details of the assimilation system used to obtain the ERA5 atmospheric forcings, please see the ERA5 document previously presented in this document.

Uncertainty estimate: Currently, ERA5-Land variable uncertainty estimates are those corresponding to ERA5. ERA5 uncertainty estimate is sampled by a 10-member lower-resolution Ensemble Data Assimilation (EDA) which provides background-error estimates for the deterministic HRES 4D-Var Data Assimilation system. The analysis method is the same for each EDA member and follows that of the HRES. Each member (except the control) is run with different random perturbations added to the observations. Likewise, the model physical tendencies are perturbed in the short forecasts that link subsequent analysis windows. Ensemble mean and spread have been pre-computed for convenience. Such uncertainty estimates are closely related to the information content of the available observing system

which has evolved considerably over time. They also indicate flow-dependent sensitive areas. To facilitate many climate applications, monthly-mean averages have been pre-calculated too, though monthly means are not available for the ensemble mean and spread.

The original plan was to apply the same methodology ERA5-Land to provide an estimate of the uncertainty fields as was done for ERA5. However, the uncertainty was estimated to be extremely low, and would have assigned unrealistically high confidence to the ERA5-Land variables. As such, it is recommended to use the corresponding ERA5 uncertainty estimates for the time being until further studies are done.

Information about the technical and scientific quality

ERA5-Land 2 m temperature represents one of the products of the latest global atmospheric reanalysis produced by Copernicus Climate Change Service at ECMWF. It is archived at a shorter (hourly) time step, has a fine spatial resolution, uses a more advanced assimilation system, and includes more sources of data than previous versions (e.g., ERA-Interim-Land). It is accompanied by extensive technical documentation and two principal scientific documentation papers. A list of 'known issues' is maintained at the online documentation (https://confluence.ecmwf.int/display/CKB/ERA5-Land%3A+data+documentation).

Information on land surface model: The land surface model of the ERA5-Land was operational in 2018 with the IFS model cycle 45r1. While most of the changes from the IFS Cy41R2 used in ERA5 are primarily technical, there were a few improvements to various fields: 1) the parameterization of the soil thermal conductivity was updated to take the ice component of frozen soil into consideration, 2) conservation of the soil-water balance was fixed and improved, and 3) rain over snow is now accounted for and is not accumulated in snow pack. Furthermore, a bug exists in IFS Cy41R2, that affects potential evapotranspiration (PET) flux calculations over forests and deserts, has been corrected in ERA5-Land, and unlike ERA5, ERA5-Land PET is an available dataset. However, PET is now determined by assuming a vegetation type of crops and no soil moisture stress. These assumptions may not be always realistic, and therefore PET should be used cautiously. This is unlikely to affect ERA5-Land 2 m temperature in Canada's north, but the user should be aware of the reason for this update. More information on the CHTESSEL land surface model used in ERA5-Land can be found in Muñoz-Sabater *et al.*, (2021, preprint).

Limitations and strengths for application in North Canada.

ERA5-Land is a newer land surface reanalysis and there are few available scientific evaluations of the dataset dedicated specifically to northern Canada. However, it should be noted that in northern Canada, there are currently no sub-daily records over a long historical period for many weather stations. Reanalyses data with hourly output cover this gap and, with suitable investigation and calibration (downscaling), could be valuable particularly for hydrological models and sub-daily extremes analyses. ERA5-Land uses ERA5 atmospheric forcings that assimilates surface temperature from stations.

As for all gridded data, observed values of 2 m temperature at local scales can differ from the values provided by the gridded dataset, which represent a statistical summary of the area surrounding a grid point. Also, changes in the amounts and types of observational data that are assimilated may produce artificial trends or variability in 2 m temperature and other reanalysis variables.

References to documents describing the methodology or/and the dataset

Muñoz Sabater, J., 2019: ERA5-Land hourly data from 1981 to present. Copernicus Climate Change Service (C3S) Climate Data Store (CDS). (Accessed on < DD-Month-YYYY >), https://doi.org/10.24381/cds.e2161bac

Muñoz-Sabater, J., E. Dutra, A. Agustí-Panareda, C. Albergel, G. Arduini, G., Balsamo, S. Boussetta, M. Choulga, S. Harrigan, H. Hersbach, B. Martens, D. G. Miralles, M. Piles, N. J. Rodríguez-Fernández, E. Zsoter, C. Buontempo, and J.-N. Thépaut, 2021: ERA5-Land: A state-of-the-art global reanalysis dataset for land applications. Earth System Science Data, 13(9), 4349-4383. https://doi.org/10.5194/essd-2021-82

Hersbach, H., B .Bell, P. Berrisford, S. Hirahara, A. Horányi, J. Muñoz-Sabater, J. Nicolas, C. Peubey, R. Radu, D. Schepers, A. Simmons, C. Soci, S. Abdalla, X. Abellan, G. Balsamo, P. Bechtold, G. Biavati, J. Bidlot, M. Bonavita, G. Chiara, P. Dahlgren, D. Dee, M. Diamantakis, R. Dragani, J. Flemming, R. Forbes, M. Fuentes, A. Geer, L. Haimberger, S. Healy, R.J. Hogan, E. Hólm, M. Janisková, S. Keeley, P. Laloyaux, P. Lopez, C. Lupu, G. Radnoti, P. Rosnay, I. Rozum, F. Vamborg, S. Villaume, and J.-N. Thépaut, 2020: The ERA5 global reanalysis. Quarterly Journal of the Royal Meteorological Society, 146(730), 1999–2049. https://doi.org/10.1002/qj.3803.

Link to download the data and format of data:

Data Access: Copernicus | ECMWF (requires login)

ERA5-Land is available in GRIB and NetCDF formats

Link to download hourly and monthly data on Copernicus:

- hourly data from 1950 to present,
- monthly averaged data from 1981 to present

Publications including dataset evaluation or comparison with other data in Canada

Sheridan, S.C., C.C. Lee, and E.T. Smith, 2020: A comparison between station observations and reanalysis data in the identification of extreme temperature events. *Geophysical Research Letters,* 47(15), e2020GL088120. (*It compares observations, ERA5, ERA5-LAND, and NARR, in the United States and Canada- only a very small number of stations are in North Canada*).

Zhang, R., S. Chan, R. Bindlish, and V. Lakshmi, 2021: Evaluation of Global Surface Water Temperature Data Sets for Use in Passive Remote Sensing of Soil Moisture. Remote Sensing, 13(10), 1872. https://doi.org/10.3390/rs13101872 (*This paper compares various lake surface water temperature products, including ERA5-Land, with in-situ observations. Comparisons are primarily made around the great lakes, with only few points in the north)*

Cao, B., S. Gruber, D. Zheng, and X. Li, 2020: The ERA5-Land soil temperature bias in permafrost regions. The Cryosphere, 14(8), 2581–2595. https://doi.org/10.5194/tc-14-2581-2020 (*The paper examines ERA5-Land soil temperature in permafrost regions across the northern hemisphere, including parts of Northern Canada)*

7.1.15 <u>Dataset</u>: ANUSPLIN Gridded Canadian dataset - temperature

Overview

This document provides an overview of minimum and maximum temperature gridded datasets created by the Canadian Forest Service, Natural Resources Canada. The dataset covers the period 1950 - 2017 at the daily, pentad and monthly time scale. 30-year averages were also created. The dataset was generated using ANUSPLIN with a 60 arc-second (approximately 2 km) and/or with a 300 arc-second (approximately 10 km) Digital Elevation Model (DEM; Lawrence et al., 2008), using station observations. Station data have been quality controlled but are not homogenized. Daily data is available over Canada, while pentad, monthly, and 30-year time scales are available for continental North America and Canada.

Provider's contact information

This spatial dataset was developed by researchers from the Integrated Ecology and Economics Division at Canadian Forest Service at Natural Resources Canada (Dr. Dan McKenney, Dr. Heather MacDonald, John Pedlar, Kevin Lawrence, Pia Papadopol, Kaitlin de Boer from the CFS and Dr. Michael Hutchinson from Fenner School of Environment and Society, Australian National University). If you have questions about this dataset, please contact Dr. Dan McKenney (dan.mckenney@canada.ca)

Licensing

Freely available. Contact Dr. Dan McKenney, Canadian Forest Service, Natural Resources Canada, dan.mckenney@canada.ca

The following scientific publications should be cited if you use these data in publications:

Canada:

Hutchinson, M.F., D.W. McKenney, K. Lawrence, J.H. Pedlar, R.F. Hopkinson, E. Milewska, and P. Papadopol, 2009: Development and testing of Canada-wide interpolated spatial models of daily minimum–maximum temperature and precipitation for 1961–2003. *J. Appl. Meteor. Climatol.*, **48**, 725–741, https://doi.org/10.1175/2008JAMC1979.1.

Hopkinson, R.F., D.W. Mckenney, E.J. Milewska, M.F. Hutchinson, P. Papadopol, and L.A. Vincent, 2011: Impact of aligning climatological day on gridding daily maximum-minimum temperature and precipitation over Canada. Journal of Applied Meteorology and Climatology, 50(8), 1654-1665, doi:10.1175/2011JAMC2684.1

North America:

MacDonald, H., D. W. McKenney, P. Papadopol, K. Lawrence, J. Pedlar, and M.F. Hutchinson, 2020: North American historical monthly spatial climate dataset. 1901–2016. Scientific Data, 7(1), 411-411. https://doi.org/10.1038/s41597-020-00737-2

Variable name and units:

Maximum temperature in degree Celsius (°C);

Minimum temperature in degree Celsius (°C);

Spatial coverage and resolution:

	Daily	Pentad	Monthly	30 –year average
Region	Canada	Canada and North America	Canada and North America	Canada and North America
Spatial resolution	~ 2 km and ~ 10 km	~ 2 km and ~ 10 km	~ 2 km and ~ 10 km	~ 2 km and ~ 10 km

Temporal coverage and resolution:

Daily – 1950-2017

Pentad – 1950-2017

Monthly – 1950-2017

30-year Average – 1961/1990, 1971/2000, 1981/2010

The data will continue to be updated regularly.

Information about observations (number, homogeneity)

Over Canada, the datasets were generated using station observations from MSC at Environment and Climate Change Canada (ECCC). Station data have been quality controlled for the time of observation but are not homogenized. The number of stations used for spatial modelling increased from 900 in 1950 to 2312 in 1985, and then declined to 1398 stations in 2017 (Figure 1). Stations are not evenly distributed in space. Many stations are located in southern Canada and fewer in northern Canada (Figure 2). For North America datasets, the ECCC stations were supplemented with GHCND hourly weather stations over the USA.

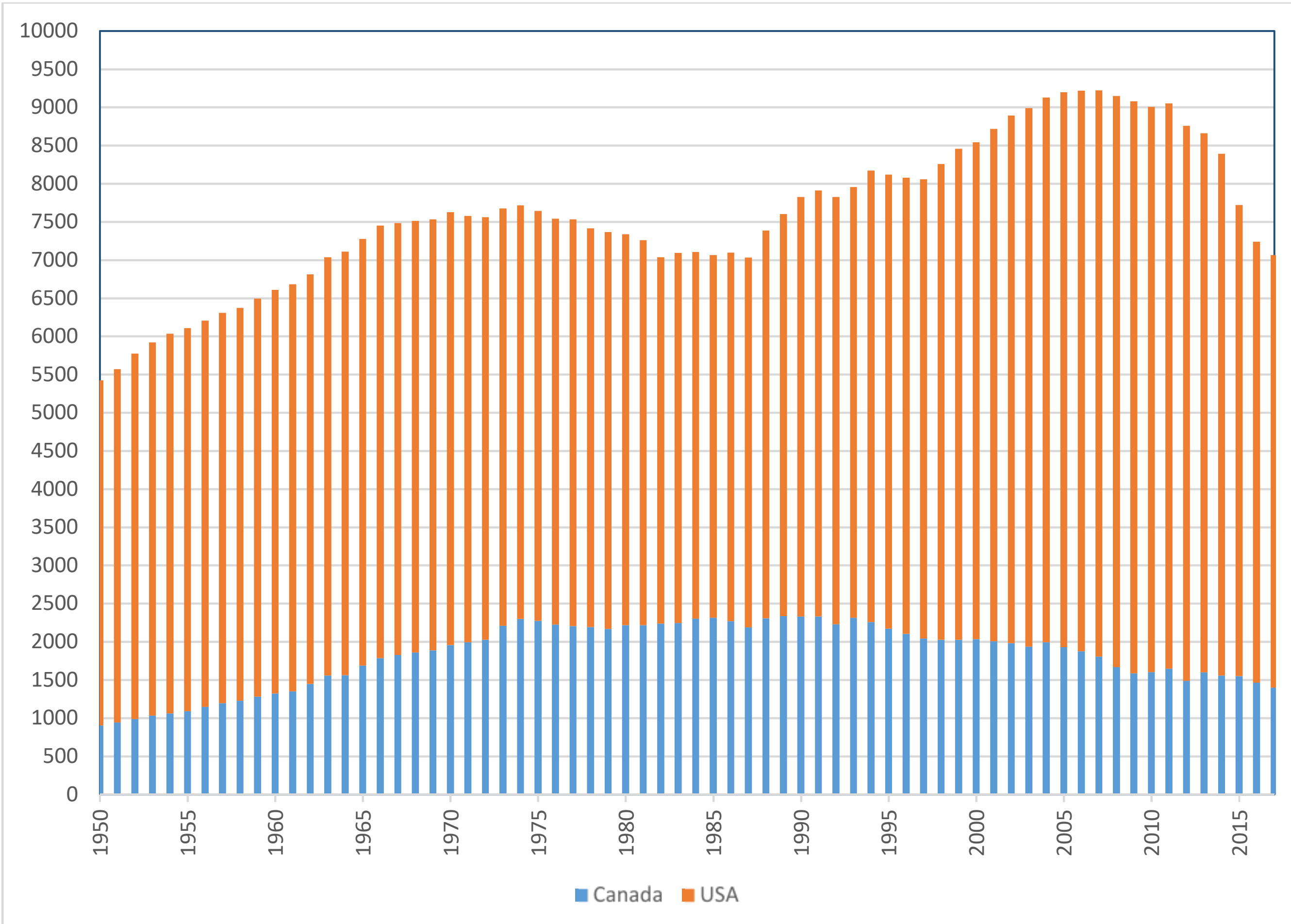


Figure 1. Number of Supporting Observing Stations by Year over Canada and USA (information provided by CFS/NRCan)

Figure 2. Location of stations used in North America ANUSPLIN datasets (from MacDonald *et al*., 2020). Note: Mexican stations were not covered by the digital elevation model.

Methodology

Daily maximum temperature and daily minimum temperature values over Canada were taken from MSC daily observations. The MSC daily data are derived from two sources depending on if the station has an automatic hourly sensor (most do now):

- hourly (temperatures are reported every hour and then the maximum temperature of the day and minimum temperature of the day are reported as daily max/min values), and
- daily (using a thermometer just for maximum temperature and a thermometer just for minimum temperature that are reported twice a day).

The daily minimum temperatures were adjusted for the change in observing time in 1961 at principal stations (see Hopkinson *et al*., 2011). Unlike other homogenized datasets (e.g., AHCCD) station joining was not implemented, and instead each record was linked to the exact observation location (see description in MacDonald *et al*., 2021).

The daily minimum and maximum temperatures over the USA, were estimated from GHCND hourly weather stations.

Spatial models were generated next using thin plate smoothing spline models as implemented in Australian National University Spline (ANUSPLIN; Hutchinson & Xu, 2013) for daily minimum/maximum temperature. For pentad, monthly and 30-year averages, the time average is first computed for each station and the result is next used with ANUSPLIN and the corresponding Digital Elevation Model.

Information about the technical and scientific quality

The data were quality controlled (see Hutchinson *et al*., 2011) and use up-to-date spatial modelling methods as detailed in MacDonald *et al*., 2020. The references provide several publications that detail the scientific quality of this data set.

The dataset is accompanied by several scientific papers.

Limitations and strengths for application in North Canada

Hutchinson *et al*., (2009) provide a comparative assessment of daily temperature spatial model quality in northern Canada.

References to documents describing the methodology or/and the dataset

Lawrence, K.M., M.F. Hutchinson, and D.W. McKenney, 2008: Multi-scale digital elevation models for Canada. Natural Resources Canada, Great Lakes Forestry Centre Frontline Tech. Note 109, 4 pp., https://d1ied5g1xfgpx8.cloudfront.net/pdfs/31499.pdf.

Hopkinson, R.F., D.W. Mckenney, E.J. Milewska, M.F. Hutchinson, P. Papadopol, and L.A. Vincent, 2011: Impact of aligning climatological day on gridding daily maximum–minimum temperature and precipitation over Canada. *J. Appl. Meteor. Climatol.*, **50**, 1654–1665, https://doi.org/10.1175/2011JAMC2684.1.

Hutchinson, M.F., and T. Xu, 2013: ANUSPLIN version 4.4 user guide. Australian National University, Fenner School of Environment and Society Doc., 55 pp., https://fennerschool.anu.edu.au/files/anusplin44.pdf.

MacDonald, H., D. W. McKenney, P. Papadopol, K. Lawrence, J. Pedlar, and M.F. Hutchinson, 2020: North American historical monthly spatial climate dataset, 1901–2016. Scientific Data, 7(1), 411-411. https://doi.org/10.1038/s41597-020-00737-2

*MacDonald, H., D.W. McKenney, X.L. Wang, J. Pedlar, P. Papadopol, K. Lawrence, Y. Feng, and M.F. Hutchinson, 2021: Spatial models of adjusted precipitation for Canada at varying time scales. Journal of Applied Meteorology and Climatology, 60(3), 291
304. https://doi.org/10.1175/JAMC-D-20-0041.1

McKenney, D. W., and et al., 2011: Customized spatial climate models for North America. *Bull. Amer. Meteor. Soc.*, **92, 1611–1622, https://doi.org/10.1175/2011BAMS3132.1.

*Describes spatial models at the pentad time scale (adjusted precipitation only, ANUSPLIN-AdjPdly)

**Describes related spatial models available on an ongoing basis at different time scales

Link to download the data and format of data:

All data is available in **asci** format at Canadian Forest Service, NRCan (contact Dr. Dan McKenney, dan.mckenney@canada.ca if you are interested in the asci datasets)

Canada-wide daily dataset and North-America wide monthly dataset, both with 300 arc-second spatial resolution in **netCDF** format, are available at Canadian Center for Climate Services, ECCC (contact the Climate Services Support Desk, https://climate-change.canada.ca/support-desk/Inquiry , if you are interested in this netCDF subset of data)

Publications including dataset evaluation or comparison with other data in northern Canada

Hutchinson, M.F., D.W. McKenney, K. Lawrence, J.H. Pedlar, R.F. Hopkinson, E. Milewska, and P.Papadopol, 2009: Development and testing of Canada-wide interpolated spatial models of daily minimum–maximum temperature and precipitation for 1961–2003. *J. Appl. Meteor. Climatol.*, **48**, 725–741, https://doi.org/10.1175/2008JAMC1979.1.

7.2 Precipitation

7.2.1 Dataset: MSC Station Observations – precipitation

Overview

This dataset provides in-situ surface observations archived by the Meteorological Service of Canada (MSC). It containes data from the MSC operational observation system as well as from their parteners. Therefore, not all stations are QC or maintained by MSC. The network of stations containes stations with only automatic instruments, and human observing (or manual) stations.

Provider's contact information

Environment and Climate Change Canada

donneesclimatiquesenligne-climatedataonline@ec.gc.ca

Licensing

Open Government Licence - Canada.

Variable name and units:

Hourly Precipitation Amount (mm)

Daily Total Rainfall (mm);

Daily Total Snowfall (cm);

Daily Total Precipitation (mm);

Daily Snow on the Ground (cm)

Monthly number of days with Precipitation 1.0 mm or more

Monthly Total Snowfall (cm)

Monthly Total Precipitation (mm)

Spatial coverage and resolution:

Canada, point locations.

Temporal coverage and resolution:

Time period varies per station with data for in the North starting in 1940's or 1950's until present.

The data is available at the hourly, daily and monthly time steps.

The data will continue to be updated regularly.

Information about observations (number, homogeneity)

The number of active stations changed over time. The following figure from Mekis et al. (2018) is presenting the locations of the surface weather stations across Canada with a Needs Index map in the background as of September 2016.

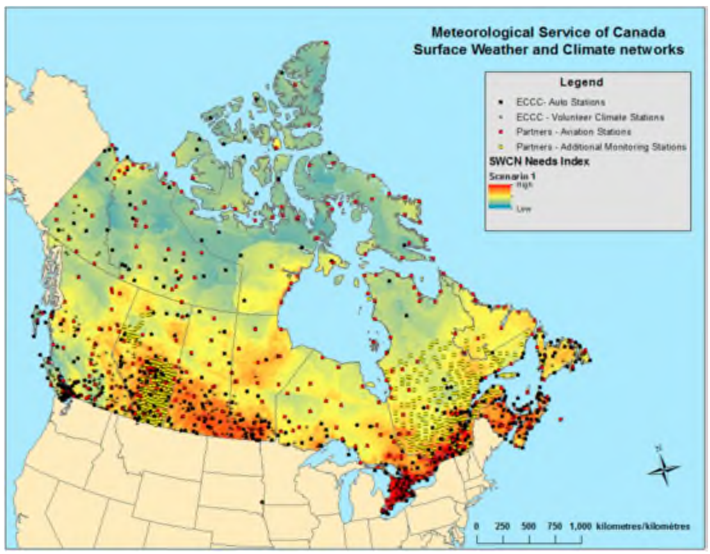


Figure 1. Surface weather stations across Canada, as of September 2016, with a Needs Index map in the background. For further details on station network evolution see Mekis et al. 2018. [Source: Mekis et al., 2018].

Most of the stations over Northern Canda are ECCC atomatic stations, stations from the Cooperative Climate Network of ECCC (a network of volunteer climate observers using high quality sensors provided and maintained by MSC), and stations from the Aviation Monitoring

Station network (which include automated and staffed weather stations) operated by NAV CANADA and the Department of National Defence (DND).

Methodology

Raw and quality-controlled station observations are archived and managed by the MSC's Archive Operations and Climate Services. Observations from different instruments are stored in different formats in the national archive. The methodology, the instruments and the location of instruments have changed in time. Many of initialy manual stations were replaced with automatic stations. The following is summarising some information regarding the manual measurements that should be considered when using historic station data.

Precipitation is defined as any and all forms of water, liquid or solid, that falls from clouds and reaches the ground. This includes drizzle, freezing drizzle, freezing rain, hail, ice crystals, ice pellets, rain, snow, snow pellets, and snow grains. Types of precipitation that originate aloft are classified under Liquid Precipitation, Freezing Precipitation and Frozen Precipitation. The measurement of precipitation is expressed in terms of vertical depth of water (or water equivalent in the case of solid forms) which reaches the ground during a stated period. The millimetre (mm) is the unit of measurement of liquid precipitation and the vertical depth of water or water equivalent is expressed to the nearest 0.2 mm. Less than 0.2 mm is called a "Trace" (also this number could vary with the instrument and the variable).

Rain is defined as the precipitation in the form of liquid water droplets greater than 0.5 mm. If widely scattered, the drop size may be smaller. The intensity of rain is based on the rate of fall. "Very light" means that the scattered drops do not completely wet a surface. "Light" means it is greater than a trace and up to 2.5 mm an hour. "Moderate" means the rate of fall is between 2.6 mm to 7.5 mm per hour. "Heavy" means 7 mm per hour or more.

Rain, drizzle, freezing rain, freezing drizzle and hail were usually measured at manual stations using the standard Canadian rain gauge, a cylindrical container 40 cm high and 11.3 cm in diameter. The precipitation is funnelled into a plastic graduate that serves as the measuring device. The standard rain gauge has changed over time and many types (some manual, some automatic) are now used (i.e. nipher, tb3, type b, genor, pluvio, TBRG, lambrecht).

Snowfall is the measured depth of newly fallen snow, measured using a snow ruler. Measurements are made at several points which appear representative of the immediate area, and then averaged. "Precipitation" in Canadian Climate Normals tables is the water equivalent of all types of precipitation.

At most ordinary stations the water equivalent of snowfall is computed by dividing the measured amount by ten. At principal stations it is usually determined by melting the snow that falls into Nipher gauges. These are precipitation gauges designed to minimize turbulence around the orifice, and are high enough above the ground to prevent most blowing snow from entering. The amount of snow determined by this method normally provides a more accurate estimate of precipitation than using the "ten-to-one" rule. Even at ordinary climate stations the normal precipitation values will not always be equal to rainfall plus one tenth of the snowfall. Missing observations is one cause of such discrepancies.

Precipitation measurements are usually made four times daily at principal stations. At ordinary sites they are usually made once or twice per day.

The total hourly precipitation is the total precipitation amount for minutes 00 through 60, inclusive, computed as the sum of the four 15-minute precipitation amounts. Precipitation amounts are stored in mm with a resolution of 0.1 mm. Prior to December 10, 2013, quality checks were not performed at the ingest stage and the status of the data is "R" (raw). From December 10, 2013, onward basic automatic quality assessment of the data is being performed at the ingest stage and the status of the data is "Q".

For climate stations operating on a 24-hour basis, before June 1, 1957, the climatological day for precipitation ended at 1230Z of the following day; from June 1, 1957, to June 30, 1961, the climatological day for precipitation ended at 1200Z of the following day; since July 1, 1961, the climatological day for precipitation ends at 0600Z of the following day. In cases where knowing time-of-observation is critical, the best approach is to check the historical inspection reports for the climate station.

Daily precipitation values are derived from: (1) the daily climate stations or Synop stations that provided daily measures separately from hourly measurements, and more resently (2) from hourly climate stations.

Monthly rainfall, snowfall and precipitation amounts represent the average or the total accumulation for a given month, and it is depending on the file.

Information about the technical and scientific quality

This dataset represents Environment and Climate Change Canada’s official station observations. Data are subject to change on an on-going basis as MSC is constantly QCing the data from ECCC stations. Not all data has the same level of QA/QC (i.e. aviation dat is not QA/QC by MSC but by NAV CANADA).

Limitations and strengths for application in North Canada

It is a challenge to sustain a cost-effective observing system over Norther Canada because of a large part of the teritory is constituted by remote areas (it is hard for technicians to fly to the site for maintenance, and they often have to wait for the thaw), and need personal to empty gauges and measure the snowfall. The special climatic conditions produce a large risk of power and telecommunication outages.

Concequently, observations in Nortehrn Canada are sparse and records are often incomplete. Since stations spatially are sparse, it is hard to QC and determine the accuracy of the record.

Other challenges are related to changes in the observing network, which involves relocation and closure of sites and changes in instruments and practices. On example is the change in gauge type in manual stations and the change from manual stations to automatic stations. At manual stations, the MSC copper gauge, also called the Type A gauge, was originally used in Canada to measure daily rainfall, while the type B was introduced in 1970s. The comparison of their measurements to the WMO reference pit gauge showed that the manual Type B gauge, in service since the 1970s, provided the most accurate measurements compared to the pit gauge data. Presently many of the stations are authomatic stations.

In general, gauge-measured precipitation has a systematic bias mainly caused by wind-induced undercatch, wetting losses (water adhering to the surface of the inner walls of the gauge that cannot be measured by the volumetric method) and evaporation losses (water lost by evaporation before the observation can be made). The wind-induced undercatch is especially important in the High Arctic.

References to documents describing the methodology or/and the dataset

The manual specific for aviation observations/reports (MANOBS): http://publications.gc.ca/collections/collection_2019/eccc/En56-238-2-2018-eng.pdf and http://publications.gc.ca/collections/collection_2019/eccc/En56-238-2-2018-fra.pdf

The manual of Climatological Observations used by the Cooperative Climate Network of ECCC (MANCLIM): https://publications.gc.ca/collections/collection_2012/ec/En56-238-3-2012-eng.pdf

https://climate.weather.gc.ca/doc/Technical_Documentation.pdf

Link to download the data and format of data:

Hourly, Daily and Monthly

Database searchable by location for CSV via CDO/MSC/ECCC: https://climate.weather.gc.ca/historical_data/search_historic_data_e.html

Only Hourly:

Map based extraction tool for GeoJSON and CSV on CCCS/ECCC: https://climate-change.canada.ca/climate-data/#/hourly-climate-data

Note: Only a subset of the total stations is shown due to size limitations. The priorities for inclusion are as follows: (1) Station is currently operational, (2) Stations with long periods of record, (3) Stations that are co-located with the categories above and supplement the period of record. For additional stations not included, go to CDO/MSC/ECCC.

Only Daily

Map based extraction tool for GeoJSON and CSV on CCCS/ECCC: https://climate-change.canada.ca/climate-data/#/daily-climate-data

CSV via MSC/ECCC: https://dd.weather.gc.ca/climate/observations/daily/

Note: Only a subset of the total stations is shown due to size limitations. The priorities for inclusion are as follows: (1) Station is currently operational, (2) Stations with long periods of record, (3) Stations that are co-located with the categories above and supplement the period of record. For additional stations not included, go to CDO/MSC/ECCC.

Only Monthly

Map based extraction tool for GeoJSON and CSV on CCCS/ECCC: https://climate-change.canada.ca/climate-data/#/monthly-climate-summaries

CSV via MSC: https://dd.weather.gc.ca/climate/observations/monthly/

Provincial and territory observation summaries in XML format for the last month are available on the MSC Datamart

Publications including dataset evaluation or comparison with other data in northern Canada

There are no publications that evaluate station data specifically on northern Canada. The following papers are providing general discussions on the issues with station data in Canada, with focus on precipitation data.

Mekis, É. and L.A. Vincent, 2011: An overview of the second generation adjusted daily precipitation dataset for trend analysis in Canada. Atmosphere-Ocean, 49(2), 163-177.

7.2.2 Dataset: MSC Climate Normals – precipitation

Overview

This dataset provides Climate Normals at the in-situ surface observations archived by the Meteorological Service of Canada (MSC), which containes data from the MSC operational observation system as well as from their parteners. The Climate Normals summarize or describe the average climatic conditions of a particular location over a period of 30 years, and they are based on Canadian climate stations with at least 15 years of data in the 30-year period. At the completion of each decade, Environment and Climate Change Canada updates its Climate Normals for as many locations and as many climatic characteristics as possible. MSC is QC the Normals but the QC of the data used in the Normal computation is done by the owers of the sites.

Provider's contact information

Environment and Climate Change Canada

donneesclimatiquesenligne-climatedataonline@ec.gc.ca

Licensing

Open Government Licence - Canada.

Variable name and units:

Rainfall (mm)

Snowfall (mm)

Precipitation (mm)

Days with rainfall

>= 0.2 mm

>= 5 mm

>= 10 mm

>= 25 mm

Days with snowfall

>= 0.2 cm

>= 5 cm

>= 10 cm

>= 25 cm

Days with precipitation

>= 0.2 mm

>= 5 mm

>= 10 mm

>= 25 mm

Extreme values and snow on ground (snow depth) are also available.

Spatial coverage and resolution:

Canada, point locations.

Temporal coverage and resolution:

The data is presented as 30-year average and has a decadal time step: 1941-1970, 1951-1980, 1961-1990, 1971-2000 and 1981-2010 periods.

The data will continue to be updated every decade.

Information about observations (number, homogeneity)

The number of active stations changed over time. The following figure from Mekis et al. (2018) is presenting the locations of the surface weather stations across Canada with a Needs Index map in the background as of September 2016.

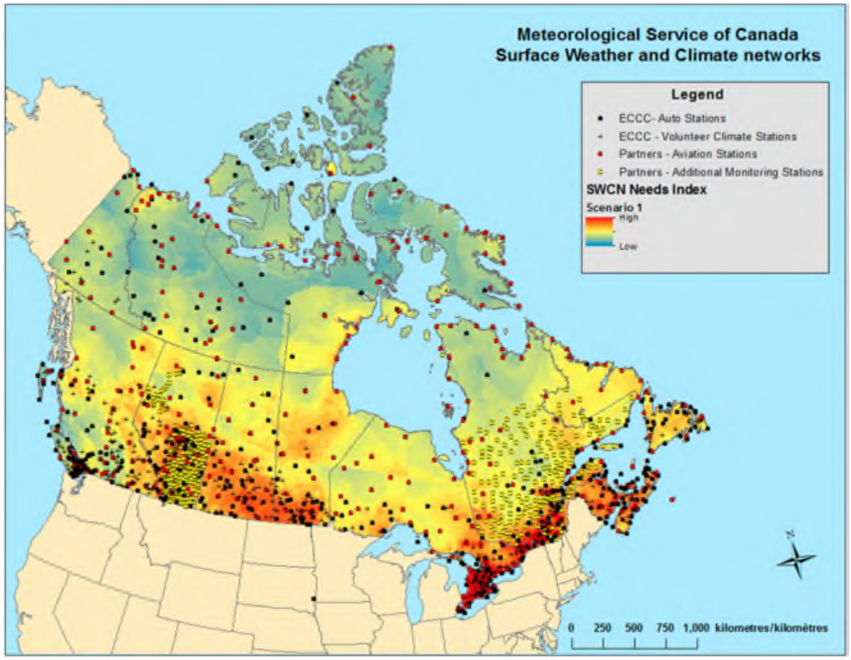


Figure 1. Surface weather stations across Canada, as of September 2016, with a Needs Index map in the background. For further details on station network evolution see Mekis et al. 2018. [Source: Mekis et al., 2018].

Stations over Northern Canda with precipitation measurements are the ECCC atomatic stations, the ECCC Volunteer Climate Stations and stations from the Aviation Monitoring Station network (which include automated and staffed weather stations) operated by NAV CANADA and the Department of National Defence (DND).

The following table presents the number of stations per region in the Northen Canada for the 1981-2010 normals (the number varies with the period of the record).

Region	No. stations 1981-2010

Yukon	19 (BEAVER CREEK A; BLANCHARD RIVER; BURWASH A; CARCROSS; DAWSON A; DRURY CREEK; FARO A; MAYO A; MAYO ROAD; MCQUESTEN; OLD CROW A; OTTER FALLS NCPC; PELLY RANCH; STEWART CROSSING; TAKHINI RIVER RANCH; TESLIN A; WATSON LAKE A; WHITEHORSE A; WHITEHORSE RIVERDALE)
NWT	11 (FORT LIARD A; FORT MCPHERSON A; FORT SIMPSON A; FORT SMITH A; HAY RIVER A; INUVIK A; NORMAN WELLS A; SACHS HARBOUR A; TUKTOYAKTUK A; ULUKHAKTOK A; YELLOWKNIFE A)
Nunavut	24 (ALERT; ARVIAT A; BAKER LAKE A; CAMBRIDGE BAY A; CAPE DORSET A; CHESTERFIELD INLET A; CLYDE A; CORAL HARBOUR A; EUREKA A; GJOA HAVEN A; HALL BEACH A; IGLOOLIK; IGLOOLIK A; IQALUIT A; KUGAARUK A; KUGLUKTUK A; LUPIN A; NANISIVIK A; POND INLET A; RANKIN INLET A; REPULSE BAY A; RESOLUTE CARS; TALOYOAK A; WHALE COVE A)
North Quebec	3 (LA GRANDE RIVIERE A; KUUJJUARAPIK A; KUUJJUAQ A)
Labrador	4 (CARTWRIGHT; GOOSE A; MAKKOVIK A; NAIN A; WABUSH LAKE A)

Methodology

The MSC computation of normal follows WMO standard procedure, which has evolved with the time. For precipitation, (1) the normal are computed over a 30 year period of consecutive records, starting January 1st and ending December 31st, (2) compute the total the amount for each month (total precipitation, total snowfall), then average (3) do not allow any missing data (use 100% completeness). Annual value is sum of monthly normals from all the individual months in the period of 30 years that sufficiently fulfilled the requirement. The calculation method for the variables that counts the days has changed in new WMO standards:

(a) The count of values for each individual month is calculated, and converted to a percentage of days with available observations. (For example, if there were 25 days with observations in February 1991 and there were 22 days with temperatures ≥ 30 °C, the value for February 1991 is calculated as 88%).

(b) The average percentage count for each month with sufficient available data within the 1991–2020 period is calculated.

(c) This average is then reconverted to an average number of days for the month by multiplying the average percentage by the number of days in the month. February percentages should be multiplied by 28.25.

(d) The sum of the monthly normals as per above instructions constitutes the annual normal.

Information about the technical and scientific quality

This dataset is produced following the standard WMO procedure. MSC is QC the Normals but the QC of the data used in the Normal computation is done by the owers of the sites.

Limitations and strengths for application in North Canada

It is a challenge to sustain a cost-effective observing system over Norther Canada because of a large part of the teritory is constituted by remote areas (need someone to frequently empty the gauges and it is hard for technicians to fly to the site for maintenance in Northern Canada remote locations). The special climatic conditions produce a large risk of power and telecommunication outages. Concequently, observations in Nortehrn Canada are sparse and records are often incomplete. Therefore, apart from any uncertainty due to site, instrument, or observing program changes, or general representativeness of the observing site with the surrounding region, the normals for most locations will have some uncertainty due to the fact that the observations are not complete for the 30-year period.

References to documents describing the methodology or/and the dataset

https://climate.weather.gc.ca/doc/Canadian_Climate_Normals_1981_2010_Calculation_Information.pdf

https://climate.weather.gc.ca/doc/Canadian_Climate_Normals_1971_2000_Calculation_Information.pdf

https://climate.weather.gc.ca/doc/Canadian_Climate_Normals_1961_1990_Calculation_Information.pdf

https://drive.google.com/open?id=1OLqRySaAdJSpajkEGmOAHd7zKR2FW72s

https://drive.google.com/open?id=1M2W8t7bG1JmseLEgm90G8O7hAc718RBD

Link to download the data and format of data:

Most recent Normals (1981-2010):

GeoJSON and CSV on CCCS/ECCC: https://climate-change.canada.ca/climate-data/#/climate-normals

CSV via MSC: https://dd.weather.gc.ca/climate/observations/normals/

CSV via ClimateData.ca: https://climatedata.ca/explore/variable/?var=weather-stations

Note: A smaller number of stations qualify for Normals compared to earlier Normals decadal publications.

For all Normals periods:

CSV via CDO/MSC/ECCC: https://climate.weather.gc.ca/climate_normals/index_e.html

Publications including dataset evaluation or comparison with other data in northern Canada

Information not available.

7.2.3 *<u>Dataset</u>: MSC Daily Climate Records – precipitation*

Overview

The daily climate records database, also known as Long Term Climate Extremes (LTCE), was developed to address the fragmentation of climate information due to station changes (opening, closing, relocation, etc.) over time. For approximately 750 locations in Canada, "virtual" climate stations have been developed by joining (threading) climate data for an urban location, from nearby stations to make long-term records. For each long-term record, the extremes (record values) of daily maximum/minimum temperatures, total precipitation and snowfall for each day of the year were identified. This dataset identifies, for example, the greatest precipitation over the record for each day of the year for the selected area (e.g., the greatest daily precipitation recorded in the Tuktoyaktuk area for July 30th was 9.4 mm and was reached in 1964).

Provider's contact information

Environment and Climate Change Canada

climatatlantique-climateatlantic@ec.gc.ca

Licensing

Open Government Licence - Canada.

Variable name and units:

Greatest daily precipitation (mm)

Spatial coverage and resolution:

Canada, point locations.

Temporal coverage and resolution:

The data is available for each day of the year. The record value over the entire recorded period and the year when the record was reached are provided.

The data will continue to be updated regularly.

Information about observations (number, homogeneity)

The following table presents the number of stations per region and variable

Region	Precipitation
Yukon	14
NWT	23
Nunavut	28
North Quebec	7
Labrador	10

Methodology

The dataset was developed using daily values from MSC stations. For climate stations operating on a 24-hour basis, since July 1, 1961, the climatological day for precipitation (as for temperature) ends at 0600Z of the next day. From June 1, 1957, to June 30, 1961, the climatological day for precipitation (and maximum temperature) ended at 1200Z of the next day. Before June 1, 1957, the climatological day for precipitation and maximum temperature ended at 1230Z of the next day.

At locations with no hourly observations, observation times are generally morning and evening local time. In general, the climatological day for precipitation (and maximum temperature) ends at the morning observation of the next day. For sites reporting only once per day, the calendar day rather than climatological day applies.

Each of the City Page locations of weather.gc.ca has a Virtual climate station. A virtual climate station is the result of threading (joining) together climate data from nearby current and historical stations to build a long-term dataset. All available data within a 20 km radius of each urban center was searched and catalogued (some latitude was permitted to include data which was close to the 20 km cut-off during the subjective review stage). The starting point is a representative, currently active station in the area of the urban center. These data were followed backward in time until it was no longer available or until it was replaced by a higher quality dataset from the same station. When the earliest or end point of a thread fragment was reached, an alternate from the catalogue was chosen, keeping in mind data quality, proximity to the prior station and any gaps in data length. This process was repeated until the thread extended back in time as far as possible.

In a small percentage of cases where there is no currently active climate station within 20 km of the urban center, an alternate station may have been chosen from representative stations at a maximum radius of 35 km**.**

Information about the technical and scientific quality

This dataset represents summaries of Environment and Climate Change Canada's official station observations.

Limitations and strengths for application in North Canada

Observations are sparse in the northern Canada and the records have missing data.

References to documents describing the methodology or/and the dataset

Technical documentation

Frequently asked questions about long term climate extremes for Canada

Link to download the data and format of data:

Map based extraction tool: GeoJSON and CSV on CCCS/ECCC: https://climate-change.canada.ca/climate-data/#/daily-climate-records

Publications including dataset evaluation or comparison with other data in northern Canada

There are no publications that evaluate this dataset in northern Canada.

7.2.4 *<u>Dataset</u>: Adjusted and homogenized Canadian climate data (AHCCD) – Second Generation of Adjusted Precipitation*

Overview

Adjusted and homogenized Canadian climate data (AHCCD) consist of daily, monthly, seasonal and annual totals of daily adjusted total precipitation (millimetres) for 467 locations in Canada. The time periods of the data vary by location. Data availability over most of the Canadian Arctic is restricted to the mid-1940s to 2017. AHCCD was developed for use in climate research, including climate change studies as the assessment of long-term trends in Canada's climate.

Provider's contact information

Environment and Climate Change Canada

Contact cccs-ccsc@ec.gc.ca for information related to monthly, seasonal and annual data.

Contact ahccd@ec.gc.ca for information relate do daily data.

Licensing and citation

Open Government Licence - Canada.

The end-user licence for Environment and Climate Change Canada's data servers specifies the conditions of use of this data.

Citation:

Variable name and units:

Total precipitation (mm)

Spatial coverage and resolution:

Canada, point location.

Temporal coverage and resolution:

Time period varies per station with data for most stations in the North starting in mid-40's or 50's and ending in 2017.

The data is available at **daily, monthly, seasonal, annual** time steps.

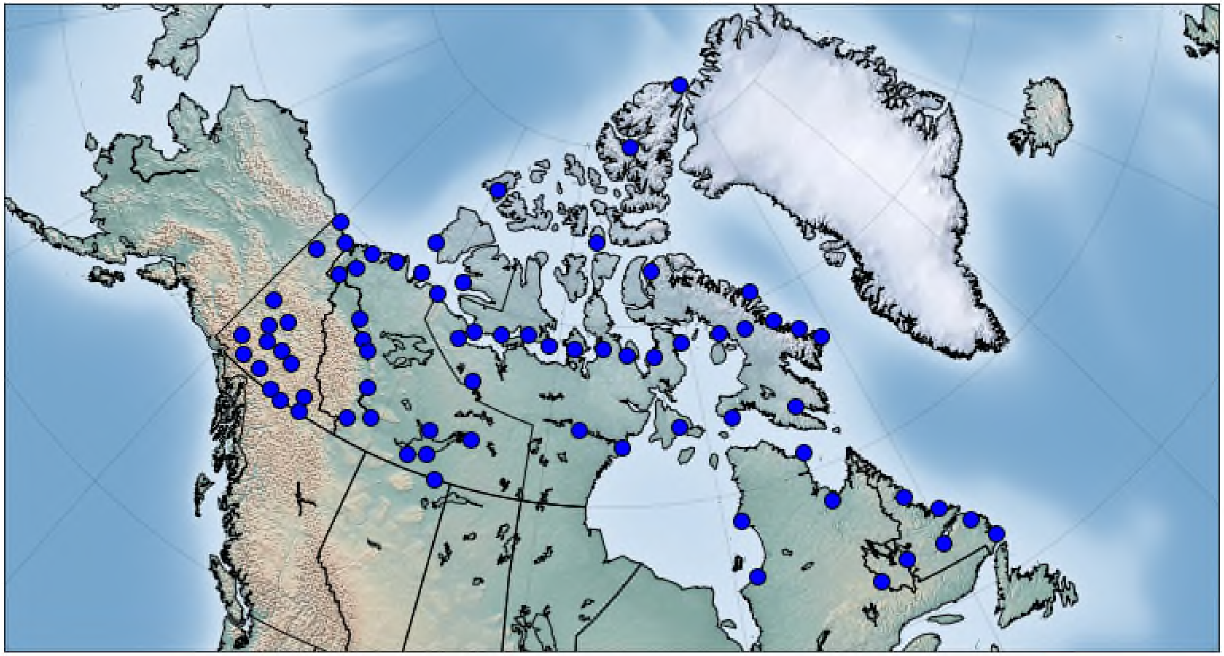
The data will continue to be updated regularly.

Information about observations (number, homogeneity)

The following table presents the number of stations per region and daily variable:

Region	No stations	List of names
Yukon	16	DAWSON ; DRURY CREEK; HAINES; JUNCTION; KOMAKUK BEACH ; MAYO; OLD CROW ; PELLY RANCH; ROSS RIVER YTG; SHINGLE POINT ; SWIFT RIVER; TESLIN ; TUCHITUA; WATSON LAKE ; WHITEHORSE
NWT	19	CAPE PARRY ; FORT GOOD HOPE ; FORT MCPHERSON ; FORT RELIANCE; FORT RESOLUTION ; FORT SIMPSON ; FORT SMITH; HAY RIVER ; INUVIK; MOULD BAY; NICHOLSON PENINSULA; NORMAN WELLS ; SACHS HARBOUR ; TUKTOYAKTUK; TULITA; ULUKHAKTOK ; WRIGLEY ; YELLOWKNIFE ; YOHIN
Nunavut	27	ALERT; BAKER LAKE ; BYRON BAY ; CAMBRIDGE BAY ; CAPE DORSET ; CAPE DYER ; CAPE HOOPER; CHESTERFIELD INLET ; CLINTON POINT; CLYDE ; CORAL HARBOUR ; DEWAR LAKES; EUREKA; FOX FIVE; GLADMAN POINT ; HALL BEACH ; IQALUIT; JENNY LIND ISLAND ; KUGAARUK ; KUGLUKTUK ; LADY FRANKLIN POINT ; LONGSTAFF BLUFF; LUPIN; MACKAR INLET; NANISIVIK ; RESOLUTE CARS; SHEPHERD BAY
North Quebec	4	INUKJUAK; KUUJJUAQ ; KUUJJUARAPIK ; QUAQTAQ
Labrador	7	CARTWRIGHT; CHURCHILL FALLS; GOOSE ; MAKKOVIK ; MARY'S HARBOUR ; NAIN ; WABUSH LAKE

The figure below show the position of the stations for northern Canada.



Note: A larger set with daily data (3346 stations instead of 467 stations across Canada) exist at http://open.canada.ca/data/en/dataset/d8616c52-a812-44ad-8754-7bcc0d8de305. This dataset is not part of AHCCD product because it was produced without joining of stations, however, it is using the same adjustments/corrections as the AHCCD precipitation data.

Methodology

The daily AHCCD station data are derived from observations made at the weather stations from the Meteorological Service of Canada (MSC) and use the same ID as MSC stations; this allows users to compare the raw station data to adjusted data. The AHCCD dataset was developed for use in climate research, including climate change studies that needs long-term data records. Also several variables were processed, the method used to adjust and homogenize station data differs for each variable. Adjusted precipitation datasets accounts for a number of known errors in precipitation measurements. The methods to adjust daily rainfall and snowfall are described in Mekis and Vincent (2011).

The adjustment of rain and snow was done separately (allowing the correction of known problems such as instrument deficiencies and changes in observing procedures) and used just measurements that were made by observers (they do not include any automatic measurements).

First, rain gauge measurements of precipitation are known to underestimate amount of actual precipitation due to the loss of rain water from the instruments during periods of high intensity rainfall. Field experiments have been undertaken at various locations to quantify these biases and correct them for the types of rain gauges used by the MSC.

Second, ruler measurements have been used historically to measure snow depth and an assumed density of 100 kg m-3 was used to convert snow depth to snow water equivalent. However, AHCCD data use more accurate density estimates that vary geographically across the country. Snow tends to be denser in the east and north of the country, and less dense in the west. Also, daily precipitation amounts below a minimum measurable amount were set to a value of zero in the past. However, the accumulated impact of these trace amounts can become significant, especially in areas like the Arctic where precipitation amounts are low. Adjustments were applied to account for this underestimation by assigning a value to these trace days: 0.1 mm was applied for rain, whereas for snow the adjustment factor ranged from 0.03 to 0.07 mm depending on the station location.

Finally, nearby observations were sometimes joined and adjustments were applied based on a simple ratio computed using available periods of overlapping data. For more information, please see Mekis and Vincent (2011).

Daily total precipitation was calculated by adding the station's adjusted daily rain gauge and snow ruler observations together. Monthly rain, snow and total precipitation were calculated by adding the station's daily rain gauge, snow ruler and total precipitation observations, over the month. A monthly value is missing if more than 3 consecutive days or more than 5 random days are missing in the month; a seasonal/annual value is missing if at least one month is missing in the respective season/year.

Information about the technical and scientific quality

The data were quality controlled (information is provided in Mekis and Vincent 2011). The dataset is accompanied by a technical documentation and a scientific paper.

Over the past decade, precipitation monitoring technology has evolved and Environment and Climate Change Canada and its partners implemented a transition from manual observations to using automatic precipitation gauges. The update of historical adjusted precipitation data has been on temporary hiatus since autumn 2017 to enable the data integration required to link the current precipitation observations from automatic precipitation gauges to the long-term historical manual observations. Updates will resume once this extensive data reconciliation effort is complete.

Limitations and strengths for application in North Canada

The data constitute the longest records at stations that were adjusted for known measurement issues such as wind undercatch, evaporation and wetting losses for each type of rain gauge, snow water equivalent from ruler measurements, trace observations and accumulated amounts from several days. As a result of adjustments, total rainfall amounts have increased by more than 20% in the Canadian Arctic, compared to the original observations, while the effect of the adjustments on snowfall was larger and more variable throughout the country. Observations from nearby stations were sometimes combined to create time series that are longer; hence, making them more useful for trend studies. This dataset is usually used to validate other historical datasets estimated using various models or methodologies.

The major limitation for applications in the North is the number restrained of locations with a record. Also, the data availability over most of the Canadian Arctic is restricted to the mid-1940s to 2017. As any data at stations, it has missing values, which may vary by variable, station and time. The missing values in daily records were taken into account when monthly, seasonal and annual data was developed (see methodology section).

References to documents describing the methodology or/and the dataset

Mekis, E. and L.A. Vincent, 2011: An overview of the second generation adjusted daily precipitation dataset for trend analysis in Canada. Atmosphere-Ocean, 49(2), 163-177.

Xu (2012) Homogenization of Canadian in-situ precipitation data, Final Report of Contract KM040-09-1134.

Technical documentation**:**

http://crd-data-donnees-rdc.ec.gc.ca/CDAS/products/EC_data/AHCCD_daily/Adj_Precipitation_Documentation_Daily.doc

Link to download the data and format of data:

For daily data:

The large set with daily data (3346 stations instead of 467 stations across Canada) without joining of stations: http://open.canada.ca/data/en/dataset/d8616c52-a812-44ad-8754-7bcc0d8de305

The second generation of daily data with joining of stations:

http://crd-data-donnees-rdc.ec.gc.ca/CDAS/products/AHCCD_daily/ (.txt on CRD/ECCC webpage)

https://climatedata.ca/download/#ahccd-download (this will be available in the following months)

For monthly, seasonal and annual data (second generation of daily data with joining of stations):

https://climate-change.canada.ca/climate-data/#/adjusted-station-data (GeoJSON and CSV on CCCS/ECCC webpage)

http://crd-data-donnees-rdc.ec.gc.ca/CDAS/products/AHCCD/ (.txt on CRD/ECCC webpage)

On MSC Datamart at https://dd.weather.gc.ca/climate/ahccd/geojson/historical/ (GeoJSON)

Publications including dataset evaluation or comparison with other data in northern Canada.

This dataset is usually used as reference in the evaluation of climate variables from other datasets.

Adjusted precipitation was used in a number of climate trends studies including the trends in annual and seasonal temperature and precipitation in Canada (Vincent *et al*., 2015, Zhang *et al*., 2000), changes in temperature and precipitation daily indices (Vincent *et al*., 2018, Vincent and Mekis, 2006 and Mekis and Vincent, 2011) and global changes in daily and extreme temperature and precipitation (Alexander *et al*., 2006).

7.2.5 *<u>Dataset</u>: Hydro Québec Datasets*

Overview

Hydro Québec provides in-situ data for northern Québec mostly south of the 55° parallel. That is data coverage corresponds mainly to Hydro Québec's area of interest, where the hydroelectric installations are. Most sites are equipped with complete weather stations (that is parameters such as temperature, humidity, wind and precipitations are covered). In the same vicinities, Hydro Quebec also has a snow data network and hydro stations (flow rate, water level, water temperatures, etc. being measured). Weather, snow and hydro sites are not necessarily situated near each other, but it can happen, especially regarding weather and snow measurements.

Provider's contact information

Open data site: https://www.hydroquebec.com/documents-donnees/loi-sur-acces/demande-acces-information.html

Licensing

Data are available under the terms of "Creative Commons Licence: Attribution-NonCommercial-ShareAlike 4.0 International". For more information, visit the Hydro-Québec webpage regarding open data licence.

https://creativecommons.org/licenses/by-nc-sa/4.0/deed.en

https://www.hydroquebec.com/documents-donnees/donnees-ouvertes/licence.html

Limitations and strengths of datasets for application in Northern Canada

As of now, open data only contains the last 10 days but upon request the complete history can be available when possible. Gaps in the datasets are common as northern sites are sensible to longer maintenance delays when there is a malfunction at the sites. Only raw datasets are offered for now and Hydro Quebec is will not be responsible for their use.

<u>Dataset</u>: **Hydro Québec Temperature**

Variable name and units:

All temperatures are in °C. Hourly and daily minimum and maximum temperatures.

Spatial coverage and resolution:

The region between the 50° and 55° parallel in Quebec encloses the northern area of Hydro Quebec's installations. A little more than 80 weather stations measuring air temperatures composes Hydro Quebec's network in the north.

Temporal coverage and resolution:

Temporal coverage varies depending on site. The earliest data begin around 1990 (some few sites) and sites have closed and opened with time. Data coverage has increased and is more stable since 2005.

Dataset: **Hydro Québec Air Humidity**

Variable name and units:

Hourly instant relative air humidity in %.

Spatial coverage and resolution:

In the province of Quebec, between 50° and 55° N, there are about 60 sites with relative air humidity data.

Temporal coverage and resolution:

Temporal coverage varies depending on site. The earliest data begin around 2005 but data coverage has increased mostly after 2010.

Dataset: **Wind**

Variable name and units:

All winds are in m/s. Hourly wind direction and speed are available.

Spatial coverage and resolution:

In the area between 50 and 55°N, up to 40 sites have wind sensors (at 2,5 or 10 m depending on the sites).

Temporal coverage and resolution:

Temporal coverage varies depending on site. The earliest data begin around 2005 with data coverage increasing in the last few years.

Dataset: **Solar Radiation**

Variable name and units:

Hourly instant solar radiation in MJ/m^2.

Spatial coverage and resolution:

In the northern portion of Quebec, Hydro Quebec has 5 sites where solar radiation is measured.

Temporal coverage and resolution:

Temporal coverage varies depending on site. The earliest data begin around 2005 but some joined later in the 2010's.

Dataset: Precipitation

Variable name and units:

All precipitation variables are in mm. Hourly and daily total precipitation, rain and snow.

Spatial coverage and resolution:

Still in the Quebec area included between the 50° and 55° parallels, Hydro Quebec a spatial coverage of roughly 90 sites with precipitation data. There are more sites with rain (that is liquid precipitation only) data available. Fewer sites have snow data (that is at the weather station itself where rain data is also available), but still there are almost 80 of them.

Temporal coverage and resolution:

Temporal coverage varies depending on site. The earliest data begin around 1990 (some few sites) and sites have closed and opened with time. Data coverage has increased since 2005.

Dataset: Snow

Variable name and units:

Hourly and daily mean snow height in cm, daily snow water equivalent in mm and daily snow density in %.

Spatial coverage and resolution:

Historically, in the north, Hydro Quebec had about 40 manual snow survey sites. That number is now down to less than 20 and they will totally disappear in the next years. These measurements have been replaced in the last years by a network (with now approximately 60 sites) of automated SWE measurements with GMON (CS725).

Temporal coverage and resolution:

Temporal coverage varies greatly depending on site. The earliest data begin around 1960 and as mentioned above, manual snow surveys sites are now closing and being replaced by GMON sites that mainly opened after 2015

Dataset: Flow rate

Variable name and units:

All flow data are in m^3/s. Hourly total flow rate, discharge rate, river discharge and turbinated flow.

Spatial coverage and resolution:

Flow rates and river discharges are measured over approximately 40 watersheds south of 55°N.

Temporal coverage and resolution:

Temporal coverage varies depending on site. The earliest data begin around 1960 and data coverage has increased in the 2000's.

7.2.6 *Dataset*: *Canadian Gridded Precipitation Anomalies (CANGRD)*

Overview

Canadian gridded temperature and precipitation anomalies (CANGRD) are datasets of historical gridded temperature and precipitation anomalies, interpolated from AHCCD at a 50 km resolution across Canada. This document is describing the precipitation data. Total precipitation anomalies represent the departure from a mean reference period (1961-1990) expressed as percentage change (%) from the mean reference period. Trends of relative total precipitation change (%) for 1948-2012 are also available for download.

Provider's contact information

Environment and Climate Change Canada (Contact the Climate Services Support Desk)

Electronic Mail Address at CRD: f.ccds.info-info.dscc.f@ec.gc.ca

Licensing and citation

Open Government Licence - Canada.

The end-user licence for Environment and Climate Change Canada's data servers specifies the conditions of use of this data.

Variable name and units:

Total precipitation (mm)

Spatial coverage and resolution:

Canada, 50 km spatial resolution, polar stereographic grid.

Temporal coverage and resolution:

Precipitation anomalies: 1954-2014

Data is available at monthly, seasonal and annual time steps.

Information about observations (number, homogeneity)

CANGRD data is based on the AHCCD data and are available from 1948 for all of Canada, and from 1900 for southern Canada (south of 60°N). AHCCD has a small number of stations in North Canada, and the distance between stations is large. The AHCCD and CANGRD are usually updated annually in the spring.

Methodology

The monthly, seasonal and annual total precipitation anomalies are computed at each observing station and for each year by subtracting the relevant baseline average (defined as average over 1961-1990 reference period) from the relevant monthly, seasonal, and annual values. They are then normalized by dividing by the mean reference period and expressed in percentage to produce normalized precipitation departures. The anomalies are interpolated to the evenly spaced (50 km) grid in polar stereographic projection using the Gandin's Optimal Interpolation. Values for grid boxes over large bodies of water such as Hudson Bay are excluded. The grid is a 125 (columns) by 95 (rows) matrix, where the SW corner (0,0) is at 40.0451°N latitude and 129.8530°W longitude. The projection is true at 60.0°N and centered on 110.0°W.

Information about the technical and scientific quality

A positive aspect of this dataset is the use of adjusted and/or homogenised data from the AHCCD (adjusted precipitation data). This station-based dataset has undergone rigorous quality control, and have been adjusted for identified inhomogeneities caused by station relocation, changes in instrumentation and in observing practices and are corrected for undercatch and regional variation in snowfall density following Mekis and Vincent (2011)

The dataset uses classical methods for the interpolation. In general, results from the interpolation of anomalies are better than those from actual values because anomalies vary less in space.

Data is available in .grd format on the CRD webpage. This format is not a standard format. Less advanced users should use the CCCS webpage to download GeoTIFF format. CCCS webpage offers the possibility to download the data in NetCDF format as well.

The dataset is accompanied by a technical report.

Limitations and strengths for application in North Canada

The data was constructed to describe large-scale climate change over Canada and for national-scale assessments. Interpolation errors are expected to increase with the distance between stations. Because there is a small number of stations available in Northern Canada (most of them in coastal and valley locations), interpolation errors in inland regions and in Yukon high elevation regions can be significant.

Consequently, the result should be interpreted as a mean change over a large region (e.g., the mean change over the North or a territory), and it is not recommended to be used for local applications.

Because it provides anomalies, not actual values, it cannot be used to compute other climate indices.

Some users may find the data in .grd difficult to use because of its custom projection and format.

References to documents describing the methodology or/and the dataset

Environment and Climate Change Canada (2018). Canadian Gridded Temperature and Precipitation Anomalies CANGRD.

Milewska, E. and W.D. Hogg, 2001: Spatial representativeness of a long-term climate network in Canada. Atmosphere-Ocean 39(2): 145–161.

Milewska, E., R.F. Hopkinson and A. Niitsoo, 2005: Evaluation of Geo-Referenced Grids of 1961 – 1990 Canadian Temperature and Precipitation Normals. Atmosphere-Ocean 43 (1): 49-75.

Link to download the data and format of data:

https://climate-change.canada.ca/climate-data/#/historical-gridded-data **(GeoTIFF and NetCDF on CCCS/ECCC webpage)**

GeoTIFF data available on the MSC Datamart

http://crd-data-donnees-rdc.ec.gc.ca/CDAS/products/EC_data/CANGRD/ **(gridded data .grd on CRD/ECCC webpage)**

Publications including dataset evaluation or comparison with other data in northern Canada

Rapaić, M., R. Brown, M. Markovic, D. Chaumont, 2015: An evaluation of temperature and precipitation surface-based and reanalysis datasets for the Canadian Arctic, 1950–2010. Atmosphere-Ocean 53(3): 283–303. https://doi.org/10.1080/07055900.2015.1045825 (*The paper compares CANGRD to several other gridded datasets and other coarse-resolution reanalysis*)

7.2.7 *Dataset: ECMWF 5th Generation Atmospheric Reanalysis (ERA5) - precipitation*

Overview

This document provides an overview of precipitation products of ERA5, in the context of the larger ERA5 dataset. As background, ERA5 is the 5th generation of the global atmospheric reanalysis (the latest – it replaces the ERA-Interim reanalysis) produced by the Copernicus Climate Change Service at ECMWF, covering the period from January 1950 to present. It provides hourly data on many atmospheric, land-surface and sea-state parameters together with estimates of uncertainty.

Provider's contact information

ERA5 is produced by the Copernicus Climate Change Service (C3S) at ECMWF.

Copernicus User support (copernicus-support@ecmwf.int (external to C3S)).

Licensing

Licence: Copernicus (Licence agreement information can be found here or here).
Dataset citable as: Copernicus Climate Change Service (C3S) (2017): ERA5: Fifth generation of ECMWF atmospheric reanalyses of the global climate . Copernicus Climate Change Service Climate Data Store (CDS), date of access.
https://cds.climate.copernicus.eu/cdsapp#!/home

Variable name and units:

Precipitation of ERA5 is the main focus of this document. The available parameters are provided in the table below.

Name	Units	Description
Total precipitation	m	Accumulated liquid and frozen water, including rain and snow, that falls to the Earth's surface. It is the sum of large-scale precipitation (that precipitation which is generated by large-scale weather patterns, such as troughs and cold fronts) and convective precipitation (generated by convection which occurs when air at lower levels in the atmosphere is warmer and less dense than the air above, so it rises). Precipitation variables do not include fog, dew or the precipitation that evaporates in the atmosphere before it lands at the surface of the Earth. This variable is accumulated from the beginning of the forecast time to the end of the forecast step. The units of precipitation are depth in metres. It is the depth the water would have if it were spread evenly over the grid box. Care should be taken when comparing model variables with observations, because

		observations are often local to a particular point in space and time, rather than representing averages over a model grid box and model time step.
Snowfall	m of water equivalent	Accumulated total snow that has fallen to the Earth's surface. It consists of snow due to the large-scale atmospheric flow (horizontal scales greater than around a few hundred metres) and convection where smaller scale areas (around 5km to a few hundred kilometres) of warm air rise. If snow has melted during the period over which this variable was accumulated, then it will be higher than the snow depth. This variable is the total amount of water accumulated from the beginning of the forecast time to the end of the forecast step. The units given measure the depth the water would have if the snow melted and was spread evenly over the grid box. Care should be taken when comparing model variables with observations, because observations are often local to a particular point in space and time, rather than representing averages over a model grid box and model time step.
Convective precipitation	m	This parameter is the accumulated precipitation that falls to the Earth's surface, which is generated by the convection scheme in the ECMWF Integrated Forecasting System (IFS). The convection scheme represents convection at spatial scales smaller than the grid box. Precipitation can also be generated by the cloud scheme in the IFS, which represents the formation and dissipation of clouds and large-scale precipitation due to changes in atmospheric quantities (such as pressure, temperature and moisture) predicted directly at spatial scales of the grid box or larger. In the IFS, precipitation is comprised of rain and snow. In the IFS, precipitation is comprised of rain and snow. This parameter is accumulated over a particular time period which depends on the data extracted. For the reanalysis, the accumulation period is over the 1 hour ending at the validity date and time. For the ensemble members, ensemble mean and ensemble spread, the accumulation period is over the 3 hours ending at the validity date and time. The units of this parameter are depth in metres of water equivalent. It is the depth the water would have if it were spread evenly over the grid box. Care should be taken when comparing model parameters with observations, because observations are often local to a particular point in space and time, rather than representing averages over a model grid box.
Convective rain rate	kg m-2 s-1	This parameter is the rate of rainfall (rainfall intensity), at the Earth's surface and at the specified time, which is generated by the convection scheme in the ECMWF Integrated Forecasting System (IFS). The convection scheme represents convection at spatial scales smaller than the grid box. Rainfall can also be generated by the cloud scheme in the IFS, which represents the formation and dissipation of clouds and large-scale precipitation due to changes in atmospheric quantities (such as pressure, temperature and moisture) predicted directly at spatial scales of the grid box or larger. In the IFS, precipitation is comprised of rain and snow. This parameter is the rate the rainfall would

		have if it were spread evenly over the grid box. 1 kg of water spread over 1 square metre of surface is 1 mm deep (neglecting the effects of temperature on the density of water), therefore the units are equivalent to mm per second. Care should be taken when comparing model parameters with observations, because observations are often local to a particular point in space and time, rather than representing averages over a model grid box.
Convective snowfall	m of water equivalent	This parameter is the accumulated snow that falls to the Earth's surface, which is generated by the convection scheme in the ECMWF Integrated Forecasting System (IFS). The convection scheme represents convection at spatial scales smaller than the grid box. Snowfall can also be generated by the cloud scheme in the IFS, which represents the formation and dissipation of clouds and large-scale precipitation due to changes in atmospheric quantities (such as pressure, temperature and moisture) predicted directly at spatial scales of the grid box or larger. In the IFS, precipitation is comprised of rain and snow. This parameter is accumulated over a particular time period which depends on the data extracted. For the reanalysis, the accumulation period is over the 1 hour ending at the validity date and time. For the ensemble members, ensemble mean and ensemble spread, the accumulation period is over the 3 hours ending at the validity date and time. The units of this parameter are depth in metres of water equivalent. It is the depth the water would have if it were spread evenly over the grid box. Care should be taken when comparing model parameters with observations, because observations are often local to a particular point in space and time, rather than representing averages over a model grid box.
Convective snowfall rate water equivalent	kg m-2 s-1	This parameter is the rate of snowfall (snowfall intensity), at the Earth's surface and at the specified time, which is generated by the convection scheme in the ECMWF Integrated Forecasting System (IFS). The convection scheme represents convection at spatial scales smaller than the grid box. Snowfall can also be generated by the cloud scheme in the IFS, which represents the formation and dissipation of clouds and large-scale precipitation due to changes in atmospheric quantities (such as pressure, temperature and moisture) predicted directly at spatial scales of the grid box or larger. In the IFS, precipitation is comprised of rain and snow. This parameter is the rate the snowfall would have if it were spread evenly over the grid box. Since 1 kg of water spread over 1 square metre of surface is 1 mm thick (neglecting the effects of temperature on the density of water), the units are equivalent to mm (of liquid water) per second. Care should be taken when comparing model parameters with observations, because observations are often local to a particular point in space and time, rather than representing averages over a model grid box.
Instantaneous large-scale surface	Dimensionless	This parameter is the fraction of the grid box (0-1) covered by large-scale precipitation at the specified time. Large-scale precipitation is rain and snow that falls to the Earth's surface, and is generated by the cloud scheme in the ECMWF Integrated Forecasting System (IFS). The cloud

precipitation fraction		scheme represents the formation and dissipation of clouds and large-scale precipitation due to changes in atmospheric quantities (such as pressure, temperature and moisture) predicted directly by the IFS at spatial scales of a grid box or larger. Precipitation can also be due to convection generated by the convection scheme in the IFS. The convection scheme represents convection at spatial scales smaller than the grid box.
Large-scale precipitation fraction	0/1	This parameter is the accumulation of the fraction of the grid box (0-1) that is covered by large-scale precipitation. This parameter is accumulated over a particular time period which depends on the data extracted. For the reanalysis, the accumulation period is over the 1 hour ending at the validity date and time. For the ensemble members, ensemble mean and ensemble spread, the accumulation period is over the 3 hours ending at the validity date and time.
Large scale rain rate	kg m-2 s-1	This parameter is the rate of rainfall (rainfall intensity), at the Earth's surface and at the specified time, which is generated by the cloud scheme in the ECMWF Integrated Forecasting System (IFS). The cloud scheme represents the formation and dissipation of clouds and large-scale precipitation due to changes in atmospheric quantities (such as pressure, temperature and moisture) predicted directly at spatial scales of the grid box or larger. Rainfall can also be generated by the convection scheme in the IFS, which represents convection at spatial scales smaller than the grid box. In the IFS, precipitation is comprised of rain and snow. This parameter is the rate the rainfall would have if it were spread evenly over the grid box. Since 1 kg of water spread over 1 square metre of surface is 1 mm deep (neglecting the effects of temperature on the density of water), the units are equivalent to mm per second. Care should be taken when comparing model parameters with observations, because observations are often local to a particular point in space and time, rather than representing averages over a model grid box.
Large-scale snowfall water equivalent	m of water equivalent	This parameter is the accumulated snow that falls to the Earth's surface, which is generated by the cloud scheme in the ECMWF Integrated Forecasting System (IFS). The cloud scheme represents the formation and dissipation of clouds and large-scale precipitation due to changes in atmospheric quantities (such as pressure, temperature and moisture) predicted directly at spatial scales of the grid box or larger. Snowfall can also be generated by the convection scheme in the IFS, which represents convection at spatial scales smaller than the grid box. In the IFS, precipitation is comprised of rain and snow. This parameter is accumulated over a particular time period which depends on the data extracted. For the reanalysis, the accumulation period is over the 1 hour ending at the validity date and time. For the ensemble members, ensemble mean and ensemble spread, the accumulation period is over the 3 hours ending at the validity date and time. The units of this parameter are depth in metres of water equivalent. It is the depth the water would have if it were spread evenly over the grid box. Care should be taken when comparing model parameters

		with observations, because observations are often local to a particular point in space and time, rather than representing averages over a model grid box.
Large scale snowfall rate	kg m-2 s-1	This parameter is the rate of snowfall (snowfall intensity), at the Earth's surface and at the specified time, which is generated by the cloud scheme in the ECMWF Integrated Forecasting System (IFS). The cloud scheme represents the formation and dissipation of clouds and large-scale precipitation due to changes in atmospheric quantities (such as pressure, temperature and moisture) predicted directly at spatial scales of the grid box or larger. Snowfall can also be generated by the convection scheme in the IFS, which represents convection at spatial scales smaller than the grid box. In the IFS, precipitation is comprised of rain and snow. This parameter is the rate the snowfall would have if it were spread evenly over the grid box. Since 1 kg of water spread over 1 square metre of surface is 1 mm deep (neglecting the effects of temperature on the density of water), the units are equivalent to mm (of liquid water) per second. Care should be taken when comparing model parameters with observations, because observations are often local to a particular point in space and time, rather than representing averages over a model grid box.
Large-scale precipitation	m	This parameter is the accumulated precipitation that falls to the Earth's surface, which is generated by the cloud scheme in the ECMWF Integrated Forecasting System (IFS). The cloud scheme represents the formation and dissipation of clouds and large-scale precipitation due to changes in atmospheric quantities (such as pressure, temperature and moisture) predicted directly at spatial scales of the grid box or larger. Precipitation can also be generated by the convection scheme in the IFS, which represents convection at spatial scales smaller than the grid box. In the IFS, precipitation is comprised of rain and snow. This parameter is accumulated over a particular time period which depends on the data extracted. For the reanalysis, the accumulation period is over the 1 hour ending at the validity date and time. For the ensemble members, ensemble mean and ensemble spread, the accumulation period is over the 3 hours ending at the validity date and time. The units of this parameter are depth in metres of water equivalent. It is the depth the water would have if it were spread evenly over the grid box. Care should be taken when comparing model parameters with observations, because observations are often local to a particular point in space and time, rather than representing averages over a model grid box.
Maximum total precipitation rate since previous	kg m-2 s-1	The total precipitation is calculated from the combined large-scale and convective rainfall and snowfall rates every time step and the maximum is kept since the last postprocessing.

post-processing		
Minimum total precipitation rate since previous post-processing	kg m-2 s-1	The total precipitation is calculated from the combined large-scale and convective rainfall and snowfall rates every time step and the minimum is kept since the last postprocessing.
Precipitation type	Dimensionless	This parameter describes the type of precipitation at the surface, at the specified time. A precipitation type is assigned wherever there is a non-zero value of precipitation. In the ECMWF Integrated Forecasting System (IFS) there are only two predicted precipitation variables: rain and snow. Precipitation type is derived from these two predicted variables in combination with atmospheric conditions, such as temperature. Values of precipitation type defined in the IFS: 0: No precipitation, 1: Rain, 3: Freezing rain (i.e. supercooled raindrops which freeze on contact with the ground and other surfaces), 5: Snow, 6: Wet snow (i.e. snow particles which are starting to melt); 7: Mixture of rain and snow, 8: Ice pellets. These precipitation types are consistent with WMO Code Table 4.201. Other types in this WMO table are not defined in the IFS.
Mean convective precipitation rate	kg m-2 s-1	This parameter is the rate of precipitation at the Earth's surface, which is generated by the convection scheme in the ECMWF Integrated Forecasting System (IFS). The convection scheme represents convection at spatial scales smaller than the grid box. Precipitation can also be generated by the cloud scheme in the IFS, which represents the formation and dissipation of clouds and large-scale precipitation due to changes in atmospheric quantities (such as pressure, temperature and moisture) predicted directly at spatial scales of the grid box or larger. In the IFS, precipitation is comprised of rain and snow. This parameter is a mean over a particular time period (the processing period) which depends on the data extracted. For the reanalysis, the processing period is over the 1 hour ending at the validity date and time. For the ensemble members, ensemble mean and ensemble spread, the processing period is over the 3 hours ending at the validity date and time. It is the rate the precipitation would have if it were spread evenly over the grid box. 1 kg of water spread over 1 square metre of surface is 1 mm deep (neglecting the effects of temperature on the density of water), therefore the units are equivalent to mm (of liquid water) per second. Care should be taken when comparing model parameters with observations, because observations are often local to a particular point in space and time, rather than representing averages over a model grid box.

Mean convective snowfall rate	kg m-2 s-1	This parameter is the rate of snowfall (snowfall intensity) at the Earth's surface, which is generated by the convection scheme in the ECMWF Integrated Forecasting System (IFS). The convection scheme represents convection at spatial scales smaller than the grid box. Snowfall can also be generated by the cloud scheme in the IFS, which represents the formation and dissipation of clouds and large-scale precipitation due to changes in atmospheric quantities (such as pressure, temperature and moisture) predicted directly at spatial scales of the grid box or larger. In the IFS, precipitation is comprised of rain and snow. This parameter is a mean over a particular time period (the processing period) which depends on the data extracted. For the reanalysis, the processing period is over the 1 hour ending at the validity date and time. For the ensemble members, ensemble mean and ensemble spread, the processing period is over the 3 hours ending at the validity date and time. It is the rate the snowfall would have if it were spread evenly over the grid box. Since 1 kg of water spread over 1 square metre of surface is 1 mm thick (neglecting the effects of temperature on the density of water), the units are equivalent to mm (of liquid water) per second. Care should be taken when comparing model parameters with observations, because observations are often local to a particular point in space and time, rather than representing averages over a model grid box.
Mean large-scale precipitation fraction	Dimensionless	This parameter is the mean of the fraction of the grid box (0-1) that is covered by large-scale precipitation. This parameter is a mean over a particular time period (the processing period) which depends on the data extracted. For the reanalysis, the processing period is over the 1 hour ending at the validity date and time. For the ensemble members, ensemble mean and ensemble spread, the processing period is over the 3 hours ending at the validity date and time.
Mean large-scale precipitation rate	kg m-2 s-1	This parameter is the rate of precipitation at the Earth's surface, which is generated by the cloud scheme in the ECMWF Integrated Forecasting System (IFS). The cloud scheme represents the formation and dissipation of clouds and large-scale precipitation due to changes in atmospheric quantities (such as pressure, temperature and moisture) predicted directly at spatial scales of the grid box or larger. Precipitation can also be generated by the convection scheme in the IFS, which represents convection at spatial scales smaller than the grid box. In the IFS, precipitation is comprised of rain and snow. This parameter is a mean over a particular time period (the processing period) which depends on the data extracted. For the reanalysis, the processing period is over the 1 hour ending at the validity date and time. For the ensemble members, ensemble mean and ensemble spread, the processing period is over the 3 hours ending at the validity date and time. It is the rate the precipitation would have if it were spread evenly over the grid box. Since 1 kg of water spread over 1 square metre of surface is 1 mm deep (neglecting the effects of temperature on the density of water), the units are equivalent to mm (of liquid water) per second. Care should be taken

		when comparing model parameters with observations, because observations are often local to a particular point in space and time, rather than representing averages over a model grid box.
Mean large-scale snowfall rate	kg m-2 s-1	This parameter is the rate of snowfall (snowfall intensity) at the Earth's surface, which is generated by the cloud scheme in the ECMWF Integrated Forecasting System (IFS). The cloud scheme represents the formation and dissipation of clouds and large-scale precipitation due to changes in atmospheric quantities (such as pressure, temperature and moisture) predicted directly at spatial scales of the grid box or larger. Snowfall can also be generated by the convection scheme in the IFS, which represents convection at spatial scales smaller than the grid box. In the IFS, precipitation is comprised of rain and snow. This parameter is a mean over a particular time period (the processing period) which depends on the data extracted. For the reanalysis, the processing period is over the 1 hour ending at the validity date and time. For the ensemble members, ensemble mean and ensemble spread, the processing period is over the 3 hours ending at the validity date and time. It is the rate the snowfall would have if it were spread evenly over the grid box. Since 1 kg of water spread over 1 square metre of surface is 1 mm deep (neglecting the effects of temperature on the density of water), the units are equivalent to mm (of liquid water) per second. Care should be taken when comparing model parameters with observations, because observations are often local to a particular point in space and time, rather than representing averages over a model grid box.
Mean total precipitation rate	kg m-2 s-1	This parameter is the rate of precipitation at the Earth's surface. It is the sum of the rates due to large-scale precipitation and convective precipitation. Large-scale precipitation is generated by the cloud scheme in the ECMWF Integrated Forecasting System (IFS). The cloud scheme represents the formation and dissipation of clouds and large-scale precipitation due to changes in atmospheric quantities (such as pressure, temperature and moisture) predicted directly at spatial scales of the grid box or larger. Convective precipitation is generated by the convection scheme in the IFS, which represents convection at spatial scales smaller than the grid box. In the IFS, precipitation is comprised of rain and snow. This parameter is a mean over a particular time period (the processing period) which depends on the data extracted. For the reanalysis, the processing period is over the 1 hour ending at the validity date and time. For the ensemble members, ensemble mean and ensemble spread, the processing period is over the 3 hours ending at the validity date and time. It is the rate the precipitation would have if it were spread evenly over the grid box. 1 kg of water spread over 1 square metre of surface is 1 mm deep (neglecting the effects of temperature on the density of water), therefore the units are equivalent to mm (of liquid water) per second. Care should be taken when comparing model parameters with observations, because observations are often local to a particular point in space and time, rather than representing averages over a model grid box.

Hourly and **monthly** subsets are available at the links below:

- hourly data on single levels from 1950 to 1978,
- hourly data on single levels from 1979 to present,
- monthly averaged data on single levels from 1950 to 1978,
- monthly averaged data on single levels from 1979 to present,

Note: ECMWF provides a conversion table for accumulated variables (total precipitation/fluxes) for ERA5-Land and ERA5 (the convention for accumulations used in ERA5-Landand in ERA5). The table shows how accumulated variables from a number of C3S and ECMWF datasets should be processed to derive values for an hour, a day, a month and a year. In the documentation, 'total precipitation' and 'solar radiation' are used for illustration, but the same processing should be applied to all precipitation and radiative flux variables.

Spatial coverage and resolution:

ERA5 precipitation, like all ERA5 data, is a global dataset. The atmospheric data is available on a regular latitude-longitude grid at 0.25° x 0.25° resolution (converted from native reduced-Gaussian grid resolution of approximately 31 km x 31 km), and on 37 pressure levels.

Temporal coverage and resolution:

ERA5 precipitation data, like all ERA5 data, is available from 1950 to present (split into two entries: primary from 1979 onwards and a back extension from 1950-1978). The back extension is a preliminary version that has been released in 2020, and an updated version (that corrects some issues in the tropics) will appear around the end of 2021.

The data is available at hourly and monthly sampling (see above).

ERA5 precipitation, like all ERA5 data, is updated daily with a latency of about 5 days in an early product and with a final release 2 to 3 months later.

Information about observations (number, homogeneity)

ERA5's data assimilation uses observations for all geophysical quantities from about 0.75 million observations per day in 1979 and about 24 Million in 2018. The 2D-OI uses surface observations at 'screen level'. The online technical documentation provides tables with the satellite and in-situ observations used as input into ERA5.

The satellite measurements used in ERA5 are: temperature, humidity, ozone, column water vapour, cloud liquid water, precipitation, ocean surface wind speed, wind vector, soil moisture, wave height.

The in-situ data is provided by WMO WIS and consists in measurements for: surface pressure, temperature, humidity, wind, wind profiles and snow depth. Figure 4 from Hersbach et al. (2020) presents the conventional observations assimilated per day in ERA5 during the period 1979–2018.

ERA5 assimilates rain rates from ground-based radar–gauge composite observations from 2009, and snow cover (NH only) from NOAA/NESDIS IMS.

The time evolving nature of the assimilated observations means that caution should be employed when using ERA5 to evaluate long-term variability and trends.

Methodology

Like any other climate variable from a reanalysis product, ERA5 precipitation is strongly influenced by the data assimilation methodology. ERA5 is produced using 4D-Var data assimilation with the ECMWF's Integrated Forecast System (IFS) model (CY41R2). The forecast model has 137 hybrid sigma/pressure (model) levels in the vertical, with the top level at 0.01 hPa. The IFS is coupled to a land-surface model and an ocean wave model. The model uses as boundary conditions the sea surface temperature, the sea ice cover, the greenhouse gases, the aerosols, and the total solar irradiance. Climate variables are offered from the atmospheric model, the surface model and the wave model.

The ERA5 dataset contains one (31 km) high resolution realization (HRES) and a reduced resolution 10-member ensemble (EDA). The model time step is 12 minutes for the HRES and 20 minutes for the Ensemble Data Assimilation (EDA), though occasionally these numbers are adjusted to cope with instabilities. Climate variables result from analyses and short (18 hour) forecasts, initialized twice daily from analyses at 06 and 18 UTC. Most of climate variables from the analyses are also available from the forecasts. However, there are several climate variables from forecast, e.g. mean rates and accumulations, that are not available from the analyses. More information on the differences between analysis, forecast, instantaneous, accumulated and mean rate parameters are provided on https://confluence.ecmwf.int/pages/viewpage.action?pageId=85402030.

The ERA5 atmospheric analysis is based on a hybrid incremental 4-dimensional variational data assimilation (4D-Var) system including variational bias correction (VarBias). The method finds the best estimate of the state of the atmosphere/land/surface ocean within an assimilation time window, given a background forecast valid at the start of the window and observations falling within that window. The 4D-Var data assimilation uses 12 hour windows from 09 UTC to 21 UTC and 21 UTC to 09 UTC (the following day).

Uncertainty estimate: An uncertainty estimate is sampled by a 10-member lower-resolution Ensemble Data Assimilation (EDA) which provides background-error estimates for the deterministic HRES 4D-Var Data Assimilation system. The analysis method is the same for each EDA member and follows that of the HRES. Each member (except the control) is run with different random perturbations added to the observations. Likewise, the model physical tendencies are perturbed in the short forecasts that link subsequent analysis windows.

Ensemble mean and spread have been pre-computed for convenience. Such uncertainty estimates are closely related to the information content of the available observing system which has evolved considerably over time. They also indicate flow-dependent sensitive areas. To facilitate many climate applications, monthly-mean averages have been pre-calculated too, though monthly means are not available for the ensemble mean and spread.

A strength of reanalysis (including ERA5) is the use of a consistent assimilation/forecast methodology throughout the analysis cycle. Thus, even though the observations assimilated are evolving in time (see above), the data assimilation approach can be considered fixed throughout the products analysis period, which adds to the homogeneity of the dataset.

Information about the technical and scientific quality

ERA5 precipitation represents one of the products of the latest global atmospheric reanalysis produced by Copernicus Climate Change Service at ECMWF. It is archived at a shorter (hourly) time step, has a finer spatial resolution, uses a more advanced assimilation system and includes more sources of data than previous versions. It is accompanied by extensive technical documentation and two principal scientific documentation papers. A list of 'known issues' is maintained at the online documentation (https://confluence.ecmwf.int/display/CKB/ERA5%3A+data+documentation#ERA5:datadocumentation-Knownissues).

A prerelease quality control revealed some problems affecting the performance in the tropics (tropical cyclones are too intense) and that the deep soil moisture tends to be too dry for the 1950-1978 dataset. A new version of the data should gradually become available by late 2021. This issue will be of little direct relevance to ERA5 precipitation in Canada's north, but the user should be aware of the reason for this update.

Information on model improvement: The forecast model of the ERA5 is the IFS Cycle 41r2. In the ten-year period between ERA-Interim (Cy31r2) and ERA5 (Cy41r2), many significant improvements have been made to the representation of atmospheric physical processes (see Section 4 of Hersbach et al. (2020)). There are several changes in ERA5's land-surface model and parameterization schemes. ERA5's HTESSEL land surface scheme (Balsamo et al., 2015) accounts for seasonally varying monthly vegetation maps specified from a MODIS-based satellite dataset. In addition, an enhanced snowpack parameterization allows a more realistic timing of runoff and terrestrial water storage variations and a better match of the albedo to satellite products. The chosen parameterization for lakes (FLake), allows consideration of both subgrid and resolved water bodies, which is potentially relevant for the lake-enriched Canadian sub-Arctic. This series of changes contributes to significant improvements in the soil moisture and land surface fluxes consistency, which allowed for the usage of satellite data in ERA5 to analyze soil moisture. This will influence the surface energy budget. Some important improvements in the wave model include: an updated model bathymetry with a more recent version of ETOPO2 and a revised unresolved bathymetry scheme. Some of these changes will also affect coastal regions as well as better accounting for wave propagation along coastlines and better modeling of the impact of previously unresolved features like islands and narrow embayments (e.g. Moore et al. in prep).

Limitations and strengths for application in North Canada

ERA5 is a new atmospheric reanalysis and there are not available scientific evaluations of the dataset dedicated specifically to northern Canada. However, it should be noted that in northern Canada, there are currently no sub-daily records over a long historical period for many weather stations. Reanalyses data with hourly output cover this gap and, with suitable investigation and calibration (downscaling), could be valuable resources.

As for all gridded data, care should be taken when comparing ERA5 precipitation with observations, because in reanalyses, precipitation is representing averages over a model grid box and model time step.

Also, as mentioned above, changes in the amounts and types of observational data that are assimilated may produce artificial trends or variability in reanlaysis variables. For ERA5 this has been observed for wind in the boundary layer (Hersbach et al. 2020).

References to documents describing the methodology or/and the dataset

Hersbach, H., Bell, B., Berrisford, P., Biavati, G., Horányi, A., Muñoz Sabater, J., Nicolas, J., Peubey, C., Radu, R., Rozum, I., Schepers, D., Simmons, A., Soci, C., Dee, D., Thépaut, J-N. (2018): ERA5 hourly data on single levels from 1979 to present. Copernicus Climate Change Service (C3S) Climate Data Store (CDS). (Accessed on < 29-Apr-2019 >), https://doi.org/10.24381/cds.adbb2d47

Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., Nicolas, J., Peubey, C., Radu, R., Schepers, D., Simmons, A., Soci, C., Abdalla, S., Abellan, X., Balsamo, G., Bechtold, P., Biavati, G., Bidlot, J., Bonavita, M., Chiara, G., Dahlgren, P., Dee, D., Diamantakis, M., Dragani, R., Flemming, J., Forbes, R., Fuentes, M., Geer, A., Haimberger, L., Healy, S., Hogan, R. J., Hólm, E., Janisková, M., Keeley, S., Laloyaux, P., Lopez, P., Lupu, C., Radnoti, G., Rosnay, P., Rozum, I., Vamborg, F., Villaume, S. and Thépaut, J.-N. (2020). The ERA5 global reanalysis. *Quarterly Journal of the Royal Meteorological Society*, *146*(730), 1999–2049. https://doi.org/10.1002/qj.3803

Online technical documentation: **https://confluence.ecmwf.int/display/CKB/ERA5%3A+data+documentation**

Link to download the data and format of data:

Data Access: Copernicus | NCAR | ECMWF

ERA5 is available in GRIB1 and NetCDF formats

Link to download hourly and monthly data on Copernicus:

- hourly data on single levels from 1950 to 1978,
- hourly data on single levels from 1979 to present,

- hourly data on pressure levels from 1950 to 1978,
- hourly data on pressure levels from 1979 to present,
- monthly averaged data on single levels from 1950 to 1978,
- monthly averaged data on single levels from 1979 to present,
- monthly averaged data on pressure levels from 1950 to 1978,
- monthly averaged data on pressure levels from 1979 to present.

Publications including dataset evaluation or comparison with other data in Canada

Tarek, Mostafa, François P. Brissette, and Richard Arsenault. "Evaluation of the ERA5 reanalysis as a potential reference dataset for hydrological modelling over North America." *Hydrology and Earth System Sciences* 24.5 (2020): 2527-2544. (It *compares ERA5 and ERA-Interim with stations in US and Canada south of 60° latitude*).

Sheridan, Scott C., Cameron C. Lee, and Erik T. Smith. "A comparison between station observations and reanalysis data in the identification of extreme temperature events." *Geophysical Research Letters* 47.15 (2020): e2020GL088120. (*It compares observations, ERA5, ERA5-LAND, and NARR, in the United States and Canada- only a very small number of stations are in North Canada*).

Betts, Alan K., Darren Z. Chan, and Raymond L. Desjardins. "Near-surface biases in ERA5 over the Canadian Prairies." Frontiers in Environmental Science 7 (2019): 129. (*ERA5 is compared with hourly data for 4 stations in Saskatchewan, Canada*).

Cao B., Quan X., Brown N., Stewart-Jone E., and Gruber S., 2019, GlobSim (v1.0): deriving meteorological time series for point locations from multiple global reanalyses, Geosci. Model Dev., 12, 4661–4679, 2019 https://doi.org/10.5194/gmd-12-4661-2019 (*2m temperature from ERA5 is compared with ERA-Interim, JRA-55 and MERRA-2 at a site located near the north shore of Lac de Gras in the Northwest Territories, Canada*)

7.2.8 *<u>Dataset</u>: The NOAA NCEP Climate Forecast System Reanalysis (CFSR) and Climate Forecast System Version 2 (CFSv2) - precipitation*

Overview

This document provides an overview of the precipitation products from the Climate Forecast system reanalysis (CFSR) and its operational extension CFSv2. The CFSR is a third generation reanalysis product, developed by the National Oceanic and Atmospheric Administration's (NOAA) National Center for Environmental Prediction (NCEP), and it is using a global, high resolution, coupled atmosphere-ocean-land surface-sea ice system. The spatial resolution of the global atmospheric data is ~38 km (T382) and many atmospheric variables are provided at hourly temporal resolution.

Provider's contact information

CFSR is developed by the National Oceanic and Atmospheric Administration's (NOAA) National Center for Environmental Prediction (NCEP).

Contact name: DOC/NOAA/NESDIS/NCEI > National Centers for Environmental Information, NESDIS, NOAA, U.S. Department of Commerce

Contact email: Contact: cfs@noaa.gov

Licensing and citation

CFSR data is freely available.

Please reference the following article when using the CFS Reanalysis (CFSR) data:

Saha, S., S. Moorthi, H. Pan, X. Wu, J. Wang, and Coauthors, 2010: The NCEP Climate Forecast System Reanalysis. Bulletin of the American Meteorological Society, 91, 1015–1057, doi:10.1175/2010BAMS3001.1.

For hourly data downloaded from UCAR RDA: **Saha**, S., et al. 2010. NCEP Climate Forecast System Reanalysis (CFSR) Selected Hourly Time-Series Products, January 1979 to December 2010. Research Data Archive at the National Center for Atmospheric Research, Computational and Information Systems Laboratory. https://doi.org/10.5065/D6513W89. Accessed dd mmm yyyy.

For monthly data downloaded from UCAR RDA: **Saha**, S., et al. 2010. NCEP Climate Forecast System Reanalysis (CFSR) Monthly Products, January 1979 to December 2010. Research Data Archive at the National Center for Atmospheric Research, Computational and Information Systems Laboratory. https://doi.org/10.5065/D6DN438J. Accessed dd mmm yyyy.

Please reference the following article when using the CFS Reforecast model or data:

Saha, S., S. Moorthi, X. Wu, J. Wang, and Coauthors, 2014: The NCEP Climate Forecast System Version 2. Journal of Climate, 27, 2185–2208, doi:10.1175/JCLI-D-12-00823.1

For hourly data downloaded from UCAR RDA: **Saha**, S., et al. 2011, updated monthly. NCEP Climate Forecast System Version 2 (CFSv2) Selected Hourly Time-Series Products. Research Data Archive at the National Center for Atmospheric Research, Computational and Information Systems Laboratory. https://doi.org/10.5065/D6N877VB. Accessed dd mmm yyyy.

For monthly data downloaded from UCAR RDA: **Saha**, S., et al. 2012. NCEP Climate Forecast System Version 2 (CFSv2) Monthly Products. Research Data Archive at the National Center for Atmospheric Research, Computational and Information Systems Laboratory. https://doi.org/10.5065/D69021ZF. Accessed dd mmm yyyy.

Variable name and units:

The following table summarizes the name of the variables available at NCAR RDA as hourly time series.

Notation (name)	Units
PRATE (precipitation rate; averaged)	kg m^{-2} s^{-1}
CPRAT (Convective precipitation rate; averaged)	kg m^{-2} s^{-1}
A PCP (Total precipitation)	kg m^{-2}

Spatial coverage and resolution:

CFSR data, is a global dataset. Precipittaion is provided on a horizontal regular latitude-longitude grid with a spatial resolution of ~38 km (T382).

Temporal coverage and resolution:

CFSR is covering 01 Jan1 979 – 31 Mar 2011 period. The product was extended beyond 2011 as an operational real-time product, using a new version: NCEP's Climate Forecast System Version 2 (CFSv2). CFSR precipitation products are available at an hourly time resolution and as monthly means.

Information about observations (number, homogeneity)

All available conventional and satellite observations were included in the CFSR. Satellite observations were used in radiance form and were bias corrected with “spin up” runs at full resolution, taking into account variable CO_2 concentrations. This procedure enabled smooth transitions of the climate record due to evolutionary changes in the satellite observing system.

The CFSR uses the NCEP operational observation quality control procedures.

Methodology

The CFSR is a third generation reanalysis product, and it is using global, high resolution, coupled atmosphere-ocean-land surface-sea ice system. It includes (1) coupling of atmosphere and ocean during the generation of the 6 hour guess field, (2) an interactive sea-ice model, and (3) assimilation of satellite radiances. The CFSR global atmosphere resolution is ~38 km (T382) with 64 levels. The global ocean is 0.25° at the equator, extending to a global 0.5° beyond the tropics, with 40 levels. The global land surface model has 4 soil levels and the global sea ice model has 3 levels. The CFSR atmospheric model contains observed variations in carbon dioxide (CO_2), together with changes in aerosols and other trace gases and solar variations.

The Precipitation Analysis used in the CFSR (Pingping.Xie@noaa.gov; Jesse.Meng@noaa.gov): Two sets of global precipitation analyses are utilized in the CFSR land surface analysis. The pentad data set of CPC Merged Analysis of Precipitation (CMAP, Xie and Arkin 1997) defines 5-day mean precipitation at a 2.5o latitude / longitude grid over the globe by merging information derived from gauge observations as well as satellite observations in infrared and passive microwave channels. The other data set used is the CPC unified global daily gauge analysis, constructed on a 0.5o latitude / longitude over the global land through the interpolation of quality controlled gauge reports from ~30,000 stations collected from the Global Telecommunication System (GTS) and many other national and international collections (Xie et al., 2010). The optimal interpolation (OI) algorithm of Xie et al. (2007) is employed to partially account for the orographic enhancements in precipitation. In addition to the analyzed values of precipitation, number of reporting stations and the ending time of daily accumulation are also included in the data set. Both analyses are generated for the entire CFSR analysis period from 1979 and updated on a real-time basis.

Information about the technical and scientific quality

The CSFR products are superior to previous NCEP reanalyses with respect to: improved model, finer resolution, advanced assimilation schemes, atmosphere-land-ocean-sea ice coupling, assimilates satellite radiances rather than retrievals, and accounts for changing CO_2 and other trace gasses, aerosols, and solar variations.

Known CFSRR data issues are explained in the August 2011 CFSRR Known Issues Technical Document.

Limitations and strengths for application in North Canada

GENERAL KEY STRENGTHS:

- Approaches the horizontal resolution of regional reanalyses like the NARR and Arctic System Reanalysis

GENERAL KEY LIMITATIONS:

- Ocean-atmosphere interactions are not used directly. Rather the information is used for background information. The actual reanalysis is uncoupled.

References to documents describing the methodology or/and the dataset

Saha, S., S. Moorthi, H. Pan, X. Wu, J. Wang, and Coauthors, 2010: The NCEP Climate Forecast System Reanalysis. Bulletin of the American Meteorological Society, 91, 1015–1057, doi:10.1175/2010BAMS3001.1.

Saha, S., S. Moorthi, X. Wu, J. Wang, S. Nadiga, P. Tripp, D. Behringer, Y. Hou, H. Chuang, M. Iredell, M.Ek, J. Meng, R. Yang, M.P. Mendez, H. van den Dool, Q. Zhang, W. Wang, M. Chen, and E. Becker, 2014: The NCEP Climate Forecast System Version 2, Journal of Climate, 27(6), 2185-2208, doi:10.1175/JCLI-D-12-00823.1.

Link to download the data and format of data:

The CFSR data (1979 to 2011) are available in GRIB-2 format and can be accessed in multiple ways.

NCEI NOMADS THREDDS Data Server: URL: https://nomads.ncdc.noaa.gov/thredds/cfsr.html

NOAA NOMADS FTP access: URL: ftp://nomads.ncdc.noaa.gov/CFSR/

At UCAR RDA data is grouped as follows:

NCEP Climate Forecast System Version 2 (CFSv2) Monthly Products (ds094.2)

NCEP Climate Forecast System Version 2 (CFSv2) Selected Hourly Time-Series Products (ds094.1)

NCEP Climate Forecast System Reanalysis (CFSR) Monthly Products, January 1979 to December 2010 (ds093.2)

NCEP Climate Forecast System Reanalysis (CFSR) Selected Hourly Time-Series Products, January 1979 to December 2010 (ds093.1)

Publications including dataset evaluation or comparison with other data in Canada

7.2.9 Dataset: Modern-Era Retrospective analysis for Research and Applications, Version 2 (MERRA-2) - precipitation

Overview

This document provides an overview of the precipitation data from the Modern-Era Retrospective analysis for Research and Applications, Version 2 (MERRA-2). MERRA-2 represents a third generation atmospheric global reanalysis produced by the Global Modeling and Assimilation Office (GMAO) at NASA. It begins in 1980 and it replaces the original MERRA reanalysis (Rienecker *et al*., 2011) using an upgraded version of the Goddard Earth Observing System Model, Version 5 (GEOS-5) data assimilation system. Alongside the meteorological data assimilation using a modern satellite database, MERRA-2 includes an interactive analysis of aerosols that feed back into the circulation, uses NASA's observations of stratospheric ozone and temperature, and takes steps towards representing cryogenic processes by including a representation of ice sheets over Greenland and Antarctica.

Provider's contact information

MERRA-2 is developed by the Global Modeling and Assimilation Office (GMAO) and produced through NASA's Modeling, Analysis and Prediction (MAP) program.

Data Download questions should go to the GES DISC help email: gsfc-help-disc@lists.nasa.gov

Science questions regarding MERRA-2 data be emailed to: merra-questions@lists.nasa.gov

When contacting these emails, provide specific information and links to where you have attempted the data downloads. They also ask you to familiarize yourself with the existing documentation first (MERRA-2: http://gmao.gsfc.nasa.gov/reanalysis/MERRA-2/docs/)

Licensing and citation

MERRA-2 data is freely available from the Goddard Earth Sciences (GES) Data Information Services center (DISC). Note that each MERRA-2 data collection has a citable DOI, that should be used in peer-reviewed publications.

Citing MERRA-2 data has 2 steps for a full citation:

(3) First pick the correct variable here.
(4) When you click on the correct variable, it will take you to a second webpage with tabs that you can click that include: (1) documentation papers you need to cite, and (2) the correct variable citation information. You need both types of citation.

Variable name and units:

Variables provided by MERRA-2 are grouped in collections. Precipitation modelled by the atmospheric model is provided in **tavg1_2d_flx_Nx** collection. Daily statistics from the model are provided in **statD_2d_slv_Nx collection.**

MERRA-2 uses observation-based precipitation data (outside the northern Canada) **as forcing for the land surface parameterization**. The precipitation derived from this approach is archived as the output variable called ''Bias corrected precipitation'' and it is available in the **tavg1_2d_flx_Nx**, **tavg1_2d_lfo_Nx** and **tavg1_2d_lnd_Nx** collections of data.

Name	Description	Units	Frequency	Collection of data
TPRECMAX	Maximum precipitation rate during one day	kg m-2 s-1	daily from 00:30 UTC (aggregated statistics)	statD_2d_slv_Nx: Single-Level Diagnostics
PRECANV	anvil precipitation	kg m-2 s-1	hourly from 00:30 UTC (time-averaged)	tavg1_2d_flx_Nx: Surface Flux Diagnostics
PRECCON	convective precipitation	kg m-2 s-1	hourly from 00:30 UTC (time-averaged)	tavg1_2d_flx_Nx: Surface Flux Diagnostics
PRECLSC	nonanvil large scale precipitation	kg m-2 s-1	hourly from 00:30 UTC (time-averaged)	tavg1_2d_flx_Nx: Surface Flux Diagnostics
PRECSNO	snowfall	kg m-2 s-1	hourly from 00:30 UTC (time-averaged)	tavg1_2d_flx_Nx: Surface Flux Diagnostics
PRECTOT	total precipitation from atm model physics	kg m-2 s-1	hourly from 00:30 UTC (time-averaged)	tavg1_2d_flx_Nx: Surface Flux Diagnostics
PRECTOTCORR	Bias corrected total precipitation	kg m-2 s-1	hourly from 00:30 UTC (time-averaged)	tavg1_2d_flx_Nx: Surface Flux Diagnostics
PRECCUCORR	liquid water convective	kg m-2 s-1	hourly from 00:30 UTC (time-averaged)	tavg1_2d_lfo_Nx: Land Surface Forcings

	precipitation, bias corrected			
PRECLSCORR	liquid water large scale precipitation, bias corrected	kg m-2 s-1	hourly from 00:30 UTC (time-averaged)	tavg1_2d_lfo_Nx: Land Surface Forcings
PRECSNOCORR	Snowfall, bias corrected	kg m-2 s-1	hourly from 00:30 UTC (time-averaged)	tavg1_2d_lfo_Nx: Land Surface Forcings
PRECSNOLAND	snowfall land; bias corrected	kg m-2 s-1	hourly from 00:30 UTC (time-averaged)	tavg1_2d_lnd_Nx: Land Surface Diagnostics
PRECTOTLAND	Total precipitation land; bias corrected	kg m-2 s-1	hourly from 00:30 UTC (time-averaged)	tavg1_2d_lnd_Nx: Land Surface Diagnostics

Each time-averaged collection consists of a continuous sequence of data averaged over the indicated interval and time stamped with the central time of the interval. For hourly data, for example, these times are 00:30 GMT, 01:30 GMT, 02:30 GMT, etc. Monthly files represent averages for the calendar months, accounting for leap years.

More broadly, **MERRA-2 File Specification** document has a comprehensive list of datasets available, as well as description of the horizontal and vertical grids.

Spatial coverage and resolution:

MERRA-2 data, is a global dataset. All variables are provided on the same horizontal regular latitude-longitude grid that has 576 points in the longitudinal direction and 361 points in the latitudinal direction, corresponding to a resolution of 0.625° × 0.5°.

Temporal coverage and resolution:

MERRA-2 data, is available from 1980 to present.

Precipittaion data is available at hourly and monthly time step.

MERRA-2 data, is updated on a monthly base (each new month is available approximately between the 15th and 20th of the next month.).

Information about observations (number, homogeneity)

Precipitation data is highly influenced by observations assimilated into the product. MERRA-2 assimilates conventional and satellite-based observations.

Conventional observations include surface, upper air, and aircraft measurements. **From land based surface meteorology stations, only surface pressure is assimilated in MERRA and MERRA-2**. Radiosonde stations may contribute to the lower level analysis (T, Qv, U, V). Likewise, commercial aircraft can provide lower level data on the ascent and descent (T, U, V). There are also wind profilers (U,V). Over ocean, ships and buoys may provide PS, T, Qv, U and V.

Spaceborne observations include satellite radiances and retrieved measurements of the temperature and moisture fields, and satellite observations of wind (derived retrievals of surface and upper-air wind). Spaceborne observations represent the majority of the global observing system, and the percentage of the global observing system that is measured from space increases from 62 % in Jan 1980 to 88 % in Dec 2014. Modern hyperspectral radiance and microwave observations, along with GPS-Radio Occultation and NASA ozone datasets are now assimilated in MERRA-2.

See the MERRA-2 Observations Tech Memo for more details.

MERRA-2 uses observation-based precipitation data **as forcing for the land surface parameterization**. Note the forcing precipitation is not purely gauge observations, as it tapers back to MERRA-2 model generated precipitation poleward of 42.5° latitude, and **is completely MERRA-2 generated precipitation poleward of 62.5°, regions that corresponds to northern Canada.**

Methodology

Like any other reanalysis, MERRA-2 data is strongly influenced by the data assimilation methodology. MERRA-2 is currently being produced with the GMAO/GEOS-5 Data Assimilation System Version 5.12.4, which incorporates the Global Statistical Interpolation (GSI) analysis scheme of Wu *et al*., (2002). The system utilizes a revised version of the GEOS global atmospheric model (Molod *et al*., 2014). MERRA-2 is intended to replace the MERRA reanalysis product (which was created with GEOS-5.2.0). Details of the MERRA-2 system, including the major changes from the MERRA system, are summarized in the companion GMAO Office Note No. 10. The major motivation for replacing MERRA with MERRA-2 is the fact that the MERRA data assimilation system was frozen in 2008 and is not capable of ingesting several important new data types as the newer microwave sounders and hyperspectral infrared radiance instruments. The GEOS-5 system actively assimilates roughly 2×10^6 observations for each analysis, including about 7.5×10^5 AIRS radiance data. The input stream is roughly twice this volume, but because of the large volume, the data are thinned commensurate with the analysis grid to reduce the computational burden. Data are also rejected from the analysis through quality control procedures.

There is a fundamental change between MERRA and MERRA-2 over land surfaces. Soil moisture in MERRA-2 is initialized using a separate observation-based precipitation product (variable PRECTOTCORR in "flx" collections). This approach improves the representation of land surface properties and runoff, and is similar to the soil moisture initialization scheme developed for MERRA-Land (Reichle *et al*., 2011; Reichle, 2012; Reichle and Liu, 2014). The forcing precipitation is primarily based on gauge observations at low and midlatitudes, and gradually tapers to the MERRA-2 modelled precipitation over a zonal range from 42.5° to 62.5° latitude. The forcing precipitation is entirely composed of the MERRA-2 modelled precipitation poleward of 62.5°.

MERRA-2 is produced as four production Streams, each of the first three covering approximately a third of the MERRA-2 period, with the fourth stream starting within a couple years of real time. Initial conditions for the four MERRA-2 streams were derived from MERRA with a subsequent single year spin-up period, which has not been released in MERRA-2.

Information about the technical and scientific quality

MERRA-2 replaces the original NASA MERRA reanalysis (Rienecker *et al*., 2011) using an upgraded version of the data assimilation system, and of the forecast model. It is accompanied by extensive technical documentation (see section below on reference to s describing the methodology or/and the dataset). It incorporates observations from the more recent satellite instruments, uses observation-corrected precipitation forcing for the land surface, includes stratospheric ozone products and assimilates interactive aerosols and observed time varying emissions.

A webpage is provided with FAQ answers here: https://gmao.gsfc.nasa.gov/reanalysis/MERRA-2/FAQ/#

Limitations and strengths for application in North Canada

Key general limitations: Discontinuities associated with major observing system variations do occur.

References to documents describing the methodology or/and the dataset

MERRA-2 Overview: The Modern-Era Retrospective Analysis for Research and Applications, Version 2 (MERRA-2), Gelaro *et al*., 2017, J. Clim., doi: 10.1175/JCLI-D-16-0758.1

The American Meteorological Society has a special collection of articles relevant to MERRA-2. This collection, coordinated by Mike Bosilovich, is available at http://journals.ametsoc.org/collection/MERRA2.

There are several MAO Technical Memoranda that document and evaluate different aspects of the MERRA-2 system aspects of the MERRA-2 system:

#43, Bosilovich et al. – MERRA-2: Initial Evaluation of the Climate

#45, Randles et al. – The MERRA-2 Aerosol Assimilation

#46, McCarty et al. – MERRA-2 Input Observations: Summary and Assessment

Description of the observation corrected precipitation process used in MERRA-2:

Reichle, R., Q. Liu, R. Koster, C. Draper, S. Mahanama, and G. Partyka, 2017: Land Surface Precipitation in MERRA-2. *J. Clim.* doi:10.1175/JCLI-D-16-0570.1 Link.

Description of the GEOS-5 model changes between the MERRA and MERRA-2 systems:

Molod, A., L. Takacs, M. Suarez, and J. Bacmeister, 2015: Development of the GEOS-5 atmospheric general circulation model: evolution from MERRA to MERRA-2, *Geosci. Model Dev.*, 8, 1339-1356, doi:10.5194/gmd-8-1339-2015. Link.

Description of the mass constraint used in MERRA-2:

Takacs, L.L., M. Suarez, and R. Todling, 2015: Maintaining Atmospheric Mass and Water Balance Within Reanalysis. *NASA/TM–2014-104606*, Vol. 37 Document.

Link to download the data and format of data:

The MERRA-2 data are available online through the Goddard Earth Sciences (GES) Data and Information Services Center (DISC) (http://disc.sci.gsfc.nasa.gov/mdisc/). All MERRA-2 data are organized into file collections that contain fields with common characteristics. 2 m temperature and skin temperature can be found in the following collections:

MERRA-2 inst1_2d_asm_Nx: contains basic assimilated fields from IAU corrector provided on a single level as hourly instantaneous values.

MERRA-2 instM_2d_asm_Nx: contains basic assimilated fields from IAU corrector provided on a single level as monthly means of the instantaneous values.

MERRA-2 tavg1_2d_lnd_Nx: 1-Hourly time averaged data containing Land Surface Diagnostics

MERRA-2 tavgM_2d_lnd_Nx: Monthly time average data containing Land Surface Diagnostics.

MERRA-2 data files are provided in netCDF-4 format. Due to the size of the MERRA-2 archive, most product collections are compressed with a GRIB like method that is invisible to the user. This method does degrade the precision of the data, but every effort has been made to ensure that differences between the product and the original, non-degraded data are not scientifically meaningful.

Publications including dataset evaluation or comparison with other data in Canada

7.2.10 Dataset: The Japanese 55-year Reanalysis (JRA-55) - precipitation

Overview

This document provides an overview of the precipitation data from JRA-55. JRA-55 is a third-generation reanalysis developed by Japanese Meteorological Agency (JMA). It is spanning 1958 to present period and represent an update of the previous Japanese 25-year Reanalysis (JRA-25). The analysis period starts in 1958, when regular radiosonde observation began on a global basis. Many of the deficiencies of JRA-25 are alleviated in JRA-55 because the Data Assimilation (DA) system used for the project featured a variety of improvements.

Provider's contact information

JRA-55 is developed by the Japanese Meteorological Agency (JMA). Contact JMA at the email address below with any questions on JRA-55:

Climate Prediction Division, Global Environment and Marine Department,

Japan Meteorological Agency,

Email: jra@met.kishou.go.jp

Contact DIAS Office at the email address below with any questions on JRA-55 stored at DIAS:

DIAS Office

Japan Agency for Marine-Earth Science and Technology

Email: dias-office@diasjp.net

Licensing and citation

The intellectual property rights of the datasets belong exclusively to JMA.

JRA-55 data are provided by collaborative organizations that are separate entities from JMA. User registration and agreement to terms and conditions of data service usage are required individually for each organization. Data at NCAR RDA is licensed under a Creative Commons Attribution 4.0 International Licence.

Individual users should provide JMA (jra@met.kishou.go.jp) with a copy of their scientific or technical papers, publications, press releases or other communications regarding these datasets. The source of the Products should be duly acknowledged in scientific or technical

papers, publications, press releases or other communications regarding the Products. This includes information on the provider of data and of the collaborative organizations from where the data was downloaded.

Example for data downloaded from DIAS Office:

" In this study, the Japanese 55-year Reanalysis (JRA-55) provided by the Japan Meteorological Agency (JMA) was utilized. This dataset was also collected and provided under the Data Integration and Analysis System (DIAS), which was developed and operated by a project supported by the Ministry of Education, Culture, Sports, Science and Technology. "

Example for downloaded from NCAR RDA:

Japan Meteorological Agency/Japan. 2013, updated monthly. JRA-55: Japanese 55-year Reanalysis, Daily 3-Hourly and 6-Hourly Data. Research Data Archive at the National Center for Atmospheric Research, Computational and Information Systems Laboratory. https://doi.org/10.5065/D6HH6H41. Accessed† dd mmm yyyy.

†Please fill in the "Accessed" date with the day, month, and year (e.g., - 5 Aug 2011) you last accessed the data from the RDA.

Spatial coverage and resolution:

JRA-55 data, is a global dataset. Data is available at two spatial resolutions: (1) data on pressure levels at 1.25 degree spatial resolution and (2) data on model TL319L60 grid (~55 km) that was processed to a regular latitude-longitude Gaussian grid (320 latitudes by 640 longitudes, nominally 0.5625 degrees) and is available on NCAR RDA.

Variable name and units:

The following table summarizes the precipitation data available at NCAR RDA a regular latitude-longitude Gaussian grid (320 latitudes by 640 longitudes, nominally 0.5625 degrees).

Notation (name)	Units	Dataset product
Convective precipitation	mm day-1	JRA-55 **3-Hourly** Model Resolution 2-Dimensional Average **Diagnostic Fields** (fcst_phy2m)
Large scale precipitation	mm day-1	JRA-55 **3-Hourly** Model Resolution 2-Dimensional Average Diagnostic Fields (fcst_phy2m)

Snowfall rate water equivalent	mm day-1	JRA-55 **3-Hourly** Model Resolution 2-Dimensional Average Diagnostic Fields (fcst_phy2m)
Total precipitation	mm day-1	JRA-55 **3-Hourly** Model Resolution 2-Dimensional Average Diagnostic Fields (fcst_phy2m)

Two-dimensional average diagnostic fields (fcst_phy2m) are produced every three hours. The parameters shown in Table 4-11 are averaged from the beginning of forecasts up to three hours for 00 - 03, 06 - 09, 12 - 15 and 18 - 21 UTC, and from three to six hours for 03 -06, 09 - 12, 15 - 18 and 21 - 24 UTC. Dates in file names indicate the beginning of the averaging period.

Temporal coverage and resolution:

JRA-55 is covering 1958 to present period. Precipitation data is provided in the Diagnostic fields, which are available at 3h time step.

Monthly statistics are computed as averages and variances for the whole month using the averages from the beginning of forecasts up to six hours for average diagnostic fields.

The data is updated on a monthly base.

Information about observations (number, homogeneity)

Surface precipitation is not assimilated in JRA-55. Most of the observational data employed in JRA-55 are those used in JRA-25. Additionally, newly reprocessed METEOSAT and GMS data were supplied by EUMETSAT and MSC/JMA respectively. The table below summarizes the conventional data assimilate in JRA-55. From 1958 to 2002, JRA-55 is using the same conventional data as ECMWF ERA-40 reanalysis.

Table 1. Conventional data assimilated in JRA-55

Obs type	Parameter	Level
SYNOP	P	surface
SHIP	P	surface
BUOY	P	surface
Upper-level	T	~100 hPa
Upper-level	T	100~1000 hPa
Upper-level	u	~100 hPa
Upper-level	u	100~1000 hPa
Upper-level	Rh	100~1000 hPa
Aircraft	u	100~1000 hPa
Profiler (US)	u	100~1000 hPa

Quality control of conventional data is basically the same as the one used for JRA-25, and it includes a climatological check, track check, removal of duplicates, consistency check and gross error check.

For satellite radiances, tropospheric temperature, and humidity channels are only used in clear sky condition and channels sensitive to the ground are excluded over land and sea ice because surface temperature and emissivity estimates over those regions are not very reliable.

Methodology

JRA-55 has been produced with the TL319 version of the Japan Meteorological Agency (JMA) operational data assimilation system (as of December 2009), which features numerous improvements made since the Japanese 25-year Reanalysis (JRA-25). These include a revised longwave radiation scheme, 4D-Var and variational bias correction for satellite radiances. It also incorporates several newly available observational datasets produced as a result of ongoing efforts to improve quality of past observations, including homogenization of radiosonde temperature observations (Haimberger *et al*., 2008, 2012) and reprocessing of satellite data at major meteorological satellite centers.

The analysis of screen-level variables (2 m temperatures, 2 m relative humidities and 10 m winds) is performed separately with a univariate 2-dimensional optimal interpolation (2D-OI). Land surface analysis fields are generated by driving an offline version of the JMA Simple Biosphere (SiB) model with forcing fields from the atmospheric model. Snow depth analysis fields are generated once a day with 2D-OI using SYNOP snow depth observations. First-guess fields are derived for each grid point using (A) snow depth of the land surface analysis and (B) satellite snow covers. Satellite snow covers are retrieved in the 0.25° × 0.25° latitude/longitude grid from microwave imager radiances.

The forecast model used for JRA-55 is based on the TL319 spectral resolution version of the JMA global spectral model (GSM) as of December 2009 (JMA 2007, 2013b), which has been extensively improved since JRA-25.

The reanalysis period was divided into two streams (A002, B002) which have been producing three discontinuities: at 00 UTC on 1 July 1958, 00 UTC on 1 September 1980, and 00 UTC on 1 October 1992. JRA-55 is presently operated on a near-real-time basis and provides monthly updates for the data.

Information about the technical and scientific quality

One important realization in JRA-55 is the increase in the model resolution (T319L60 vs T106L40 in JRA-25). Among the improvements in the product are reduced biases in stratospheric temperature and Amazonian rainfall, and greater temporal consistency of the temperature analysis. Some notable biases persist, including a dry bias in the upper and middle troposphere, and a warm bias in the upper troposphere. The impacts of changes in the observing system on the forecast error are generally more evident in the Southern Hemisphere than the Northern Hemisphere.

The data is updated on a monthly base. JMA provide a webpage where the issues with JRA-55 are described: JRA-55 Quality Issues

Limitations and strengths for application in North Canada

GENERAL KEY STRENGTHS:

- Longest-running full observing system reanalysis with 4DVar

GENERAL KEY LIMITATIONS:

- Excessive precipitation is observed over the tropics. Generally, great caution is needed when hydrological variables from reanalyses are used, especially for model diagnostic variables such as precipitation and evaporation. From NCAR climate Data Guide: '' Due to the practice of observational correction for forecasts (also known as analysis increment), the energy balance is not exactly preserved in reanalysis. The introduction of analysis increment also creates an artificial sink or source in the water budget, which in turn leads to spin up issues (in which precipitation is insufficient immediately after the start of forecasts and then gradually increases) or spin-down issues (the reverse) with the hydrological cycle. (Bosilovich *et al*., 2011; Trenberth *et al*., 2011).''
- Dry bias in upper and middle troposphere and in regions of deep convection
- Tropical cyclone strength analyzed in JRA-55 exhibits unrealistic trends.

- The impact of changes in observing systems is particularly apparent for July 2006, when Global Navigation Satellite System-Radio Occultation (GNSS-RO) refractivity data were introduced into JRA-55.

References to documents describing the methodology or/and the dataset

Kobayashi, S., Y. Ota, Y. Harada, A. Ebita, M. Moriya, H. Onoda, K. Onogi, H. Kamahori, C. Kobayashi, H. Endo, K. Miyaoka, and K. Takahashi, 2015: The JRA-55 Reanalysis: General specifications and basic characteristics. Journal of the Meteorological Society of Japan. Ser. II, 93(1), 5-48, doi:10.2151/jmsj.2015-001.

Harada, Y., H. Kamahori, C. Kobayashi, H. Endo, S. Kobayashi, Y. Ota, H. Onoda, K. Onogi, K. Miyaoka, and K. Takahashi, 2016: The JRA-55 Reanalysis: Representation of atmospheric circulation and climate variability, J. Meteor. Soc. Japan, 94, 269-302, doi:10.2151/jmsj.2016-015.

Link to download the data and format of data:

The JRA-55 data are available in GRIB-2 format and can be accessed from the following organizations:

DIAS: Data Integration & Analysis System (data from 1958 to 2012, on a grid of approx. 1.25 deg.): http://search.diasjp.net/en/dataset/JRA55

NCAR: National Center for Atmospheric Research (USA) (data from 1958 to present, on both spatial grids):

- Daily, 3-Hourly and 6-Hourly Data http://rda.ucar.edu/datasets/ds628.0/
- Monthly Means and Variances http://rda.ucar.edu/datasets/ds628.1/
- Near Real-Time Data http://rda.ucar.edu/datasets/ds628.8/
- Near Real-Time Data -- Monthly Means and Variances http://rda.ucar.edu/datasets/ds628.9/

Publications including dataset evaluation or comparison with other data in Canada

7.2.11 *__Dataset__: The NCAR Arctic System Reanalysis (ASRv2) - precipitation*

Overview

This document provides an overview of precipitation products of ASRv2. ASRv2 is a multi-agency, university-led regional reanalysis product that covers the Arctic. It is produced using high-resolution versions of the Polar Weather Forecast Model (PWRF) and the WRF-VAR and High Resolution Land Data Assimilation (HRLDAS) systems that have been optimized for the Arctic. The final version, which has 15 km horizontal resolution and spans 2000-2016 period, is available online through the NCAR's RDA.

Provider's contact information

ASRv2 is produced by Polar Meteorology Group, Byrd Polar & Climate Research Center, the Ohio State University **and is available at NCAR CISL RDA.**

RDA NCAR user support manager : schuster@ucar.edu.

Licensing

Licence: This data are licensed under Creative Commons Attribution 4.0 International Licence (Licence agreement information can be found here)

Dataset citable as: National Center for Atmospheric Research/University Corporation for Atmospheric Research, and Polar Meterology Group/Byrd Polar and Climate Research Center/The Ohio State University. 2017. Arctic System Reanalysis version 2. Research Data Archive at the National Center for Atmospheric Research, Computational and Information Systems Laboratory. https://doi.org/10.5065/D6X9291B , https://rda.ucar.edu/datasets/ds631.1/

Bromwich, D., L. Bai, K. Hines, S. Wang, Z. Liu, H. Lin, Y. Kuo, and M. Barlage, 2012: Arctic System Reanalysis (ASR) Project. Research Data Archive at the National Center for Atmospheric Research, Computational and Information Systems Laboratory.

Variable name and units:

ASRv2 provides 2 products kind, analysis and forecast. The table below provide details on precipitation products from ASRv2, which are available just from forecast.

Name (parameter)	Units	dataset

RAINC (ACCUMULATED 3 hours TOTAL CUMULUS PRECIPITATION)	mm	ASRv2.0 2D surface forecast
RAINNC (ACCUMULATED 3 hours TOTAL GRID SCALE PRECIPITATION)	mm	ASRv2.0 2D surface forecast
SNOWNC (ACCUMULATED 3 hours TOTAL GRID SCALE SNOW AND ICE)	mm	ASRv2.0 2D surface forecast
GRAUPELNC (ACCUMULATED 3 hours TOTAL GRID SCALE GRAUPEL)	mm	ASRv2.0 2D surface forecast
SR (fraction of frozen precipitation)	0~1	ASRv2.0 2D surface forecast

Spatial coverage and resolution:

Geographical Coverage: 15 km x 15 km (at 60 N) oriented 175 W (720 x 720 North Polar Stereographic).

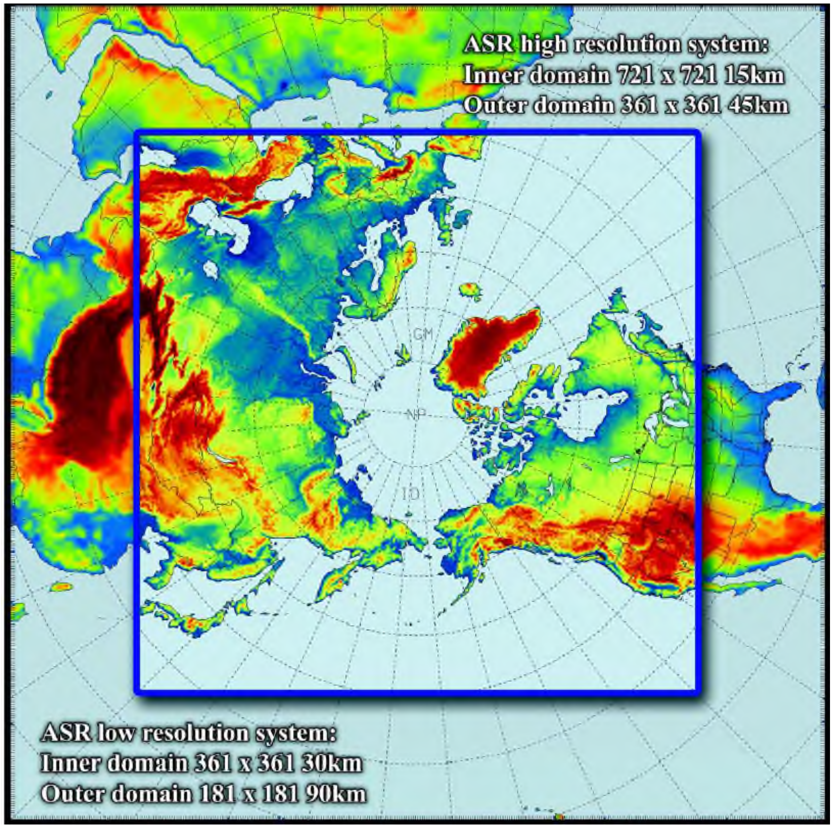


Figure 1. ASR domain (from http://polarmet.osu.edu/ASR/)

Temporal coverage and resolution:

ASRv2 precipitation products are available from 2000 to 2016 as **3-hourly** subsets and monthly means.

Methodology

ASRv2 provides a high resolution description of the atmosphere-sea ice-land surface system of the Arctic. It is using the polar version of the Weather Research and Forecasting (WRF) model version 3.6.0. It uses the 3DVAR technique and the High Resolution Land Data Assimilation (HRLDAS) data assimilation systems that have been optimized for the Arctic.

A full description of ASRv2 is presented in the Bulletin of the American Meteorological Society (PDF).

Observations data in ASRv2

The observations data used in ASRv2 (Figure 2) includes synoptic surface observations (black dots), METARs (purple plus signs), ship observations (royal blue dots), buoys (navy-blue dots), radiosondes (purple asterisks), global positioning system refractivity observations (red dots), wind profiler (yellow dots), aviation in-flight weather reports (green dots), QuikSCAT sea surface winds (orange dots), and satellite atmospheric motion vectors (aqua dots).

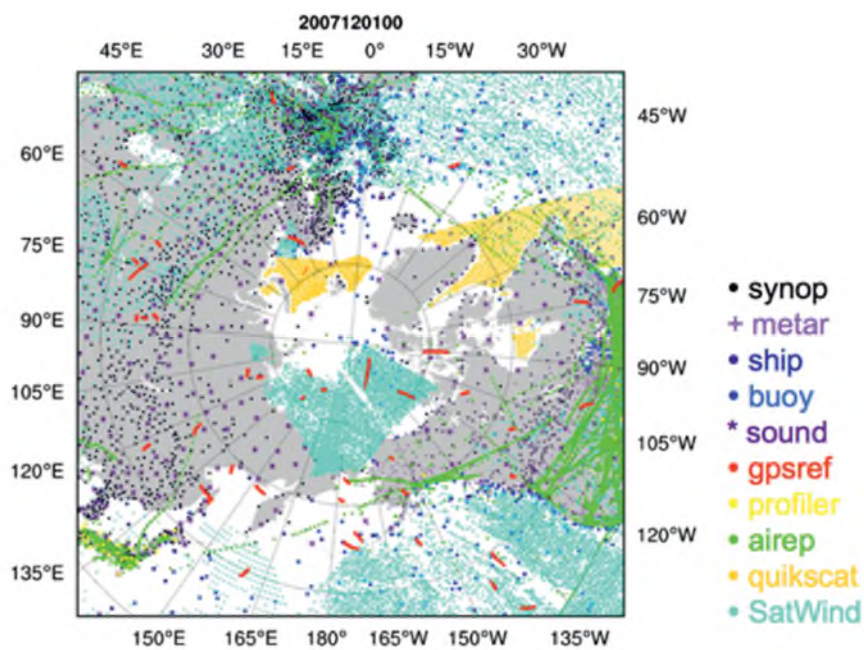


Figure 2. Sample distribution of observations

Information about the technical and scientific quality

New features in ASRv2 compared to ASRv1 are higher horizontal resolution, updated model physics including sub-grid scale cloud fraction interaction with radiation, and a dual outer loop routine for more accurate data assimilation.

Presently there are plans to update ASRv2. The updated version will use the latest version of WRF and WRFDA, a more advanced data assimilation procedure, implement Morrison microphysics with a specified variable aerosol concentration, change to Noah-MP land surface model, incorporate a thermodynamic sea ice model, and increase the horizontal resolution to at least 10 km with ~ 100 vertical levels. This version will be known as ASRv3. Plans are to conduct a reanalysis of the MOSAiC drift period (fall 2019 - fall 2020) and it will be available through NCAR.

Limitations and strengths for application in North Canada

The following notes are general observations provided at https://climatedataguide.ucar.edu/climate-data/arctic-system-reanalysis-asr :

Key Strengths: Marked improvement in summertime precipitation for ASRv2 versus ASRv1.

Key Limitations: Surplus downward shortwave and a small deficit downward longwave radiation still indicate room for improvement in cloud physics including aerosol concentrations and cloud-radiative feedbacks. A dry bias is still present during the cooler months in ASRv2.

References to documents describing the methodology or/and the dataset

Bromwich, D., Y.-H. Kuo, M. Serreze, J. Walsh, L.S. Bai, M. Barlage, K. Hines, and A. Slater, 2010: Arctic System Reanalysis: Call for community involvement. Eos, Transactions American Geophysical Union, 91(2), 13-14, https://doi.org/10.1029/2010EO020001

Online technical description: **https://rda.ucar.edu/datasets/ds631.0/#!docs**

Link to download the data and format of data:

Data Access:NCAR/RDA

ASRv2 is available in NetCDF formats

Link to download 3 hourly and monthly data on RDA:

3 hourly data surface forecast from 2000 to 2016

ASR 15 km monthly means of forecast products

Publications including dataset evaluation or comparison with other data in Canada

Bromwich, D.H., A.B. Wilson, L. Bai, G.W.K. Moore, and P. Bauer, 2016: A comparison of the regional Arctic System Reanalysis and the global ERA-Interim Reanalysis for the Arctic. Q. J. R. Meteorol. Soc., 142, 644-658. https://doi.org/10.1002/qj.2527

Bromwich, D.H., K.M. Hines, and L.-S. Bai, 2009: Development and testing of Polar WRF: 2. Arctic Ocean. J. Geophys. Res., 114, D08122. https://doi.org/10.1029/2008JD010300

Smirnova, J., and P. Golubkin, 2017: Comparing polar lows in atmospheric reanalyses: Arctic System Reanalysis versus ERA-Interim. Mon. Wea. Rev., 145, 2375-2383, https://doi.org/10.1175/MWR-D-16-0333.1

Avila-Diaz, A., D.H. Bromwich, A.B. Wilson, F. Justino, S.-H. Wang, 2021: Climate extremes across the North American Arctic in modern reanalyses. J. Climate, , 34, 2385–2410, https://doi.org/10.1175/JCLI-D-20-0093.1

Chanona, M., and S. Waterman, 2020: Temporal Variability of Internal Wave-Driven Mixing in Two Distinct Regions of the Arctic Ocean. J. Geophys. Res. Oceans, 125, https://doi.org/10.1029/2020JC016181

Edel, L., C. Claud, C. Genthon, C. Palerme, N. Wood, T. L'Ecuyer, and D. Bromwich, 2020: Arctic snowfall from CloudSat observations and reanalyses. J. Clim., 33, 2093-2109, https://doi.org/10.1175/JCLI-D-19-0105.1

Kaiser-Weiss, A.K., M. Borsche, D. Niermann, F. Kaspar, C. Lussana, F.A. Isotta, E. van den Besselaar, G. van der Schrier, and P. Undén, 2019: Added value of regional reanalyses for climatological applications. Environ. Res. Commun., 1, https://doi.org/10.1088/2515-7620/ab2ec3

Gutjahr, O., and G. Heinemann, 2018: A model-based comparison of extreme winds in the Arctic and around Greenland. Int. J. Clmatol., 38, 5272-5292, https://doi.org/10.1002/joc.5729

Rabatel, M., P. Rampal, A. Carrassi, L. Bertino, and C. K. Jones, 2018: Impact of rheology on probabilistic forecasts of sea ice trajectories: Application for search and rescue operations in the Arctic. Cryosphere, 12, 935-953, https://doi.org/10.5194/tc-12-935-2018

Kohnemann, S.H., G. Heinemann, D.H. Bromwich, and O. Gutjahr, 2017: Extreme warming in the Kara Sea and Barents Sea during the winter period 2000-16. J. Clim., 30, 8913-8927, https://doi.org/10.1175/JCLI-D-16-0693.1

Kolstad, E.W., 2017: Higher ocean wind speeds during marine cold air outbreaks. Quarterly J. Roy. Meteor. Soc., 143, 2084-2092, https://doi.org/10.1002/qj.3068

Rampal, P., S. Bouillon, E. Ólason, and M. Morlighem, 2016: neXtSIM: a new Lagrangian sea ice model. The Cryosphere, 10, 1055-1073, https://doi.org/10.5194/tc-10-1055-2016

Wang, F., W. Li, and S. Wang, 2016: Polar cyclone identification from 4D climate data in a knowledge-driven visualization system. Climate, 4, https://doi.org/10.3390/cli4030043

7.2.12 ***Dataset*: NCEP North American Regional Reanalysis (NARR) - precipitation**

Overview

This document focuses on precipitation related data from NARR. NARR is a regional reanalysis covering the North America using a Northern Lambert Conformal Conic grid with an approximately 0.3 degrees (32 km) spatial resolution at the lowest latitude. Dataset was originally produced at NOAA's National Center for Atmospheric Prediction (NCEP), and detailed description is provided at https://psl.noaa.gov/data/gridded/data.narr.html#detail with online Analysis and Plotting Tools at https://psl.noaa.gov/cgi-bin/data/getpage.pl.

Provider's contact information

Physical Sciences Laboratory: Data Management

NOAA/ESRL/PSL

325 Broadway

Boulder, CO 80305-3328

psl.data@noaa.gov.

Licensing

This work is licensed under a Creative Commons Attribution 4.0 International Licence.

There are no restrictions for the use of data.

If the data are taken from PSD, the providers ask that the data is acknowledged by including text such as NCEP Reanalysis data provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, from their Web site at http://www.esrl.noaa.gov/psd/ in any documents or publications using these data.

If the data are taken from NCAR, the citation should include the following: National Centers for Environmental Prediction/National Weather Service/NOAA/U.S. Department of Commerce. 2005, updated monthly. NCEP North American Regional Reanalysis (NARR). Research Data Archive at the National Center for Atmospheric Research, Computational and Information Systems Laboratory. https://rda.ucar.edu/datasets/ds608.0/. Accessed dd mmm yyyy.

Variable name and units:

The variables are divided into three sections: Pressure level, Monolevel (surface and others) and Subsurface. Precipitation rate data are available in the list of Monolevel variables and they are the output of the analysis and first guess forecast.

Precipitation rate [kg/m^2/s] with

* Categorical snow [yes=1;no=0]

* Categorical ice pellets [yes=1;no=0]

* Categorical freezing rain [yes=1;no=0]

* Categorical rain [yes=1;no=0]

Some variables are available just from the first guess forecast:

Accumulated total precipitation [kg/m^2]

Accumulated convective precipitation [kg/m^2]

Table with snow variables available in NetCDF format at NOAA

Variable	**Statistic**	**Level**	**Download File**
Accumulated total precipitation	3-hourly Accumulation	Surface	apcp.yyyy.nc
Accumulated total precipitation	Daily Accumulation	Surface	apcp.yyyy.nc
Accumulated total precipitation	Monthly average of Daily Accumulation	Surface	apcp.mon.mean.nc
Accumulated total precipitation	Longterm Monthly Mean of daily totals	Surface	apcp.mon.ltm.nc
Accumulated convective precipitation	3-hourly Accumulation	Surface	acpcp.yyyy.nc

Accumulated convective precipitation	Daily Accumulation	Surface	acpcp.yyyy.nc
Accumulated convective precipitation	Monthly Mean of Daily Accumulation	Surface	acpcp.mon.mean.nc
Accumulated convective precipitation	Longterm Monthly Mean of Daily Accumulation	Surface	acpcp.mon.ltm.nc
Precipitation rate	3-hourly values	Surface	prate.yyyy.nc
Precipitation rate	Daily Mean	Surface	prate.yyyy.nc
Precipitation rate	Long-term Daily Mean	Surface	prate.day.ltm.nc
Precipitation rate	Monthly Mean	Surface	prate.mon.mean.nc

Values labelled 3 hourly values are output at that exact time (no averaging).

Values labelled accumulations are 3 hours later.

Values labelled 3 hourly averages are averaged over 0 to 3 hr later.

For a complete list of model output variables, see NCEP's variable list. Details for Monolevel variables are provided on https://psl.noaa.gov/data/gridded/data.narr.monolevel.html .

Spatial coverage and resolution:

The data is available for all of North America at an approximate 0.3 degrees (32 km) spatial resolution at the lowest latitude, on a Northern Lambert Conformal Conic grid. Corners of this grid are 1.000001 N, 145.5 W; 0.897945 N, 68.32005 W; 46.3544 N, 2.569891 W; 46.63433 N, 148.6418E. A page describing the coverage along with information on reading the projection is available.

Temporal coverage and resolution:

Data is available as 3h values, Daily and Monthly means for the period 1979/01/01 to 2021/05/31.

Information about observations

The data that are assimilated in order to initialize the model are temperatures, winds, and moisture from radiosondes as well as pressure data from surface observations. Also included in this dataset are dropsondes, pibals, aircraft temperatures and winds, satellite radiance (a measure of heat) from polar (orbiting Earth) satellites, and cloud-drift winds from geostationary (fixed at one location viewing Earth) satellites. The sources of observations are summarized in the table below.

Dataset	Details	Source
Precipitation	Continental United States: comes from a 1/8-degree gauge dataset analyzed using PRISM and a least-squares distance-weighting algorithm. Canada and Mexico: comes from 1-degree gauge datasets and is disaggregated using NCEP R2 hourly precipitation weighting factors. Over oceans (<42.5°N): comes from the Climate Prediction Center (CPC) CMAP (CPC Merged Analysis of Precipitation), a merged combination of satellite and gauge precipitation. It is using a 15-degree "blending belt" between 27.5 and 42.5 N, with no CMAP north of 42.5 N.	NCEP/CPC,Canada, Mexico
TOVS-1B radiances	Temperature, precipitable water over ocean	NESDIS
NCEP Surface	Wind, moisture	GR
TDL Surface	Pressure, wind, moisture	NCAR
COADS (ships/buoys)	Pressure, wind, moisture	NCEP/EMC

Air Force Snow	Snow depth (The Air Force Weather Agency snow depth is estimated daily by merging satellite-derived snow cover data with daily snow depth reports from ground stations.)	COLA and NCEP/EMC
SST	1-degree Reynolds, with Great Lakes SSTs	NCEP/EMC, GLERL
Sea and lake ice	Contains data on Canadian lakes, Great Lakes	NCEP/EMC, GLERL, Ice Services Canada
Tropical cyclones	Locations used for blocking of CMAP Precipitation	Lawrence Livermore National Laboratory

The following figure presents sample distributions of surface assimilated data.

a) b)

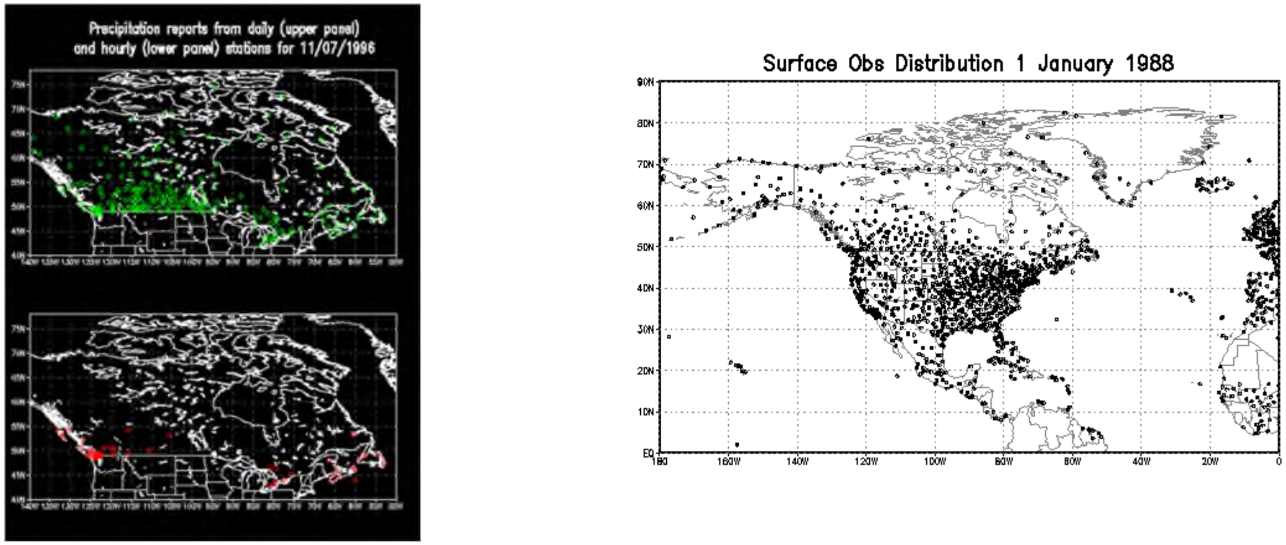


Figure 1. a) Sample distribution of Canadian precipitation assimilated data; b) Sample distribution of surface observations

Methodology

The NARR project is an extension of the NCEP Global Reanalysis which is run over the North American Region. The NARR model uses a high-resolution NCEP Eta Model (32 km/45 layer) together with the Regional Data Assimilation System (RDAS) using 3DVAR method, and it is one of the few reanalysis that assimilates precipitation along with other variables, also over Canada this feature is much reduced comparable to the US. It is using the ETA / NOAH land surface model and it is assimilating snow depths from US Air Force daily snow depth analysis.

For more information, please refer to the publication in the references section below.

Information about the technical and scientific quality

The improvements in the model/assimilation have resulted in a dataset with substantial improvements in the overall accuracy of temperature, winds and precipitation compared to the NCEP-DOE Global Reanalysis 2 (the parent global reanalysis). Wind improvement is especially greatest in the upper troposphere in winter. The 10 m winds improved greatly in winter, a little bit in summer. Relative humidity also improved in both analysis and first guess forecast.

The analyzed precipitation used for precipitation assimilation comes from four sources. Over the continental United States, the analysis comes from a gage dataset and is analyzed onto a 1/8-degree grid using the PRISM mountain mapper and a least-squares distance weighting scheme. Over Mexico and Canada, the analysis comes from gage datasets analyzed onto 1-degree grids. Neither of those datasets has PRISM or a least-squares weighting scheme. Over the rest of the domain, the CMAP dataset is used. CMAP is a combination of gage and satellites, analyzed onto a 1-degree grid. Despite an attempt at a smooth blending, we still see discontinuities between the different datasets, especially around coastlines and borders of countries**. It is important to note also that the number of gauge observations available over Canada is insufficient for the precipitation over Canada from reanalysis to do better than the model is doing.**

Useful information can be found at NCEP's NARR FAQ page: http://www.emc.ncep.noaa.gov/mmb/rreanl/faq.html

Data is updated on a monthly base.

Limitations and strengths for application in North Canada

A very small number of surface measurements are assimilated for norther Canada.

References to documents describing the methodology or/and the dataset

Mesinger, F., G. DiMego, E. Kalnay,K. Mitchell, P. C. Shafran, W. Ebisuzaki, D. Jović, J. Woollen, E. Rogers, E. H. Berbery, M. B. Ek, Y. Fan, R. Grumbine, W. Higgins, H. Li, Y. Lin, G. Manikin, D. Parrish, and W. Shi, 2006: North American Regional Reanalysis. Bulletin of the American Meteorological Society, 87(3), 343-360, doi:10.1175/BAMS-87-3-343.

Link to download the data and format of data:

NARR is available through NOAA ftp page, UCAR and from NCDC page.

NOAA: ftp://ftp.cdc.noaa.gov/Datasets/NARR/ (NetCDF standard format; the data are divided by variable and year and month into separate files; Missing data is flagged with a value of 9.96921e+36f.)

NCDC: https://www.ncdc.noaa.gov/data-access/model-data/model-datasets/north-american-regional-reanalysis-narr (GRIB format)

UCAR: https://rda.ucar.edu/datasets/ds608.0/ (GRIB format)

Publications including dataset evaluation or comparison with other data in northern Canada

7.2.13 *<u>Dataset</u>: North American Precipitation and Land Surface Reanalysis - Regional Deterministic Reforecast System (RDRS) - precipitation*

Overview

This document focuses on precipitation data from RDRSv2. RDRSv2 is a precipitation and surface reanalysis developed at the Canadian Centre for Meteorological and Environmental Prediction (CCMEP) of Environment and Climate Change Canada (ECCC). It provides various forecasted meteorological variables obtained with the Regional Deterministic Reforecast System (RDRS) two-way coupled with the Canadian Land Data Assimilation System (CaLDAS) and Precipitation Analysis (CaPA), and initialized and driven by ERA-Interim reanalysis. Results are provided at a spatial resolution of 10 km across North America. Data is currently available for the period of 1981-2017.

Provider's contact information

Data developed by the Canadian Centre for Meteorological and Environmental Prediction (CCMEP) of Environment and Climate Change Canada (ECCC)

Electronic Mail Address of the provider: The Canadian Surface Prediction Archive (caspar.data@uwaterloo.ca)

Licensing

The end-user licence for Environment and Climate Change Canada's data servers specifies the conditions of use of this data.

The Canadian Surface Prediction Archive Terms of Service

Variable name and units:

The RDRS-v2 product contains two precipitation variables at hourly time step:

1) RDRS_v2_P_PR0_SFC [m]: Model forecasted total quantity of precipitation in metres (background field used by CaPA to produce the analysis).
2) RDRS_v2_A_PR0_SFC [m]: Analyzed total quantity of precipitation in meters.

Information about other variables available for download can be found on CaSPAr data portal.

Spatial coverage and resolution:

The data is available for all of North America at an approximate 10 km x 10 km spatial resolution on a rotated pole grid.

Temporal coverage and resolution:

RDRSv2 is available for the period of 1981-2017 at hourly time steps.

Information about observations (number, homogeneity)

RDRSv2 is initialized and driven by ERA-Interim reanalysis and rely only on surface observations and no remote sensing observations, such as satellite or radar data. Observations were taken from ECCC's operational and climate data archives and include total precipitation. The Integrated Surface Data (ISD, DS463.3) is used in the version v2.1 for the years prior to 2000. Table 3 from Gasset et al. (2021) summarizes the surface observation datasets used in the assimilation processes.

Table 3. Surface networks and variables used by CaLDAS and CaPA.

Network	Domain covered	Availability at CCMEP	Variables used by CaLDAS	Variables used by CaPA-6h	Variables used by CaPA-24h
METAR	North America	1992-present	T, T_d	P, T, $\|\|U\|\|$	P, T, $\|\|U\|\|$
SWOB	North America	2013-present	T, T_d, S_d	Not used	P, T, $\|\|U\|\|$
SYNOP	North America	1992-present	T, T_d, S_d	P, T, $\|\|U\|\|$	P, T, $\|\|U\|\|$
AdjDlyRS	Canada	1980-present	Not used	Not used	P
RMCQ	Province of Quebec	2011-present	Not used	Not used	P, T, $\|\|U\|\|$
SHEF	USA	1998-present	Not used	Not used	P, T, $\|\|U\|\|$

T: temperature, T_d: dew point temperature, S_d: snow depth, P: total precipitation, $||U||$: wind speed

Figure 1 from Lespinas et al. (2010) is presenting the spatial distribution of the meteorological stations assimilated by CaPA and geographical limits of the Canadian terrestrial ecozones.

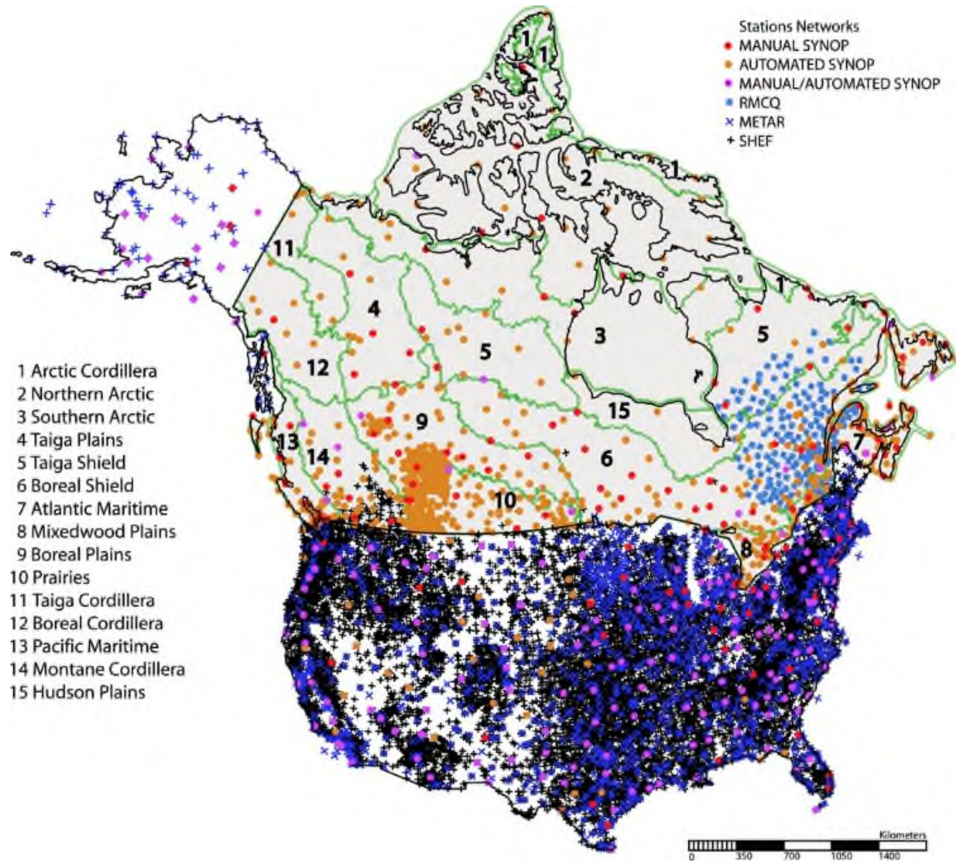


Figure 1. Spatial distribution of the meteorological stations assimilated by CaPA. Source: Journal of Hydrometeorology 16, 5; [10.1175/JHM-D-14-0191.1](10.1175/JHM-D-14-0191.1))

Supplementary information relevant for precipitation, soil moisture and snow: The 24 h a posteriori precipitation analysis, CaPA-24, is also using the Adjusted Daily Rain and Snow (AdjDlyRS) observations dataset (Wang *et al*., 2017). AdjDlyRS data features 3346 stations that are mainly manual stations from the Canadian synoptic network, and are known as the most reliable observations (they were adjusted for systematic errors, and in particular undercatch and evaporation caused by wind effects, gauge-specific wetting loss, as well as for trace precipitation amounts.).

Methodology

ERA-Interim reanalysis is first used to initialize the atmospheric conditions of the Global Deterministic Reforecast System (GDRS) at a spatial resolution of 39 km. Additional surface conditions are input via the GEM-Surf model, which is also initialized by ERA-Interim. The GDRS output is then dynamically downscaled to 10 km using the RDRS. These finer resolution outputs are two-way coupled with the Canadian Land Data Assimilation System (CaLDAS) and Precipitation Analysis (CaPA) system (this means that outputs from RDRS is used to drive both the CaLDAS and CaPA system, and these results are then fed back into RDRS). This coupling results in significantly improved near-surface atmospheric and land-surface predictions.

Both GDRS and RDRS are based on the latest stable version of the Global Environment Multiscale (GEM v4.8-LTS) model and they are both using the same geophysical fields (i.e. orography, vegetation characteristics, soil thermal and hydraulic coefficients, glaciers fraction) as the corresponding forecast operational versions. The coupling with CaLDAs and CaPA allows for combining surface observations of temperature, humidity, snow depth and precipitation with the first guess provided by the RDRS. CaLDAS uses a one-dimensional Ensemble Kalman Filter (EnKF) to estimate soil moisture and soil temperature, and an optimal interpolation (OI) scheme to estimate snow depth. CaPA combines precipitation observations with a background field obtained from the short-term reforecast provided by the RDRS through an OI method. CaPA also serves to provide CaLDAS with 6-h precipitation analysis.

Procedures to calculate final off-line hourly precipitation:

- CaPA-6h is disaggregated to an hourly time step by linearly rescaling the atmospheric model's hourly precipitation rates in order to match the 6-h accumulations estimated by CaPA-6h.

- The same procedure is applied to the CaPA-24h precipitation analysis, but using the disaggregated CaPA-6h product as the reference.

- In cases where the model precipitation was negligible, but precipitation was observed, a constant precipitation rate was assumed for that time period.

For more information, please refer to the publication in the references section below.

Information about the technical and scientific quality

Version 2 was evaluated and compared to the operational numerical weather prediction system (RDPS) over the period of 2010-2017. Gasset *et al.* (2021) mentions that the RDRS improves upon RDPS in most regions and for most variables, notably for Alaska and the Canadian Arctic, as well as Western USA.

In general, reanalyses often do not assimilate any observations of precipitation and of the land-surface state, but instead only provide short-term forecasts of these variables. RDRS do assimilate precipitation observations through the coupling with CaPA. Gasset *et al*. (2021) mentions that the coupling approach of the GDRS, RDRS, CaLDAS, and CaPA demonstrates significant improvements in the surface layer compared to the results obtained without coupling.

Strict quality control procedures are in place in CaPA to avoid the assimilation of biased observations, and in particular wind-induced undercatch of solid precipitation (based on a temperature analysis, different wind speed thresholds are used depending on the network, the type of gauge and whether the station is manned or automated).

In Gasset *et al.* (2021), short-term absolute temperature, dew point temperature, and wind speed forecasts from RDRSv2 were compared to observations from synoptic stations across North America. Results indicate that these data may be suitable in driving other environmental models. Likewise, a preliminary streamflow modelling study has also demonstrated that the RDRSv2 has some skill in driving hydrological models to predict runoff into Lake Erie, suggesting that the RDRSv2 may be useful for hydrological purposes.

Internal analyses at ECCC showed that RDRSv2 has good skill in estimating relative humidity in southeast Canada. However, no analysis was performed for northern Canada.

Data is available in netCDF format on CaSPAr data portal. Two scientific papers accompany the dataset, one detailing CaSPAr and the other detailing the RDRSv2 dataset. It is expected that the data will be updated regularly.

Limitations and strengths for application in North Canada

RDRSv2 is initialized and driven by ERA-Interim, a reanalysis dataset that has been since superseded by ERA5. The pending data for the years 1980-1999 and 2018 will continue to use ERA-Interim, and tests are currently being conducted to determine the suitability and impacts of switching to another dataset. Furthermore, a bug that was identified during the development of the 2000-2017 reanalysis data: snow depth was expressed in metres in the code whereas it is supposed to be expressed in centimetres. It was verified that while biases and other errors for snow depth itself wasn't heavily impacted, snow density and snow water equivalent demonstrated significant differences. As such, these two fields are not distributed for 2000-2017 until later releases.

References to documents describing the methodology or/and the dataset

Gasset, N., V. Fortin, M. Dimitrijevic, M. Carrera, B. Bilodeau, R. Muncaster, É.,Gaborit, G. Roy, N. Pentcheva, M. Bulat, X. Wang, R. Pavlovic, F. Lespinas, and D. Khedhaouiria, 2021: A 10 km North American Precipitation and Land Surface Reanalysis Based on the GEM Atmospheric Model. Hydrology and Earth System Sciences, 25(9), 4917-4945, https://doi.org/10.5194/hess-25-4917-2021

Link to download the data and format of data:

The data can be accessed through the CaSPAr data catalogue as well as directly from their data portal:

Data catalogue: https://github.com/julemai/CaSPAr/wiki/Available-products

Data portal: https://caspar-data.ca/caspar **(NetCDF)**

Publications including dataset evaluation or comparison with other data

Mai, J., B.A. Tolson, H. Shen, É. Gaborit, V. Fortin, N. Gasset, H. Awoye, T. A. Stadnyk, L. M. Fry, E. A. Bradley, F. Seglenieks, A. G. T. Temgoua, D. G. Princz, S. Gharari, A. Haghnegahdar, M. E. Elshamy, S. Razavi, M. Gauch, J. Lin, X. Ni, Y. Yuan, M. McLeod, N. B. Basu, R. Kumar, O. Rakovec, L. Samaniego, S. Attinger, N. K. Shrestha, P. Daggupati, T. Roy, S. Wi, T. Hunter, J. R. Craig, and A. Pietroniro, 2021: Great Lakes Runoff Intercomparison Project Phase 3: Lake Erie (GRIP-E), Journal of Hydrologic Engineering, 26(9), 05021020-1-19. https://doi.org/10.1061/(ASCE)HE.1943-5584.0002097

Reference for CaPA:

Mahfouf, J.-F., B. Brasnett, and S. Gagnon, 2007: A Canadian precipitation analysis (CaPA) project: Description and preliminary results, Atmosphere-Ocean, 45(1), 1-17, DOI: 10.3137/ao.v450101.

Fortin, V., G. Roy, T. Stadnyk, K. Koenig, N. Gasset, and A. Mahidjiba, 2018: Ten Years of Science Based on the Canadian Precipitation Analysis: A CaPA System Overview and Literature Review, Atmosphere-Ocean, 56(3), 178-196, DOI: 10.1080/07055900.2018.1474728.

Lespinas, F., V. Fortin, G. Roy, P. Rasmussen, and T. Stadnyk, 2015: Performance Evaluation of the Canadian Precipitation Analysis (CaPA), Journal of Hydrometeorology, 16(5), 2045-2064. Retrieved May 26, 2021, from

https://journals.ametsoc.org/view/journals/hydr/16/5/jhm-d-14-0191_1.xml

7.2.14 <u>Dataset</u>: NOAA-CIRES-DOE Twentieth Century Reanalysis (20CRv3) - precipitation

Overview

This document provides an overview of the precipitation data from Twentieth Century Reanalysis (20CRv3). The 20th Century Reanalysis Project is an effort led by NOAA's Physical Sciences Laboratory (PSL) and CIRES at the University of Colorado, supported by the Department of Energy (DOE), to produce reanalysis datasets spanning the entire 20th century and much of the 19th century. These reanalyses assimilate only surface observations of synoptic pressure into NOAA's Global Forecast System, and prescribed sea surface temperature and sea ice distribution in order to estimate atmospheric variables, from the surface to the top of the atmosphere throughout the 19th and 20th centuries. 20CRv3 is version 3 of the project. For version 3, the ensemble mean and standard deviation for each value were calculated over a set of 80 analyses and short-term forecasts.

Provider's contact information

20CRv3 is developed by the NOAA's Physical Sciences Laboratory (PSL) and CIRES at the University of Colorado, supported by the Department of Energy (DOE).

For help with the dataset please contact

Gilbert P. Compo

CIRES, University of Colorado at Boulder, and Physical Sciences Laboratory, National Oceanic and Atmospheric Administration

gilbert.p.compo at noaa.gov

Laura C. Slivinski

CIRES, University of Colorado at Boulder, and Physical Sciences Laboratory, National Oceanic and Atmospheric Administration

laura.slivinski at noaa.gov

Licensing and citation

20CRv3 data are provided by several collaborative organizations. User registration and agreement to terms and conditions of data service usage are required individually for each organization.

Data at NCAR RDA is licensed under a Creative Commons Attribution 4.0 International Licence.

The following citation should be used for data downloaded from NCAR RDA:

" **Slivinski**, L. C., et al. 2019. NOAA-CIRES-DOE Twentieth Century Reanalysis Version 3. Research Data Archive at the National Center for Atmospheric Research, Computational and Information Systems Laboratory. https://doi.org/10.5065/H93G-WS83. Accessed† dd mmm yyyy.

†Please fill in the "Accessed" date with the day, month, and year (e.g., - 5 Aug 2011) you last accessed the data from the RDA. "

The following citation should be used for data downloaded from Physical Sciences Laboratory (PSL) or from National Energy Research Scientific Computing Center (NERSC):

Papers using the NOAA-CIRES-DOE Twentieth Century Reanalysis Project version 3 dataset are requested to include the following text in their acknowledgments: "Support for the Twentieth Century Reanalysis Project version 3 dataset is provided by the U.S. Department of Energy, Office of Science Biological and Environmental Research (BER), by the National Oceanic and Atmospheric Administration Climate Program Office, and by the NOAA Physical Sciences Laboratory."

If you acquire 20th Century Reanalysis V3 data products from PSL, we are asked to acknowledge PSL by including also a text such as *20th Century Reanalysis V3 data provided by the NOAA/OAR/ESRL PSL, Boulder, Colorado, USA, from their Web site at /* in any documents or publications using these data and send a copy of the relevant publications to:

Physical Sciences Laboratory: Data Management

NOAA/ESRL/PSL

325 Broadway

Boulder, CO 80305-3328

psl.data@noaa.gov

Spatial coverage and resolution:

20CRv3 data, is a global dataset. 20CRv3 has a Gaussian T-254 grid (approximately 75 km at the equator).

Variable name and units:

The following table summarizes the precipitation data available.

Notation (name)	Units	Organisation (type)

PRATE (Precipitation Rate)	kg/m^2/s	PSL; NERSC; NCAR (Analysis Fields)
CPRAT (Convective Precipitation Rate)	kg/m^2/s	PSL; NCAR (Analysis Fields)
APCP (Precipitation amount)	kg/m^2	PSL; NCAR (Analysis Fields)
ACPCP (convective precipitation accumulation)	kg/m^2	PSL; NCAR (Analysis Fields)
CFRZR (Categorical freezing rain)	1	PSL; NERSC; NCAR (Analysis Fields)
CICEP (Categorical ice pellets)	1	PSL; NERSC; NCAR (Analysis Fields)
CRAIN (Categorical rain)	1	PSL; NERSC; NCAR (Analysis Fields)
CSNOW (Categorical snow)	1	PSL; NERSC; NCAR (Analysis Fields)

Temporal coverage and resolution:

On PSL website, 20CRv3.SI is available for years 1836-1980 and 20CRv3.MO is available for years 1981-2015 (the only differences between these two versions are the prescribed sea surface temperatures and dates of availability):

- 3-hourly values for 1836/01/01 0Z to 2015/12/31 21Z.
- Daily average values for 1836/01/01 to 2015/12/31.
- Monthly values for 1836/01 to 2015/12 (Combined SI-MO).

At NCAR RDA, 20CRv3 is available from:

- 1835/12/31 18Z to 2016/01/01 0Z (Yearly Time Series 3-Hourly Analysis Fields (Gaussian T-254))
- 1806/12/31 18Z to 2015/12/31 12Z (Yearly Time Series 3-Hourly First Guess Forecast Fields (Gaussian T-254))
- 1806/12/31 21Z to 2015/12/31 15Z (Yearly Time Series 6-Hourly Analysis Fields (Gaussian T-254))

The data is updated on an irregular base.

Information about observations (number, homogeneity)

These reanalyses assimilate only surface observations of synoptic pressure. Boundary conditions of pentad sea surface temperature and monthly sea ice concentration and time-varying solar, volcanic, and carbon dioxide radiative forcings are prescribed.

The surface pressure observations: ISPD version 4.7, made available through international cooperation facilitated by the Atmospheric Circulation Reconstructions over the Earth (ACRE) initiative and working groups of the Global Climate Observing System and World Climate Research Program.

Sea Ice Concentration Boundary Condition: monthly HadISST2.3 sea ice (Slivinski *et al*., 2019; Titchner & Rayner 2014; Walsh *et al*., 2015)

Sea Surface Temperature Boundary Condition: prior to 1981(20CRv3.SI): 8 members of pentad interpolated to daily Simple Ocean Data Assimilation with Sparse Input (SODAsi) version 3 (SODAsi.3, Giese *et al*., 2016) seasonally adjusted to the 1981-2010 HadISST2.2 climatology. Regions where sea ice was ever indicated in HadISST2.3 are filled with: HadISST2.2 daily (1963+); HadISST2.1 monthly interpolated to daily (1850-1962); or the 1861–1891 HadISST2.1 climatology (1849 and earlier). **1981 and later (20CRv3.MO)**: 8 members of pentad interpolated to daily HadISST2.2 sea surface temperatures.

Methodology

20CRv3 assimilates only surface observations of synoptic pressure into an 80-member the coupled Global Forecast System land-atmospheric model with prescribed sea surface temperatures and sea ice concentration. A coupled one-dimensional thermodynamic sea-ice model is also used. Boundary conditions of pentad sea surface temperature and monthly sea ice concentration and time-varying solar, volcanic, and carbon dioxide radiative forcings are prescribed.

Forecast model: 20CRv3 uses the atmospheric model from the NCEP Global Forecast System v14.0.1 coupled with the Noah land surface model and 2.5-layer thermodynamic sea ice model (Compo *et al*., 2011). The forecast system is run at a resolution of T254 (approximately 75 km at the equator) with 64 vertical levels up to .3 mb and it has 80 individual ensemble members.

Assimilation model: The data assimilation algorithm is the Ensemble Square Root Filter (Whitaker and Hamill 2002) with 4D Incremental Analysis Update (4D-IAU; Bloom *et al*., 1996, Lei & Whitaker 2016). The snow relaxes to a monthly climatology (Saha *et al*., 2010) over 60 days.

Streams: Every 5th year a stream is produced for a continuous 5 year period. Stream years are 1835, 1840, ... , 2005, 2010. Stream year 2010 will be extended beyond 2015.

Information about the technical and scientific quality

There are three previous versions of the reanalysis: V1, V2, and V2c. Several adjustments were made to the model prior to implementation in the 20CRv3 system. Updates to the parameterizations are described in Saha *et al*. (2010) and include revised solar radiation transfer, boundary layer vertical diffusion, cumulus convection, and gravity wave drag parameterizations. In addition, the cloud liquid water is a prognostic quantity with a simple cloud microphysics parameterization. Another important improvement is in the resolution and ensemble size. Previous 20CR versions were using a 56-member ensemble with a coarser spatial resolution (T62 28 levels), while the 20CRv3 is using 80 ensemble members with a finer spatial resolution (T254 64 levels). 20CRv3 also assimilates a larger set of observations, and includes an improved data assimilation system relative to its predecessor 20CRv2c.

Observations are first grossly tested for quality control: if the observation is outside the range 850 and 1090 hPa, or if the absolute difference between the observation and the first guess value is greater than 3.2 times the square root of the sum of the forecast ensemble variance and the observation error variance, the observation is rejected. (Slivinski *et al*., 2018). They are then subject to adaptive quality control and adaptive localization control.

Limitations and strengths for application in North Canada

Key Strengths: Length of record and estimates of uncertainty

Key Limitations: As with all reanalyses, users should take care in interpreting long-term trends - inconsistencies between 20CR and other data have been reported, especially on a regional scale.

References to documents describing the methodology or/and the dataset

Compo, G.P., J.S. Whitaker, P.D. Sardeshmukh, N. Matsui, R.J. Allan, X. Yin, B.E. Gleason, R.S. Vose, G. Rutledge, P. Bessemoulin, S. Brönnimann, M. Brunet, R.I. Crouthamel, A.N. Grant, P.Y. Groisman, P.D. Jones, M. Kruk, A.C. Kruger, G.J. Marshall, M. Maugeri, H.Y. Mok, Ø. Nordli, T.F. Ross, R.M. Trigo, X.L. Wang, S.D. Woodruff, and S.J. Worley, 2011: The Twentieth Century Reanalysis Project. Quarterly Journal of the Royal Meteorological Society, 137(654), 1-28, DOI: 10.1002/qj.776.

Slivinski, L.C., G. P. Compo, J. S. Whitaker, P. D. Sardeshmukh, B. S. Giese, C. McColl, R. Allan, X. Yin, R. Vose, H. Titchner, J. Kennedy, L. J. Spencer, L. Ashcroft, S. Brönnimann, M. Brunet, D. Camuffo, R. Cornes, T. A. Cram, R. Crouthamel, F. Domínguez-Castro, J. E. Freeman, J. Gergis, E. Hawkins, P. D. Jones, S. Jourdain, A. Kaplan, H. Kubota, F. Le Blancq, T.-C. Lee, A. Lorrey, J. Luterbacher, M. Maugeri, C. J. Mock, G.W. K. Moore, R. Przybylak, C. Pudmenzky, C. Reason, V. C. Slonosky, C. A. Smith, B. Tinz, B. Trewin, M. A. Valente, X. L. Wang, C. Wilkinson, K. Wood, and P. Wyszyński, 2019: Towards a more reliable historical reanalysis: Improvements for version 3 of the Twentieth Century Reanalysis system. Quarterly J. Roy. Meteorol. Soc., in press. DOI: 10.1002/qj.3598.

Link to download the data and format of data:

20CRv3 data are available at several organizations.

At NOAA/PSL, the ensemble mean and the ensemble uncertainty files are available in netCDF4 format: https://psl.noaa.gov/data/gridded/data.20thC_ReanV3.monolevel.html

At National Center for Atmospheric Research (NCAR), the ensemble mean and the ensemble uncertainty files are available in netCDF4 format: https://rda.ucar.edu/datasets/ds131.3/

At NERSC Science Gateway, data for every member of 20CRv3 are available in netCDF4 format: https://portal.nersc.gov/project/20C_Reanalysis/

Publications including dataset evaluation or comparison with other data in Canada

7.2.15 <u>Dataset</u>: ECMWF 5th Generation Land Reanalysis (ERA5-Land) - precipitation

Overview

This document provides an overview of the total precipitation of ERA5-Land, in the context of the larger ERA5-Land dataset. ERA5-Land is a replay of the land component of the ERA5 atmospheric global reanalysis using a finer spatial resolution and including a series of improvements making it more accurate for all types of land applications. ERA5-Land is produced by ECMWF framed within the Copernicus Climate Change Service (C3S) of the European Commission. The data covers a period from January 1950 to the present. It provides hourly data for many near-surface atmospheric and land-surface parameters.

Provider's contact information

ERA5-Land is produced by the Copernicus Climate Change Service (C3S) at ECMWF.

Copernicus User support: copernicus-support@ecmwf.int (external to C3S)

Licensing

Licence: Copernicus (Licence agreement information can be found here or here).

Dataset citable as: **Muñoz Sabater**, J., 2019: ERA5-Land hourly data from 1981 to present. Copernicus Climate Change Service (C3S) Climate Data Store (CDS). (Accessed on < DD-MMM-YYYY >), 10.24381/cds.e2161bac

Variable name and units:

Total precipitation of ERA5-Land over northern Canada is the focus of this document. This variable is available as **hourly** and **monthly** subsets. The table below provides the units and details on the variable.

Name	Units	Description
Total precipitation	m	Accumulated liquid and frozen water, including rain and snow, that falls to the Earth's surface. It is the sum of large-scale precipitation (that precipitation which is generated by large-scale weather patterns, such as troughs and cold fronts) and convective precipitation (generated by convection which occurs when air at lower levels in the atmosphere is warmer and less dense than the air above, so it rises). Precipitation variables do not include fog, dew

		or the precipitation that evaporates in the atmosphere before it lands at the surface of the Earth. This variable is accumulated from the beginning of the forecast time to the end of the forecast step. The units of precipitation are depth in metres. It is the depth the water would have if it were spread evenly over the grid box.

Total precipitation can be found by selecting its name from the table with parameters on the pages below:

- hourly data from 1950 to present,
- monthly averaged data from 1981 to present.

Note: The convention for accumulations used in ERA5-Land differs with that for ERA5. In ERA5-Land, they are accumulated from the beginning of the forecast to the end of the forecast step. Therefore, the hour 00 UTC at day 'd' gives the total accumulation value for the previous day 'd-1'. Care should be taken when using CDO functions as 'daysum' or any equivalent operator to compute daily sums.

ECMWF provides a conversion table for accumulated variables (total precipitation/fluxes) for ERA5-Land and ERA5. The table shows how accumulated variables from a number of C3S and ECMWF datasets should be processed to derive values for an hour, a day, a month and a year. In the documentation, 'total precipitation' and 'solar radiation' are used for illustration, but the same processing should be applied to all precipitation and radiative flux variables.

Spatial coverage and resolution:

ERA5-Land is a global land-surface dataset. The atmospheric data is available on a regular latitude-longitude grid at 0.1° x 0.1° resolution (converted from native reduced-Gaussian grid resolution of approximately 9 km x 9 km), and on 4 surface layers. Oceans have been masked out and the data is available only over landmasses and inland lakes.

Temporal coverage and resolution:

ERA5-Land data is available from 1950 to present at hourly time step. The data at monthly time step is available for the period 1981 to present (the 1950 – 1980 back extension is scheduled to be available in 2022).

ERA5-Land data updates are made synchronously with ERA5 updates, approximately 2-3 months behind real time.

Information about observations (number, homogeneity)

ERA5-Land is not directly influenced by observations, but rather, indirectly influenced through the ERA5 atmospheric forcings. ERA5's data assimilation uses observations for all geophysical quantities from about 0.75 million observations per day in 1979 and about 24 million in 2018. The 2D-OI uses surface observations at 'screen level'. The online technical documentation provides tables with the satellite and in-situ observations used as input into ERA5. Further details can also be found in the ERA5 document previously prepared by the CCCS.

Methodology

ERA5-Land is produced under a single simulation of the land component of the ERA5 climate reanalysis, without coupling to the atmospheric module of the ECMWF's Integrated Forecasting System (IFS) and without data assimilation. The low atmospheric forcing is provided by the ERA5 reanalysis, with additional lapse-rate correction. The core of ERA5-Land is the Tiled ECMWF Scheme for Surface Exchanges over Land incorporating land surface hydrology (H-TESSEL). Because it runs without data assimilation, it makes it computationally affordable for relatively quick updates. For example, if significant improvements of the land surface model are implemented, the whole or part of the dataset can be reprocessed in a relatively short period. Updates are possible in case improved auxiliary datasets are used as input for the production.

Production of ERA5-Land is not produced as a single continuous segment, but instead as three segments: Stream-1 (2001 onwards), Stream-2 (1981-2000), and Stream-3 (1950-1980). This is because it allows parallel production of data enabling sooner public access to the data, and because the atmospheric forcings used by ERA5-Land is derived from ERA5, thus needing corresponding completed ERA5 segment. Each stream is initialized with various meteorological fields from ERA5 (temperature, precipitation, humidity, radiation, etc.). While ERA5-Land does not assimilate observations directly, they are introduced via the ERA5 atmospheric forcings. These forcings are adjusted using ERA5 derived lapse rates before being integrated with the ECMWF Carbon Hydrology-Tiled ECMWF Scheme for Surface Exchanges over Land (CHTESSEL) land surface model. This is done in 24-hour cycles, generating hourly outputs and the evolution of the land surface state and water and energy fluxes. For further details of the assimilation system used to obtain the ERA5 atmospheric forcings, please see the ERA5 document previously prepared by the CCCS.

Uncertainty estimate: Currently, ERA5-Land variable uncertainty estimates are those corresponding to ERA5. ERA5 uncertainty estimate is sampled by a 10-member lower-resolution Ensemble Data Assimilation (EDA) which provides background-error estimates for the deterministic HRES 4D-Var Data Assimilation system. The analysis method is the same for each EDA member and follows that of the HRES. Each member (except the control) is run with different random perturbations added to the observations. Likewise, the model physical tendencies are perturbed in the short forecasts that link subsequent analysis windows. Ensemble mean and spread have been pre-computed for convenience. Such uncertainty estimates are closely related to the information content of the available observing system

which has evolved considerably over time. They also indicate flow-dependent sensitive areas. To facilitate many climate applications, monthly-mean averages have been pre-calculated too, though monthly means are not available for the ensemble mean and spread.

The original plan was to apply the same methodology ERA5-Land was to provide an estimate of the uncertainty fields as was done for ERA5. However, the uncertainty was estimated to be extremely low, and would have assigned unrealistically high confidence to the ERA5-Land variables. As such, it is recommended to use the corresponding ERA5 uncertainty estimates for the time being until further studies are done.

Information about the technical and scientific quality

ERA5-Land represents one of the products of the latest global atmospheric reanalysis produced by Copernicus Climate Change Service at ECMWF. It is archived at a shorter (hourly) time step, has a fine spatial resolution, uses a more advanced assimilation system and includes more sources of data than previous versions (e.g., ERA-Interim-Land). It is accompanied by extensive technical documentation and two principal scientific documentation papers. A list of 'known issues' is maintained at the online documentation (https://confluence.ecmwf.int/display/CKB/ERA5-Land%3A+data+documentation).

Information on land surface model: The land surface model of the ERA5-Land was operational in 2018 with the IFS model cycle 45r1. While most of the changes from the IFS Cy41R2 used in ERA5 are primarily technical, there were a few improvements to various fields: 1) the parameterization of the soil thermal conductivity was updated to take the ice component of frozen soil into consideration, 2) conservation of the soil-water balance was fixed and improved, and 3) rain over snow is now accounted for and is not accumulated in snow pack. Furthermore, a bug exists in IFS Cy41R2, that affects potential evapotranspiration (PET) flux calculations over forests and deserts, has been corrected in ERA5-Land, and unlike ERA5, ERA5-Land PET is an available dataset. However, PET is now determined by assuming a vegetation type of crops and no soil moisture stress. These assumptions may not be always realistic, and therefore PET should be used cautiously. More information on the CHTESSEL land surface model used in ERA5-Land can be found in Muñoz-Sabater *et al.* (2021, preprint) and the ERA5 document previously prepared by the CCCS

Limitations and strengths for application in North Canada

ERA5-Land is a newer land surface reanalysis and there are few available scientific evaluations of the dataset dedicated specifically to northern Canada. However, it should be noted that in northern Canada, there are currently no sub-daily records over a long historical period for many weather stations. Reanalyses data with hourly output cover this gap and, with suitable investigation and calibration (downscaling), could be valuable particularly for sub-daily extremes analyses. The ERA5-Land high-resolution improved land surface hydrology scheme incorporates surface runoff and drainage with functional dependencies on orography and soil texture, respectively.

The units of precipitation are depth in metres, which is the depth the water would have if it were spread evenly over the grid box. Care should be taken when comparing model variables with observations, because observations are often local to a particular point in space and time, rather than representing averages over a model grid box and model time step.

As all reanalyses, the changes in the amounts and types of observational data that are assimilated may have an adverse impact on trends or variability. Care should be taken when trends or variability are analyzed.

References to documents describing the methodology or/and the dataset

Muñoz Sabater, J., 2019: ERA5-Land hourly data from 1981 to present. Copernicus Climate Change Service (C3S) Climate Data Store (CDS). (Accessed on < 25-Jun-2021 >), https://doi.org/10.24381/cds.e2161bac

Muñoz-Sabater, J., E. Dutra, A. Agustí-Panareda, C. Albergel, G. Arduini, G., Balsamo, S. Boussetta, M. Choulga, S. Harrigan, H. Hersbach, B. Martens, D. G. Miralles, M. Piles, N. J. Rodríguez-Fernández, E. Zsoter, C. Buontempo, and J.-N. Thépaut, 2021: ERA5-Land: A state-of-the-art global reanalysis dataset for land applications. Earth System Science Data, 13(9), 4349-4383. https://doi.org/10.5194/essd-2021-82

Hersbach, H., B .Bell, P. Berrisford, S. Hirahara, A. Horányi, J. Muñoz-Sabater, J. Nicolas, C. Peubey, R. Radu, D. Schepers, A. Simmons, C. Soci, S. Abdalla, X. Abellan, G. Balsamo, P. Bechtold, G. Biavati, J. Bidlot, M. Bonavita, G. Chiara, P. Dahlgren, D. Dee, M. Diamantakis, R. Dragani, J. Flemming, R. Forbes, M. Fuentes, A. Geer, L. Haimberger, S. Healy, R.J. Hogan, E. Hólm, M. Janisková, S. Keeley, P. Laloyaux, P. Lopez, C. Lupu, G. Radnoti, P. Rosnay, I. Rozum, F. Vamborg, S. Villaume, and J.-N. Thépaut, 2020: The ERA5 global reanalysis. Quarterly Journal of the Royal Meteorological Society, 146(730), 1999–2049. https://doi.org/10.1002/qj.3803.

Link to download the data and format of data:

Data Access: Copernicus | ECMWF (requires login)

ERA5-Land is available in GRIB and NetCDF formats

Link to download hourly and monthly data on Copernicus:

- hourly data from 1950 to present,
- monthly averaged data from 1981 to present

Publications including dataset evaluation or comparison with other data in Canada

7.2.16 Dataset: ANUSPLIN Gridded Canadian dataset - precipitation

Overview

This document provides an overview of precipitation gridded datasets created by the Canadian Forest Service, Natural Resources Canada. The dataset covers the period 1950 - 2017 at the daily, pentad and monthly time scale. 30-year averages were also created. The dataset was generated using ANUSPLIN with a 60 arc-second (approximately 2 km) and/or with a 300 arc-second (approximately 10 km) Digital Elevation Model (DEM; Lawrence *et al*., 2008), using station observations. Station data have been quality controlled, but are not homogenized. Daily data is available over Canada, while pentad, monthly, and 30-year time scales are available for continental North America and Canada.

Provider's contact information

This spatial dataset was developed by researchers from the Integrated Ecology and Economics Division at Canadian Forest Service at Natural Resources Canada (Dr. Dan McKenney, Dr. Heather MacDonald, John Pedlar, Kevin Lawrence, Pia Papadopol, Kaitlin de Boer from the CFS and Dr. Michael Hutchinson from Fenner School of Environment and Society, Australian National University). If you have questions about this dataset, please contact Dr. Dan McKenney (dan.mckenney@canada.ca)

Licensing

Freely available. Contact Dr. Dan McKenney, Canadian Forest Service, Natural Resources Canada, dan.mckenney@canada.ca

The following scientific publications should be cited if you use these data in publications:

Canada:

Hutchinson, M. F., D. W. McKenney, K. Lawrence, J. H. Pedlar, R. F. Hopkinson, E. Milewska, and P.Papadopol, 2009: Development and testing of Canada-wide interpolated spatial models of daily minimum–maximum temperature and precipitation for 1961–2003. *J. Appl. Meteor. Climatol.*, **48**, 725–741, https://doi.org/10.1175/2008JAMC1979.1.

Hopkinson, R.F., D.W. Mckenney, E.J. Milewska, M.F. Hutchinson, P. Papadopol, and L.A. Vincent, 2011: Impact of aligning climatological day on gridding daily maximum-minimum temperature and precipitation over Canada. Journal of Applied Meteorology and Climatology, 50(8), 1654-1665, doi:10.1175/2011JAMC2684.1.

North America:

MacDonald, H., D. W. McKenney, P. Papadopol, K. Lawrence, J. Pedlar, and M. F. Hutchinson, 2020: North American historical monthly spatial climate dataset, 1901–2016. Scientific Data, 7(1), 1-11, https://doi.org/10.1038/s41597-020-00737-2

Variable name and units:

Total precipitation (mm)

Spatial coverage and resolution:

	Daily	Pentad	Monthly	30 –year average
Region	Canada	Canada and North America	Canada and North America	Canada and North America
Spatial resolution	~ 2 km and ~ 10 km	~ 2 km and ~ 10 km	~ 2 km and ~ 10 km	~ 2 km and ~ 10 km

Temporal coverage and resolution:

Daily – 1950-2017

Pentad – 1950-2017

Monthly – 1950-2017

30-year Average – 1961/1990, 1971/2000, 1981/2010

The data will continue to be updated regularly.

Information about observations (number, homogeneity)

Over Canada, the datasets were generating using station observations from MSC at Environment and Climate Change Canada (ECCC). Station data have been quality controlled for the time of observation, but are not homogenized. The number of stations used for spatial modelling increased from 900 in 1950 to 2312 in 1985, and then declined to 1398 stations in 2017 (Figure 1). Stations are not evenly distributed in space. Many stations are located in southern Canada and fewer in northern Canada (Figure 2). For North America datasets, the ECCC stations were supplemented with GHCND hourly weather stations over the USA.

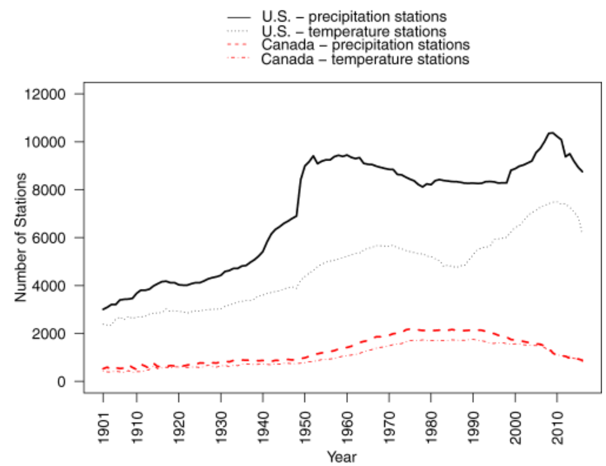


Figure 1. Number of Supporting Observing Stations by Year over Canada and USA (from MacDonald et al. (2020))

Figure 2. Location of precipitation stations used in North America ANUSPLIN datasets (from MacDonald *et al.*, 2020). Note: Mexican stations were not covered by the digital elevation model.

Methodology

Quality-controlled, but unadjusted, station data from the National Climate Data Archive (NCDA) of Environment and Climate Change Canada data (Hutchinson *et al*., 2009) were interpolated onto the high-resolution grid using the trivariate thin plate splines interpolation method. As mentioned above, station density varies over time with changes in station availability, peaking in the 1970s with a general decrease towards the present day (Hutchinson *et al*., 2009). Thus, the number of stations active across Canada between 1950 and 2011 ranged from 2000 to 3000 for precipitation and 1500 to 3000 for air temperature (Hopkinson *et al*., 2011).

Daily precipitation data were corrected when flags indicated trace values and accumulated values over multiple days. Trace values were corrected depending on precipitation type and accumulated values were disaggregated using nearby stations if they were not covering periods longer than 4 days and stations within a 100 km radius could be used. For details see Hutchinson *et al*. (2009).

Spatial models were then generated using the trivariate thin plate splines interpolation method as implemented in Australian National University Spline (ANUSPLIN; Hutchinson & Xu, 2013) for daily precipitation. For pentad, monthly and 30-year averages, the time average is first computed for each station and the result is next used with ANUSPLIN and the corresponding Digital Elevation Model.

The models were updated with improvements in the bias for the data from 1900-2015 (MacDonald *et al*., 2021)

Information about the technical and scientific quality

The data were quality controlled (see Hutchinson et al., 2009) and use up-to-date spatial modelling methods as detailed in MacDonald *et al*., 2020. The references provide several publications that detail the scientific quality of this data set.

The dataset is accompanied by several scientific papers.

Limitations and strengths for application in North Canada

Hutchinson *et al*., (2009) provides a comparative assessment of the precipitation spatial model quality over Canada.

References to documents describing the methodology or/and the dataset

Lawrence, K.M., M.F. Hutchinson, and D.W. McKenney, 2008: Multi-scale digital elevation models for Canada. Natural Resources Canada, Great Lakes Forestry Centre Frontline Tech. Note 109, 4 pp., https://d1ied5g1xfgpx8.cloudfront.net/pdfs/31499.pdf

Hopkinson, R.F., D.W. Mckenney, E.J. Milewska, M.F. Hutchinson, P. Papadopol, and L.A. Vincent, 2011: Impact of aligning climatological day on gridding daily maximum–minimum temperature and precipitation over Canada. *J. Appl. Meteor. Climatol.*, **50**, 1654–1665, https://doi.org/10.1175/2011JAMC2684.1.

Hutchinson, M.F., and T. Xu, 2013: ANUSPLIN version 4.4 user guide. Australian National University, Fenner School of Environment and Society Doc., 55 pp., https://fennerschool.anu.edu.au/files/anusplin44.pdf.

MacDonald, H., D. W. McKenney, P. Papadopol, K. Lawrence, J. Pedlar, and M.F. Hutchinson, 2020: North American historical monthly spatial climate dataset, 1901–2016. Scientific Data, 7(1), 411-411. https://doi.org/10.1038/s41597-020-00737-2

*__MacDonald__, H., D.W. McKenney, X.L. Wang, J. Pedlar, P. Papadopol, K. Lawrence, Y. Feng, and M.F. Hutchinson, 2021: Spatial models of adjusted precipitation for Canada at varying time scales. Journal of Applied Meteorology and Climatology, 60(3), 291 304. https://doi.org/10.1175/JAMC-D-20-0041.1

__McKenney__, D. W., and et al., 2011: Customized spatial climate models for North America. *Bull. Amer. Meteor. Soc.*, **92, 1611–1622, https://doi.org/10.1175/2011BAMS3132.1.

*Describes spatial models at the pentad time scale (adjusted precipitation only, ANUSPLIN-AdjPdly)

**Describes related spatial models available on an ongoing basis at different time scales

Link to download the data and format of data:

All data is available in **asci** format at Canadian Forest Service, NRCan (contact Dr. Dan McKenney, dan.mckenney@canada.ca if you are interested in the asci datasets)

Canada-wide daily dataset and North-America wide monthly dataset, both with 300 arc-second spatial resolution in **netCDF** format, are available at Canadian Center for Climate Services, ECCC (contact the Climate Services Support Desk, https://climate-change.canada.ca/support-desk/Inquiry , if you are interested in this netCDF subset of data)

Publications including dataset evaluation or comparison with other data in northern Canada

Hutchinson, M. F., D. W. McKenney, K. Lawrence, J. H. Pedlar, R. F. Hopkinson, E. Milewska, and P.Papadopol, 2009: Development and testing of Canada-wide interpolated spatial models of daily minimum–maximum temperature and precipitation for 1961–2003. *J. Appl. Meteor. Climatol.*, **48**, 725–741, https://doi.org/10.1175/2008JAMC1979.1

7.2.17 <u>Dataset</u>: WorldClim Version 2 - precipitation

Overview

WorldClim Version 2 is a dataset of spatially interpolated monthly climate data for global land areas at a very high spatial resolution (approximately 1 km^2). Precipitation data was aggregated across a target temporal range of 1970–2000. Weather station data was interpolated using thin-plate splines with covariates which include elevation (from SRTM), distance to the coast and three satellite-derived covariates: maximum and minimum land surface temperature and cloud cover, obtained from the MODIS satellite platform. Interpolation was done for 23 regions of varying size depending on station density. The dataset also includes monthly temperature (minimum, maximum and average), solar radiation, vapour pressure and wind speed.

Provider's contact information

This spatial dataset was developed by Stephen E. Fick and Robert J. Hijmans at the University of California.

Licensing

Freely available.

WorldClim by worldclim.org is licensed under a Creative Commons Attribution-NonCommercial-ShareAlike 4.0 International Licence.

Variable name and units:

Total precipitation (mm)

Spatial coverage and resolution:

The dataset is made available in four different resolutions: 30 arc seconds (~1 km^2), 2.5 arc minutes (~85km^2), 5 arc minutes (~170km^2)and 10 arc minutes (~340 km^2)

Temporal coverage and resolution:

Monthly values for the period 1970-2000.

Information about observations (number, homogeneity)

Data from between 9000 and 60 000 weather stations were collected from multiple sources at daily and monthly resolution and was interpolated using thin-plate splines with covariates, including elevation, distance to the coast. (No covariates from satellites were used for precipitation). The interpolation was done separately for 23 regions, selecting the best performing model for each region and variable. Observations station metadata were checked to match the stations' elevation with the elevation information used in the production.

Methodology

The dataset was generated using ANUSPLIN (Hutchinson & Xu, 2013) for monthly precipitation (and other variables). Daily values were aggregated to monthly values. Duplicates from the multiple sources of station data used were removed as much as possible, giving preference to the stations with the most stringent error-checking procedures. Surface fitting was done for stations with observations for at least 25 years. Stations with shorter periods of data availability were used if they were located at a minimum distance of 25 km (for precipitation) from all stations selected in the first pass. For precipitation 34 542 stations were used, with 13 763 meeting the 25 years of data availability between 1970 and 2000 criterion.

Data for Canada were produced over a relatively large region covering Canada and parts of the US.

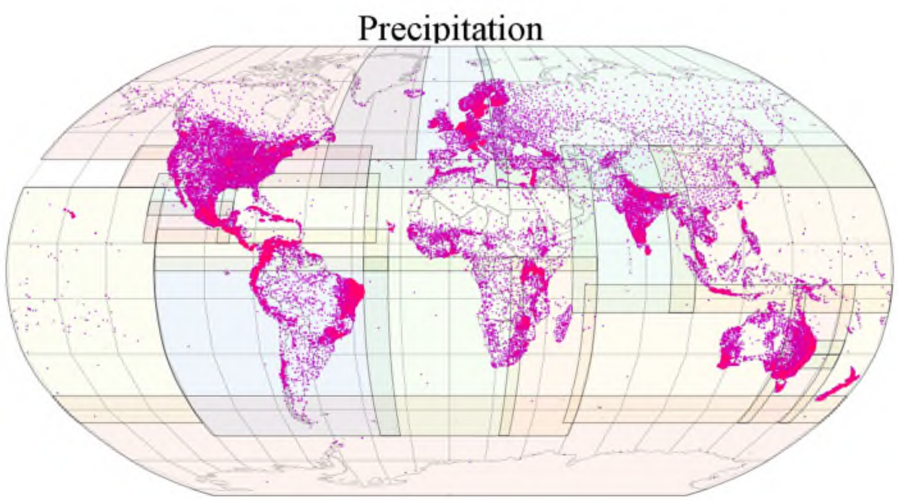


Figure 1: Precipitation stations and regions used for the interpolation of precipitation (from Fick and Hijmans, 2017)

Information about the technical and scientific quality

In the evaluation by Fick and Hijmans (2017), accuracy for precipitation (ρ=0.86) was the second lowest (after wind speed ρ=0.76). The authors state that relatively low performance for precipitation is similar to what was reported for previously published climate surfaces and relates to the fact that precipitation can be highly variable in time and space and some regions have abrupt changes (rain shadows). Such very strong gradients tend to come out too smooth in the climate surfaces.

Limitations and strengths for application in North Canada

Although a global dataset it can be considered interpolated for Canada since a separate region covering Canada was used for the production.

The dataset also contains 19 derived bioclimatic variables: annual mean temperature, mean diurnal range, isothermality, temperature seasonality, max. temperature of the warmest month, min. temperature of the coldest month, temperature annual range, mean temperature of the wettest quarter, mean temperature of the driest quarter, mean temperature of the warmest quarter, mean temperature of coldest quarter, annual precipitation, precipitation of the wettest month, precipitation of the driest month, precipitation seasonality (coefficient of variation), precipitation of wettest quarter, precipitation of driest quarter, precipitation of warmest quarter, precipitation of the coldest quarter.

References to documents describing the methodology or/and the dataset

Fick, S.E. and R.J. Hijmans, 2017: WorldClim 2: new 1 km spatial resolution climate surfaces for global land areas. Int. J. Climatol, 37, 4302-4315. https://doi.org/10.1002/joc.5086

Link to download the data and format of data:

Data is available as "zip" files containing 12 GeoTiff (.tif) files, one for each month of the year (January is 1; December is 12) at https://worldclim.org/data/worldclim21.html

Publications including dataset evaluation or comparison with other data in northern Canada

Noce, S., L. Caporaso, and M. Santini, 2020: A new global dataset of bioclimatic indicators. Sci Data 7, 398, https://doi.org/10.1038/s41597-020-00726-5

7.2.18 <u>Dataset</u>: PCIC meteorology for northwestern North America (PNWNAmet) - precipitation

Overview

The PNWNAmet dataset covers a domain of northwest North America (NWNA; 40°N to 72°N and -169°W to -101°W) at a spatial resolution of 1/16° (~6 km). PNWNAmet uses the trivariate thin plate spline interpolation method with the algorithm implemented by Nychka *et al*. (2017). Precipitation was interpolated using latitude, longitude and a 1971-2000 climatology from ClimateWNA (v5.10) as predictors.

ClimateWNA uses bilinear interpolation and an elevation adjustment to create a scale-free, smooth at the boundaries, mosaic of available climatologies.

Provider's contact information

This dataset was created circa 2014 by Werner *et al*. (2019) at the Pacific Climate Impacts Consortium (PCIC).

Licensing

Freely available for download at https://data.pacificclimate.org/portal/gridded_observations/map/

Variable name and units:

Total precipitation (mm)

Spatial coverage and resolution:

The dataset has a 1/16° (~6 km) spatial resolutions and covers the northwestern part of Canada and Alaska. The Eastern limit is slightly to the east of Saskatchewan and Yukon Territory.

NWNA: 40°N to 72°N and -169°W to -101°W

Temporal coverage and resolution:

Temporally consistent gridded daily meteorological data for northwest North America covering 1945 through 2012.

Information about observations (number, homogeneity)

The PNWNA Precipitation dataset over Canada is based on station records from the second generation of Environment and Climate Change Canada's (ECCC) Adjusted and Homogenized Canadian Climate Data (AHCCD). Corresponding daily data from the conterminous United States was from the United States Historical Climatology Network-Daily (USHCN-Daily). Daily data (not homogenized) for Alaska were from the Global Historical Climatology Network-Daily (GHCN-Daily). Selected stations had to have at least 40 years of complete record (<10% missing days within a year) over the 1945–2012 period. To supplement areas with sparse observations along the periphery of the domain, specifically around the western and northern coasts of Alaska, daily outputs from the 20th Century Reanalysis V2 (20CR2) were used as virtual stations. For precipitation, the median number of reporting stations was 442 (minimum of 262 and maximum of 476).

Methodology

The PNWNAmet dataset is based on daily precipitation (and other variables) of the homogeneized Canadian AHCCD station data and USHCN-Daily station data that is subject to a number of additional quality assurance checks. The interpolated grid was generated using the trivariate thin plate spline interpolation method, as implemented by Nychka *et al*. (2017) which is similar to the algorithm used for the ANUSPLIN dataset. However, PNWNAmet uses ClimateWNA v5.10 monthly climate normals rather than elevation as the third predictor variable, where 5 different climatologies were merged to a single spatially homogeneous, 1971–2000 monthly climatology (Werner *et al*. 2019).

Information about the technical and scientific quality

The PNWNAmet dataset was designed as a dataset well suited for driving hydrological models and training statistical downscaling schemes. It performs comparably well to two gridded meteorological datasets (NRCANmet = ANUSPLIN and PBCmet), for standardize performance measures against an independent climate network for climatology, extremes and variability. However, it potentially has a greater number of wet days than other gridded meteorological datasets, which may be due to its lower stations density. It performs better than other datasets in terms of resolving the timing of periods of increasing/decreasing precipitation and minimum temperature in the observed series than the NRCANmet and PBCmet datasets, while PBCmet performs slightly better for maximum temperature. Based on a comparison between PNWNAmet and NRCANmet climatologies, PNWNAmet likely better resolves spatial patterns of precipitation. (Werner *et al*., 2019).

Limitations and strengths for application in North Canada

The dataset was specifically designed for hydrological applications and statistical downscaling of climate simulation data. However it only covers the western part of Canada.

References to documents describing the methodology or/and the dataset

PCIC Website: https://www.pacificclimate.org/data/daily-gridded-meteorological-datasets

Werner, A.T., M. A. Schnorbus, R. R. Shrestha, A. J. Cannon, F. W. Zwiers, G. Dayon G., and F. Anslow, 2019: A long-term, temporally consistent, gridded daily meteorological dataset for northwestern North America, Scientific Data, 6, 180299, doi:10.1038/sdata.2018.299

Link to download the data and format of data:

Data citation:

Werner, A. T. et al. fig share https://doi.org/10.6084/m9.figshare.c.3965337 (2018).

The data can also be found at the Pacific Climate Impacts Consortium's public and persistent data portal at https://data.pacificclimate.org/portal/gridded_observations/map/

Publications including dataset evaluation or comparison with other data in northern Canada

Werner, A.T., M. A. Schnorbus, R. R. Shrestha, A. J. Cannon, F. W. Zwiers, G. Dayon G., and F. Anslow, 2019: A long-term, temporally consistent, gridded daily meteorological dataset for northwestern North America, Scientific Data, 6, 180299, doi:10.1038/sdata.2018.299.

Eum, H.-I. and A. Gupta, 2019: Hybrid climate datasets from a climate data evaluation system and their impacts on hydrologic simulations for the Athabasca River Basin in Canada, Hydrol. Earth Syst. Sci., 23, 5151–5173, https://doi.org/10.5194/hess-23-5151-2019.

7.2.19 <u>Dataset</u>: Met1km dataset - precipitation

Overview

The Met1km dataset at daily temporal resolution covers the time period from 1901 to 2100. The historical part described here spans 1901-2017. Met1km is generated based on four coarser gridded meteorological datasets for the historical period: CRU JRA, PNWNAmet, NRCANmet, and the Princeton dataset which were downscaled to 1 km resolution using the re-baselining method based on the WorldClim2 dataset as spatial templates. The dataset was specifically developed for modelling and mapping permafrost at high spatial resolutions in Canada.

Provider's contact information

This dataset was created by Natural Resources Canada and Agriculture and Agri-Food Canada Please contact the authors for data: yu.zhang@canada.ca

Licensing

Unknown.

Published by Yu Zhang, Canada Centre for Remote Sensing, Canada Centre for Mapping and Earth Observation, Natural Resources Canada, yu.zhang@canada.ca

Variable name and units:

Total precipitation (mm)

Spatial coverage and resolution:

Spatial coverage: The entire Canadian landmass.

Spatial resolution: 1 km

Temporal coverage and resolution:

The historical period covers 1901-2017. However the dataset expands until 2100 based on climate model projections.

Information about observations (number, homogeneity)

For the historical period Met1km was built from four datasets:

- CRU JRA for the period from 1901 to 1947 and the year 2017
- Princeton dataset for the period 1948 to 2016
- NRCANmet (=ANUSPLIN) for air temperature and precipitation from 1950 to 2013 (replacing the daily air temperature and precipitation from the Princeton dataset)
- PNWNAmet for air temperature, precipitation, and wind speed from 1945 to 2013 for western Canada

Methodology

Four observation datasets were downscaled to a resolution of 30 arc seconds latitude/longitude (about 1-km) based on the WorldClim2 dataset (Fick & Hijmans, 20217) using the re-baselining method proposed by Way and Bonnaventure (2015). The WorldClim2 dataset was selected since it has fine spatial resolution and includes the climate variables required for the objective of creating a dataset for permafrost studies (except downward longwave radiation). The re-baselining is a method to fill missing observations using gridded regional climate anomalies. The method is based on the commonly observed phenomenon that climate anomalies at the regional scale typically co-vary, whereas long-term averages at different sites can be different due to local topography and other site conditions. The method can easily integrate datasets of various spatial resolutions without affecting their temporal variations and trends. (Yang *et al*., 2020)

Information about the technical and scientific quality

According to the authors the accuracy of Met1km is similar to or better than the four coarser gridded datasets on which it is based. Errors in long-term averages and average seasonal patterns are reported to be small and occur mainly in day-to-day fluctuations. This error can be reduced significantly when averaging over 5 to 10 days.

Limitations and strengths for application in North Canada

The dataset was specifically developed for modelling and mapping permafrost and is available at a particularly high spatial resolution.

References to documents describing the methodology or/and the dataset

Zhang, Y., B. Qian, and G. Hong, 2020: A Long-Term, 1 km Resolution Daily Meteorological Dataset for Modeling and Mapping Permafrost in Canada. Atmosphere. 11(12),1363, https://doi.org/10.3390/atmos11121363

Link to download the data and format of data:

The data can be obtained from the authors.

Publications including dataset evaluation or comparison with other data in northern Canada

Zhang, Y., B. Qian, and G. Hong, 2020: A Long-Term, 1 km Resolution Daily Meteorological Dataset for Modeling and Mapping Permafrost in Canada. Atmosphere. 11(12),1363, https://doi.org/10.3390/atmos11121363

7.2.20 Dataset: Global Precipitation Climatology Centre (GPCC) Precipitation Data

Overview

GPCC products are gauge-based gridded precipitation data sets for the global land surface. They are available in spatial resolutions of 1.0° latitude by longitude. Depending on the product, finer spatial resolutions of 0.25°, 0.5° and 2.5° are available. The latest global precipitation climatology V.2020 is available in 2.5°, 1.0°, 0.5° and 0.25° resolution. It is based on data from ca. 84,800 stations and is used as background climatology for the other GPCC analyses. The database contains data from more than 123,000 different stations, being the largest precipitation database of the world.

Provider's contact information

The Global Precipitation Climatology Centre (GPCC) provides global precipitation analyses for monitoring and research of the earth's climate. The centre is a German contribution to the World Climate Research Program (WCRP) and the Global Climate Observing System (GCOS).

Licensing

Corresponding to international agreement, station data provided by Third Parties are protected in order to respect the copyright of the data providers. However, the gridded GPCC analysis products are freely available via Internet (http://gpcc.dwd.de)

Variable name and units:

Depending on product, total precipitation (mm) or anomaly (mm)

Spatial coverage and resolution:

Spatial coverage: Global.

Spatial resolution: 2.5°, 1.0°, 0.5° and 0.25° resolution (V.2020)

Temporal coverage and resolution:

Daily, monthly and climatologies, depending on product.

Information about observations (number, homogeneity)

GPCC's new global precipitation climatology V.2020 is based on data from ca. 84,800 stations and is used as background climatology for the other GPCC analyses. The database contains data from more than 123,000 different stations. The gridded gauge-analysis products provided by the GPCC are not bias corrected for systematic gauge measuring errors. However, the GPCC provides estimates for that error (climatological estimates up to Dec. 2006; since Jan. 2007 taking the weather conditions during the month into account) as well as the number of gauges used on the grid (accessible via the Visualizer). In addition to that, information about the proportion of the different precipitation phases (liquid, solid, mixed) is available since Jan. 2007

Methodology

All data reaching the GPCC are checked, processed, reformatted and integrated in a Relational Database Management System (RDBMS). Since 2009, all data being imported into the RDBMS are checked against background statistics enabling the GPCC to detect and correct data errors in this early stage. Within the data bank, the records from the different sources (SYNOP, CLIMAT, national data etc.) are stored in parallel (source specific slots) under addition of quality flags indicating the results of data processing. By this an intercomparison and crosscheck is possible, which is very helpful in the quality control (QC) and product generation process.

The data processing steps include QC and harmonization of the metadata (station identification), quality assessment of the precipitation data, selection and intercomparison of the data from the different sources for the particular products is described in Schneider *et al.* (2014), the interpolation of the station-related data to a regular mesh system, and calculation of the spatial means on the 2.5°, 1.0° and 0.5° latitude/longitude grid box area is described in Becker *et al*. (2013). GPCC uses the very robust empirical interpolation method SPHEREMAP. The method constitutes a spherical adaptation (Willmott *et al*., 1985) of Shepard's empirical (angular distance) weighting scheme (Shepard, 1968). The Full Data Monthly, as well as the Precipitation Climatology are available on a 0.25° resolution, too. For additional information, please consult GPCC's website (http://gpcc.dwd.de) (from Schneider *et al*., 2021)

Information about the technical and scientific quality

Summary overview of the datasets listed on http://gpcc.dwd.de :

First Guess Monthly of monthly precipitation anomalies based on SYNOP messages of approx. 7,000 stations arriving with DWD (Offenbach).

First Guess Daily analysis of global precipitation totals and anomalies based on SYNOP messages of meanwhile approx. 7,000 stations arriving with DWD (Offenbach). The data product becomes available 5 days after the observation month through the GPCC Download Gate.

Monitoring Product (Version 2020) for the period 1982 to present based on quality-controlled monthly data from 7,000-9,000 stations.

Full Data Monthly V.2020 for the period 1891 to 2019 based on quality-controlled data from all stations in GPCC's database available at the month of regard with a maximum number of more than 53,000 stations in 1986/1987. This product is optimized for best spatial coverage and use for water budget studies.

Full Data Daily V.2020 of daily global land-surface precipitation is based on data provided by national meteorological and hydrological services, global and regional data collections as well as WMO GTS-data. This product contains the daily totals on a regular grid with a spatial resolution of 1.0° x 1.0° latitude by longitude. The temporal coverage of the dataset ranges from January 1982 until December 2019. This GPCC product is recommended to be used when the daily precipitation information is of highest importance, e.g., for analyses of extreme events and related statistics at daily resolution and available as netCDF files through the GPCC Download Gate.

Gridded Precipitation Climatology (V.2020) based on monthly means focussing on the period 1951-2000 for approx. 85,000 stations. The gridded climatology fields (0.25°, 0.5°, 1.0° and 2.5°) form the background fields for the anomaly interpolation utilized on all DOI referenced GPCC products.

Further products for trend analysis and drought indices are also available.

Limitations and strengths for application in North Canada

The dataset is updated monthly and is available 5 days after the observation month. Only some products are available at a resolution of 0.5˚ or higher.

References to documents describing the methodology or/and the dataset

GPCC Home Page: http://gpcc.dwd.de

Schneider, U., P. Finger, E. Rustemeier, M. Ziese, A. Becker, 2021: Global Precipitation Analysis Products of the GPCC, Global Precipitation Climatology Centre (GPCC), Deutscher Wetterdienst, Offenbach a. M., Germany, https://opendata.dwd.de/climate_environment/GPCC/PDF/GPCC_intro_products_lastversion.pdf

Becker, A., P. Finger, A. Meyer-Christoffer, B. Rudolf, K. Schamm, U. Schneider, and M. Ziese, 2013: A description of the global land-surface precipitation data products of the Global Precipitation Climatology Centre with sample applications including centennial (trend) analysis from 1901–present, Earth Syst. Sci. Data, 5, 71–99, https://doi.org/10.5194/essd-5-71-2013

Schneider, U., A. Becker, P. Finger, A. Meyer-Christoffer, M. Ziese and B. Rudolf, 2014: GPCC's new land surface precipitation climatology based on quality-controlled in situ data and its role in quantifying the global water cycle. Theor. Appl. Climatology 115, 15-40, DOI:10.1007/s00704-013-0860-x.

Schneider, U., P. Finger, A. Meyer-Christoffer, E. Rustemeier, M. Ziese and A. Becker, 2017: Evaluating the hydrological cycle over land using the newly-corrected precipitation climatology from the Global Precipitation Climatology Centre (GPCC)", Atmosphere, 8 (3), 52, DOI: 10.3390/atmos8030052.

Link to download the data and format of data:

GPCC Home Page: http://gpcc.dwd.de

https://opendata.dwd.de/climate_environment/GPCC/html/download_gate.html

Publications including dataset evaluation or comparison with other data in northern Canada

Rapaić, M., R. Brown, M. Markovic, and D. Chaumont, 2015: An Evaluation of Temperature and Precipitation Surface-Based and Reanalysis Datasets for the Canadian Arctic, 1950–2010, Atmosphere-Ocean, 53:3, 283-303, https://doi.org/10.1080/07055900.2015.1045825

Lindsay, R., M. Wensnahan, A. Schweiger, and J. Zhang, 2014: Evaluation of Seven Different Atmospheric Reanalysis Products in the Arctic, *Journal of Climate*, *27*(7), 2588-2606. Retrieved Nov 1, 2021, from https://journals.ametsoc.org/view/journals/clim/27/7/jcli-d-13-00014.1.xml

7.2.21 *__Dataset__: **CRU TS (Climatic Research Unit gridded Time Series) - precipitation***

Overview

The gridded Climatic Research Unit (CRU) Time-series (TS) data version 4.05 data are month-by-month variations in climate over the period 1901-2020, provided on high-resolution (0.5 x 0.5 degrees) grids, produced by CRU at the University of East Anglia and funded by the UK National Centre for Atmospheric Science (NCAS), a NERC collaborative centre.

Provider's contact information

University of East Anglia Climatic Research Unit (CRU)

Licensing

Access to these data is available to any registered CEDA user. Users need to register and login for an account to gain access.

Use of these data is covered by the following licence: http://www.nationalarchives.gov.uk/doc/open-government-licence/version/3/. When using these data, you must cite them correctly using the citation given on the CEDA Data Catalogue record.

Variable name and units:

Monthly precipitation in mm/month, % for anomalies.

Spatial coverage and resolution:

Spatial coverage: Global.

Spatial resolution: 0.5° x 0.5˚

Temporal coverage and resolution:

Monthly.

Information about observations (number, homogeneity)

Monthly land station observations for precipitation (and six other variables: Mean, Minimum and Maximum Temperatures, Vapour Pressure, Wet Days and Cloud Cover) are updated regularly from several principal monthly sources: CLIMAT messages, exchanged internationally between WMO (World Meteorological Organisation) countries, obtained as quality-controlled files via the UK Met Office; MCDW (Monthly Climatic Data for the World) summaries, obtained from the US National Oceanographic and Atmospheric Administration (NOAA) via its National Climate Data Centre (NCDC); and updates of minimum and maximum temperatures for Australia, obtained from the Bureau of Meteorology (BoM). In addition, ad hoc collections of stations are incorporated (after quality control checks including location, correspondence to existing holdings, and outlier checking) (see Harris *et al*., 2020)

Methodology

For version 4 of the CRU TS dataset the interpolation process has been changed to use angular-distance weighting (ADW), which delivers full traceability back to station measurements. The ADW method was adopted from New *et al*. (2000). The station measurements of precipitation are provided as well as the gridded dataset and national averages for each country. Cross-validation was performed at a station level, and the results can be examined in the paper by Harris *et al*. (2020) as a guide to the accuracy of the interpolation.

The overall process is always being refined and improved, an approach made possible by NCAS funding as part of the NCAS Long-Term Global Change theme.

Information about the technical and scientific quality

CRU TS shows a broad range of outcomes but is dominated by positive cross-validation correlations (95% are >=0.38). Larger errors are found in dry regions with Canada being positively validated. Differences in precipitation when compared to the GPCC dataset are small for the northern Hemisphere (Harris *et al*., 2020)

Limitations and strengths for application in North Canada

CRU TS compiles station data of multiple variables from numerous data sources into a consistent format. The station data are also used to compute secondary variables such as potential evapotranspiration, diurnal temperature range, and number of frost and rain days. Although many of the input data were homogenized, the data set is not strictly homogenous. Derived trends should be used with caution.

References to documents describing the methodology or/and the dataset

Harris, I., T.J. Osborn, P. Jones, and D. Lister, 2020: Version 4 of the CRU TS monthly high-resolution gridded multivariate climate dataset. Scientific data, 7(1), 1-18 , https://doi.org/10.1038/s41597-020-0453-3

Link to download the data and format of data:

The data are available in two formats: NetCDF, and space-separated ASCII text.

Data can be accessed via the CEDA Archive: https://archive.ceda.ac.uk/

Version 4.05. is available at: https://catalogue.ceda.ac.uk/uuid/c26a65020a5e4b80b20018f148556681

Publications including dataset evaluation or comparison with other data in northern Canada

Rapaić, M., R. Brown, M. Markovic, and D. Chaumont, 2015: An Evaluation of Temperature and Precipitation Surface-Based and Reanalysis Datasets for the Canadian Arctic, 1950–2010, Atmosphere-Ocean, 53:3, 283-303, https://doi.org/10.1080/07055900.2015.1045825

Lindsay, R., M. Wensnahan, A. Schweiger, and J. Zhang, 2014: Evaluation of Seven Different Atmospheric Reanalysis Products in the Arctic, Journal of Climate, 27(7), 2588-2606. Retrieved Nov 1, 2021, from https://journals.ametsoc.org/view/journals/clim/27/7/jcli-d-13-00014.1.xml (Previous version of CRU)

7.2.22 <u>Dataset:</u> Climate Prediction Center (CPC) Merged Analysis of Precipitation (CMAP)

Overview

This document provides an overview of the precipitation products available from the CloudSat 94 GHz nadir-looking cloud profiling radar (CPR). This precipitation dataset is particularly valuable for high-latitude and cold-region observations of precipitation, which have previously been limited by infrequent sampling and sparse observational networks. Rain data is not available over land (snowfall is), but precipitation occurrence data is available everywhere.

Provider's contact information

The CloudSat CPR was developed jointly by NASA/JPL and the Canadian Space Agency (CSA). The Standard Data Products are distributed by the CloudSat Data Processing Center, located at the Cooperative Institute for Research in the Atmosphere at Colorado State University in Fort Collins.

Dataset Point of Contact:

NOAA CDR Program
DOC/NOAA/NESDIS/NCEI > National Centers for Environmental Information, NESDIS, NOAA, U.S. Department of Commerce
+1 (828) 271-4800
gpcp_contacts@noaa.gov

Licensing and citation

Cite as:

Haynes, J. M.,T. S. L'Ecuyer, G. L . Stephens, S. D. Miller, C. Mitrescu, N. B. Wood, and S. Tanelli, 2009: Rainfall retrieval over the ocean with spaceborne W-band radar. J. Geophys. Res., 114, D00A22, https://doi.org/10.1029/2008JD009973.

Variable name and units

Name	Description	Units	Frequency	Collection of data
2C-PRECIP-COLUMN, precip_flag	Precipitation occurrence	Flag for phase (rain, snow, mixed) and likelihood of		Available everywhere

		precipitation (certain, probable possible)		
2C-RAIN-PROFILE, rain_rate	Rain rate for "certain" rain or mixed phase precipitation	mm/hr		Only values available are over ocean
2C-SNOW-PROFILE, snowfall_rate_sfc	Surface snowfall rate for mixed (melted fraction < 0.1) or snowy phase.	mm (liquid water)/hr		Available everywhere.

Spatial coverage and resolution

Satellite observations lie between 82°N-S. The satellite has a 1.7 km × 1.3 km footprint. Global coverage is achieved in 16 days for cells of 100 km side.

Temporal coverage and resolution

Local overpass times are nominally at 1:31 A.M. and 1:31 P.M. This may have changed in recent years as the satellite orbit changed in 2018, when CloudSat exited the A-train.

Information about observations (number, homogeneity)

More observations available at higher latitudes. For example, see figure 1(a) in Palerme *et al.* (2014). Monthly mean data are created only based on a limited number of samples since the ground track repeats every 16 days.

Methodology

The Cloud Profiling Radar (CPR) is a 94 GHz nadir-looking radar which measures the backscatter from clouds and hydrometeors as a function of distance from the radar. The main objective of this instrument is to provide vertical cross sections of non-precipitating cloud liquid and ice water content and particle size, but it also resolves precipitation systems. This relatively low frequency radar achieves excellent cloud detection sensitivity.

The algorithm determines the presence of surface precipitation, and quantifies the intensity, based on the CPR observations. The algorithm makes use of the radar reflectivity near the surface of the earth and an estimate of path integrated attenuation (PIA) determined from the surface reflection characteristics to determine precipitation occurrence (over all surface types) and intensity (over water surfaces).

Auxiliary data: The current state of the atmosphere, including the atmospheric temperature, pressure, specific humidity, surface wind speed, and sea surface temperature are assessed from the ECMWF forecast model matched to the CPR track. The presence of sea ice (and inland lake ice) is determined from the daily sea-ice product from SSM/I (Special Sensor Microwave Imager/Sounder) produced by the National Snow and Ice Data Center.

Information about the technical and scientific quality

Note that the radar signal used in the CloudSat algorithm can be saturated in intense rain, so a tendency to underestimate precipitation has been noted by users of the product. It is the most sensitive sensor to low intensity rain and snow events.

Normal satellite performance only between 2006-2011, after which a malfunction has caused offline periods and reduced observations. It should be noted that daytime only refers to times when the satellite has line-of-sight to the sun, so surface nighttime measurements may still be available.

Limitations and strengths for application in North Canada

Good sampling over the high latitudes, unlike many other sensors. This makes it suited to North Canada applications.

Only describes precipitation occurrence over land.

References to documents describing the methodology and/or the dataset

Haynes, J. M.,T. S. L'Ecuyer, G. L . Stephens, S. D. Miller, C. Mitrescu, N. B. Wood, and S. Tanelli, 2009: Rainfall retrieval over the ocean with spaceborne W-band radar. J. Geophys. Res., 114, D00A22, https://doi.org/10.1029/2008JD009973.

Overview of the 2C-PRECIP-COLUMN precipitation algorithms for CloudSat (https://www.cloudsat.cira.colostate.edu/cloudsat-static/info/dl/2c-precip-column/2C-PRECIP-COLUMN_PDICD.P1_R05.rev1_.pdf)

Overview of the 2C-RAIN-PROFILE algorithms for CloudSat (https://www.cloudsat.cira.colostate.edu/cloudsat-static/info/dl/2c-rain-profile/2C-RAIN-PROFILE_PDICD.P1_R05.rev0_.pdf)

Overview of the 2C-SNOW-PROFILE algorithms for CloudSat (https://www.cloudsat.cira.colostate.edu/cloudsat-static/info/dl/2c-snow-profile/2C-SNOW-PROFILE_PDICD.P1_R05.rev0_.pdf)

Link to download the data and format of data

Download here after logging in (http://www.cloudsat.cira.colostate.edu/data-products/level-2c)

File naming conventions (http://www.cloudsat.cira.colostate.edu/data-products)

Basics on granules, etc. (https://ccplot.org/pub/resources/CloudSat/CloudSat%20Data%20Users%20Handbook.pdf)

Examples of reading HDF4 file with Python:

- https://moonbooks.org/Articles/How-to-read-CloudSat-2B-GEOPROF-GRANULE-HDF4-file-using-python-and-pyhdf-/
- https://hdfeos.org/zoo/index_openCDPC_Examples.php

Publications including dataset evaluation or comparison with other data in Canada

Behrangi, A., Y. Tian, B. H. Lambrigtsen, and G. L. Stephens, 2014: What does CloudSat reveal about global land precipitation detection by other spaceborne sensors? Water Resources Research, 50(6), 4893–4905. https://doi.org/10.1002/2013wr014566.

Kay, J. E., C. Genthon, T. L'Ecuyer, N. B. Wood, and C. Claud, 2014: How much snow falls on the Antarctic ice sheet? The Cryosphere, 8(4), 1577–1587, https://doi.org/10.5194/tc-8-1577-2014.

Kodamana, R., and C. G. Fletcher, 2021: Validation of CloudSat-CPR Derived Precipitation Occurrence and Phase Estimates across Canada. Atmosphere, 12(3), 295. https://doi.org/10.3390/atmos1203.

L'Ecuyer, T. S., and G. L. Stephens, 2002: An estimation-based precipitation retrieval algorithm for attenuating radars., J. Appl. Meteor., 41, 272-285. https://doi.org/10.1175/1520-0450(2002)041<0272:AEBPRA>2.0.CO;2.

Wood, N. B., T. S. L'Ecuyer, F. L. Bliven, and G. L. Stephens, 2013: Characterization of video disdrometer uncertainties and impacts on estimates of snowfall rate and radar reflectivity, Atmos. Meas. Tech., 6, 3635-3648, doi:10.5194/amt-6-3635-2013.

Wood, N. B., T. S. L'Ecuyer, A. J. Heymsfield, G. L. Stephens, D. R. Hudak, and P. Rodrigues, 2014: Estimating snow microphysical properties using collocated multisensor observations. J. Geophys. Res. Atmos., 119, 8941-8961, doi:10.1002/2013JD021303.

7.2.23 <u>Dataset:</u> Global Precipitation Climatology Project, Monthly (GPCP V2.3 and V3.1)

Overview

This document mainly provides an overview of the precipitation data from the Global Precipitation Climatology Project, version 2.3 (GPCP V2.3). The data provided is of monthly frequency and is considered a Climate Data Record. Monthly mean data comes with uncertainty estimates. The data are archived at the NOAA National Centers for Environmental Information (NCEI). The dataset is part of the Global Energy and Water Cycle Exchanges (GEWEX) effort under the World Climate Research Program (WCRP). A 1 Degree Daily (1DD) precipitation estimate from GPCP also exists.

With the recent release of version 3.1 (GPCP V3.1), some information is found in this document about it. Information about the new version was released (as of March 10, 2021) and can be found in the Algorithm Theoretical Basis Document. GPCP V3.1 products are at monthly resolution with daily and 3-hourly products to come next.

Provider's contact information

GPCP is produced through a joint effort between the University of Maryland and NASA.

Dataset Point of Contact:

NOAA CDR Program
DOC/NOAA/NESDIS/NCEI > National Centers for Environmental Information, NESDIS, NOAA, U.S. Department of Commerce
+1 (828) 271-4800
gpcp_contacts@noaa.gov

Additional information is available from U of Maryland at http://eagle1.umd.edu/GPCP_ICDR/.

Licensing and citation

For V2.3, cite as:

Adler, R.F., M.R.P. Sapiano, G.J. Huffman, J.-J. Wang, G. Gu, D. Bolvin, L. Chiu, U. Schneider, A. Becker, E. Nelkin, P. Xie, R. Ferraro, and D.-B. Shin, 2018: The Global Precipitation Climatology Project (GPCP) Monthly Analysis (New Version 2.3) and a Review of 2017 Global Precipitation. Atmosphere, 9, 138. https://doi.org/10.3390/atmos9040138

Variable name and units (for V2.3)

Name	Description	Units	Frequency	Collection of data
Rainfall	Grid-cell value of total rainfall for the month	mm/day	Monthly	

Spatial coverage and resolution

This dataset combines observations and satellite precipitation data into a 2.5°x2.5° global grid.

Monthly precipitation from GPCP V3.1 will be at 0.5°x0.5° spatial resolution.

Temporal coverage and resolution

Monthly precipitation values are provided through from 1979/01 through present, with recent months considered 'interim'.

For V3.1, the monthly precipitation record will begin from January 1983.

Information about observations (number, homogeneity)

Satellite data over the land and ocean are combined with gauge analysis over land. Passive Microwave estimates are based on Special Sensor Microwave Imager/Special Sensor Microwave Imager Sounder (SSMI/SSMIS) data. Infrared precipitation estimates are included using Geostationary Operational Environmental Satellite (GOES) data and Polar-orbiting Operational Environmental Satellite (POES) data, as well as other low earth orbit data and in situ observations.

Primary sensors include:

- RSS SSMI T_b CDR from 1996-2008
- RSS SSMIS T_b CDR from 2009-present
- GPCP Monthly Analysis V2.3 from 1996-present
- TOVS precipitation from 1996-2002
- AIRS V6 precipitation from 2003-present (replaces TOVS)
- IR 3 hourly files, T_b from CPC from 1996-present

See Climate Algorithm Theoretical Basis Document for GPCP Monthly Analysis for sensor data timeline and details.

Methodology

The GPCP monthly precipitation dataset combines observations and satellite precipitation to populate a 2.5°x2.5° global grid. Gauge data comes from the Global Precipitation Climatology Center (GPCC) of the Deutscher Wetterdienst (DWD). Precipitation estimates come from polar-orbit passive microwave satellites (SSMI, SSMIS), polar orbit IR sounders (TOVS, AIRS), and geostationary infrared satellites (GOES, MeteoSat, GMS, MTSat).

Note a major update in V3.1: there is input from the Tropical Combined Climatology (TCC) and the Merged CloudSat, Tropical Rainfall Measuring Mission (TRMM), and Global Precipitation Climatology (GPM) Climatology (MCTG). The MCTG climatology is applied as a ratio to adjust the mid- and high-latitude precipitation values, which may improve the representation of precipitation in the Canadian North. Poleward of 65 N, the precipitation climatology is only based on CloudSat (it does not have a signal saturation issue).

Specific to higher latitudes (V2.3): Note that the polar orbit of the Special Sensor Microwave/Imager (SSM/I) and Special Sensor Microwave Imager/Sounder SSMIS give nominal coverage between 85° N-S but limitations in retrieval techniques prevent useful precipitation estimates over cold land (scattering), land (emission), or sea ice (both scattering and emission). From 70°N to North Pole, TOVS data are adjusted to the bias of the available monthly rain gauge data. From 60°-70°, there is a smooth transition with increased weighting of TOVS data relative to SSM/I with increasing latitude except where SSM/I observations are missing.

Information about the technical and scientific quality

While GPCP V2.3 has been used for global applications, it is somewhat limited in skill at high latitudes due to poor retrieval performance over icy or snowy surfaces, limited station measurements, or gaps requiring interpolation. Previous studies have used CloudSat climatology to adjust GPCP V2.3 values before performing analysis. For this reason, it may be preferable to use GPCP V3.1 when it becomes available, though it is not considered a Climate Data Record, so may have inhomogeneity (specifically in the TOVS/AIRS record)

Limitations and strengths for application in North Canada

V2.3 is not leveraging satellites and datasets which improve sampling over North Canada.

Different satellites are used at different latitudes, leading to spatial heterogeneity.

References to documents describing the methodology and/or the dataset

Adler, R.F., G.J. Huffman, A. Chang, R. Ferraro, P. Xie, J. Janowiak, B. Rudolf, U. Schneider, S. Curtis, D. Bolvin, A. Gruber, J. Susskind, and P. Arkin, 2003: The Version 2 Global Precipitation Climatology Project (GPCP) Monthly Precipitation Analysis (1979-Present). J. Hydrometeor., 4, 1147-1167.

Climate Algorithm Theoretical Basis Document for GPCP Monthly Analysis V2.3 (https://www.ncei.noaa.gov/data/global-precipitation-climatology-project-gpcp-monthly/doc/CDPR-ATBD-0848%20Rev%201%20Precipitation%20-%20GPCP%20Monthly%20C-ATBD%20(01B-34)%20(DSR-1083).pdf)

Climate Algorithm Theoretical Basis Document for GPCP Monthly Analysis V3.1 (https://docserver.gesdisc.eosdis.nasa.gov/public/project/MEaSUREs/GPCP/GPCP_ATBD_V3.1.pdf)

Source code is available for reference to maintain the transparency of the algorithm and processes. Found here (https://www1.ncdc.noaa.gov/pub/data/sds/cdr/CDRs/Precipitation_GPCP-Monthly/SourceCode_01B-34.tar.gz)

Link to download the data and format of data

NCEI Direct Download of Monthly V2.3 Data (https://www.ncei.noaa.gov/data/global-precipitation-climatology-project-gpcp-monthly/)

Download Monthly V3.1 data from the NASA GESDISC DATA ARCHIVE (https://measures.gesdisc.eosdis.nasa.gov/data/GPCP/GPCPMON.3.1/)

Data are in netCDF-4 file format.

Publications including dataset evaluation or comparison with other data in Canada

Hegyi, B. M., and Y. Deng, 2011: A dynamical fingerprint of tropical Pacific sea surface temperatures on the decadal-scale variability of cool-season Arctic precipitation. Journal of Geophysical Research, 116(D20). https://doi.org/10.1029/2011jd016001

Kusunoki, S., R. Mizuta, and M. Hosaka, 2015: Future changes in precipitation intensity over the Arctic projected by a global atmospheric model with a 60-km grid size. Polar Science, 9(3), 277–292. https://doi.org/10.1016/j.polar.2015.08.001

Song, Y., A. Behrangi, and E. Blanchard-Wrigglesworth, 2020: Assessment of satellite and reanalysis cold season snowfall estimates over Arctic sea ice. Geophysical Research Letters, 47, e2020GL088970. https://doi-org.myaccess.library.utoronto.ca/10.1029/2020GL088970.

7.2.24 *Dataset:* *Global Precipitation Climatology Project, Daily (GPCP V1.3)*

Overview

This document mainly provides an overview of the precipitation data from the Global Precipitation Climatology Project 1 Degree Daily Analysis, version 1.3 (GPCP1DD V1.3). It is a Climate Data Record. The data provided is of daily frequency and is a companion to the monthly analysis for users requiring higher temporal and spatial resolutions.

Provider's contact information

GPCP is produced through a joint effort between the University of Maryland and NASA.

Dataset Point of Contact:

NOAA CDR Program
DOC/NOAA/NESDIS/NCEI > National Centers for Environmental Information, NESDIS, NOAA, U.S. Department of Commerce
+1 (828) 271-4800
gpcp_contacts@noaa.gov

Additional information is available from U of Maryland at http://eagle1.umd.edu/GPCP_ICDR/.

Licensing and citation

For V1.3, acknowledge as:

The Precipitation – GPCP Daily CDR used in this study was acquired from the NOAA National Centers for Environmental Information (NCEI; formerly NCDC) (https://www.ncei.noaa.gov). This CDR was developed by Robert Adler, Jian-Jian Wang, Mathew Sapiano of the University of Maryland College Park.

Cite data as:

Adler, R., J.-J. Wang, M. Sapiano, G. Huffman, D. Bolvin, E. Nelkin, and NOAA CDR Program (2017). Global Precipitation Climatology Project (GPCP) Daily Analysis (Version 1.3) [Indicate subset used.]. NOAA National Centers for Environmental Information. doi:10.7289/V5RX998Z [access date]

Variable name and units (for V2.3)

Name	Description	Units	Frequency	Collection of data
Rainfall	Grid-cell value of total rainfall for day	mm/day	Daily	

Spatial coverage and resolution

This dataset combines observations and satellite precipitation data into a 1°x1° global grid.

Temporal coverage and resolution

Monthly precipitation values are provided through from 1996/10 through present.

Information about observations (number, homogeneity)

Satellite data over the land and ocean are combined with gauge analysis over land. Passive Microwave estimates are based on Special Sensor Microwave Imager/Special Sensor Microwave Imager Sounder (SSMI/SSMIS) data. Infrared precipitation estimates are included using Geostationary Operational Environmental Satellite (GOES) data and Polar-orbiting Operational Environmental Satellite (POES) data, as well as other low earth orbit data and in situ observations.

Daily analysis primary sensors include:

- RSS SSMI T_b CDR from 1996-2008
- RSS SSMIS T_b CDR from 2009-present
- TOVS precipitation from 1996-2002
- AIRS V6 precipitation from 2003-present (replaces TOVS)
- IR 3 hourly files, T_b from CPC from 1996-present
- GPCP Monthly Analysis V2.3 from 1996-present

See Climate Algorithm Theoretical Basis Document for GPCP Daily Analysis for sensor data timeline and details.

Methodology

The GPCP monthly precipitation dataset combines observations and satellite precipitation to populate a 1°x1° global grid. Gauge data comes from the Global Precipitation Climatology Center (GPCC) of the Deutscher Wetterdienst (DWD). Precipitation estimates come from polar-orbit passive microwave satellites (SSMI, SSMIS), polar orbit IR sounders (TOVS, AIRS), and geostationary infrared satellites (GOES, MeteoSat, GMS, MTSat).

Information about the technical and scientific quality

Limitations and strengths for application in North Canada

V2.3 is not leveraging satellites and datasets which improve sampling over North Canada.

Different satellites are used at different latitudes, leading to spatial heterogeneity.

References to documents describing the methodology and/or the dataset

Huffman, G. J., R. F. Adler, M. M. Morrissey, D. T. Bolvin, S. Curtis, R. Joyce, B. McGavock, and J. Susskind, 2001: Global Precipitation at One-Degree Daily Resolution from Multisatellite Observations. Journal of Hydrometeorology 2, 1, 36-50, https://doi.org/10.1175/1525-7541(2001)002<0036:GPAODD>2.0.CO;2

Climate Algorithm Theoretical Basis Document for GPCP Daily Analysis V1.3 (https://www.ncei.noaa.gov/data/global-precipitation-climatology-project-gpcp-daily/doc/CDRP-ATBD-0913%20Rev%200%20Precipitation%20-%20GPCP%20Daily%20C-ATBD%20(01B-35)%20(DSR-1159).pdf)

Source code is available for reference to maintain the transparency of the algorithm and processes. Found here: (https://www1.ncdc.noaa.gov/pub/data/sds/cdr/CDRs/Precipitation_GPCP-Monthly/SourceCode_01B-34.tar.gz)

Link to download the data and format of data

NCEI Direct Download of Daily V1.3 Data (https://www.ncei.noaa.gov/data/global-precipitation-climatology-project-gpcp-daily/access/)

Data are in netCDF-4 file format.

Publications including dataset evaluation or comparison with other data in Canada

Hegyi, B. M., and Y. Deng, 2011: A dynamical fingerprint of tropical Pacific sea surface temperatures on the decadal-scale variability of cool-season Arctic precipitation. Journal of Geophysical Research, 116(D20). https://doi.org/10.1029/2011jd016001

Kusunoki, S., R. Mizuta, and M. Hosaka, 2015: Future changes in precipitation intensity over the Arctic projected by a global atmospheric model with a 60-km grid size. Polar Science, 9(3), 277–292. https://doi.org/10.1016/j.polar.2015.08.001

Song, Y., A. Behrangi, and E. Blanchard-Wrigglesworth, 2020: Assessment of satellite and reanalysis cold season snowfall estimates over Arctic sea ice. Geophysical Research Letters, 47, e2020GL088970. https://doi-org.myaccess.library.utoronto.ca/10.1029/2020GL088970.

7.2.25 *<u>Dataset:</u> Climate Prediction Center (CPC) Merged Analysis of Precipitation (CMAP)*

Overview

This document provides an overview of the precipitation data Climate Prediction Center (CPC) Merged Analysis of Precipitation (CMAP). There are monthly and pentad global (nearly spatially complete) gridded precipitation rate values derived from five types of satellite estimates.

Provider's contact information

The datase is produced the NOAA Climate Prediction Center

Dataset Point of Contact:

Physical Sciences Laboratory: Data Management
NOAA/ESRL/PSL
325 Broadway
Boulder, CO 80305-3328
psl.data@noaa.gov

Licensing and citation

Cite as:

Xie, P., and P.A. Arkin, 1997: Global precipitation: A 17-year monthly analysis based on gauge observations, satellite estimates, and numerical model outputs. Bull. Amer. Meteor. Soc., 78, 2539 - 2558.

Variable name and units

Name	Description	Units	Frequency
Rainfall	Grid-cell value of monthly average rainfall or pentad average rainfall	mm/day	Monthly or pentad

Spatial coverage and resolution

This dataset combines observations and satellite precipitation data into a 2.5°x2.5° global grid.

Temporal coverage and resolution

The monthly dataset covers the period 1979/01-present. The pentad dataset covers 1979/01 to 2016/12/27.

Information about observations (number, homogeneity)

Coverage by satellites degrades at higher latitudes. May have some inhomogeneity due to using different sensors over different parts of the record.

Methodology

CMAP record is assembled by maximum-likelihood method which determines weighting coefficients to the input data:

- IR-based GPI
- OLR-based OPI
- MSU-based Spencer data set
- SSM/I-scattering-based NOAA/NESDIS dataset
- SSM/I-emission-based Chang data set

Next, variational blending method combines this remote sensed hybrid product with the gauge-based analyses to improve the bias.

More detail, from NOAA source (https://www.cpc.ncep.noaa.gov/products/global_precip/html/wpage.cmap.html):

First, the random error is reduced by linearly combining the satellite estimates using the maximum likelihood method, in which case the linear combination coefficients are inversely proportional to the square of the local random error of the individual data sources. Over global land areas the random error is defined for each time period and grid location by comparing the data source with the rain gauge analysis over the surrounding area. Over oceans, the random error is defined by comparing the data sources with the rain gauge observations over the Pacific atolls.

Information about the technical and scientific quality

CMAP has been shown to represent a suppressed annual cycle amplitude and low precipitation over land compared to other products.

Limitations and strengths for application in North Canada

Quality of the analysis is highly dependent on the amount and type of input data, improving where there are high gauge densities. There is no inclusion of AIRS/TOVS or CloudSat satellite observations (increase high latitude observations) nor is there adjustment for undercatch in gauge measurements.

Generally, greater uncertainty with increasing latitude; poorest quality in polar regions.

While CMAP (like GPCP) are valuable because of their long record, it is likely that more recently developed datasets are more accurate for the common periods of record, due to greater uniformity of input data sources and more advanced satellite-derived products.

References to documents describing the methodology and/or the dataset

Xie, P., Arkin P.A., Janowiak J.E. (2007) CMAP: The CPC Merged Analysis of Precipitation. In: Levizzani V., Bauer P., Turk F.J. (eds) Measuring Precipitation From Space. Advances In Global Change Research, vol 28. Springer, Dordrecht. https://doi.org/10.1007/978-1-4020-5835-6_25

Xie, P., and P. A. Arkin, 1997: Global Precipitation: A 17-Year Monthly Analysis Based on Gauge Observations, Satellite Estimates, and Numerical Model Outputs. Bulletin of the American Meteorological Society, 78(11), 2539–2558. https://doi.org/10.1175/1520-0477(1997)078<2539:gpayma>2.0.co;2

Yin, X. G., A. Gruber, and P. Arkin, 2004: Comparison of the GPCP and CMAP merged gauge-satellite monthly precipitation products for the period 1979–2001. Journal of Hydrometeorology, 5(6), 1207– 1222.

Link to download the data and format of data

Link to download available here: https://psl.noaa.gov/data/gridded/data.cmap.html

Data are in netCDF-4 file format.

Publications including dataset evaluation or comparison with other data in Canada

Anderson, B. T., N. Feldl, and B. R. Lintner, 2018: Emergent Behavior of Arctic Precipitation in Response to Enhanced Arctic Warming. Journal of Geophysical Research: Atmospheres, 123(5), 2704–2717. https://doi.org/10.1002/2017jd026799

Behrangi, A., et al. (2016), Status of high-latitude precipitation estimates from observations and reanalyses, J. Geophys. Res. Atmos., 121, 4468– 4486, doi:10.1002/2015JD024546.

7.2.26 ***Dataset:*** *Climate Prediction Center (CPC) Merged Analysis of Precipitation Enhanced (CMAP/A)*

Overview

This document provides an overview of the precipitation data Climate Prediction Center (CPC) Merged Analysis of Precipitation Enhanced Version (CMAP/A). There are monthly and pentad global (nearly spatially complete) gridded precipitation rate values derived from five types of satellite estimates and gauge measurements, as well as additional filling of missing data using the NCEP reanalysis.

Provider's contact information

The dataset is produced the NOAA Climate Prediction Center

Dataset Point of Contact:

Physical Sciences Laboratory: Data Management
NOAA/ESRL/PSL
325 Broadway
Boulder, CO 80305-3328
psl.data@noaa.gov

Licensing and citation

Cite as:

Xie, P., and P.A. Arkin, 1997: Global precipitation: A 17-year monthly analysis based on gauge observations, satellite estimates, and numerical model outputs. Bull. Amer. Meteor. Soc., 78, 2539 - 2558.

Variable name and units

Name	Description	Units	Frequency
Rainfall	Grid-cell value of monthly average rainfall or pentad average rainfall	mm/day	Monthly or pentad

Spatial coverage and resolution

This dataset combines observations, satellite precipitation, and reanalysis precipitation data into a 2.5°x2.5° global grid.

Temporal coverage and resolution

The monthly dataset covers the period 1979/01-present. The pentad dataset covers 1979/01 to 2016/12/27.

Poor coverage at high latitudes, so uses reanalysis precipitation to fill the gaps.

Methodology

CMAP/A (enhanced) record is assembled by maximum-likelihood method which determines weighting coefficients to the input data:

- IR-based GPI
- OLR-based OPI
- MSU-based Spencer data set
- SSM/I-scattering-based NOAA/NESDIS dataset
- SSM/I-emission-based Chang data set

Next, variational blending method combines this remote sensed hybrid product with the gauge-based analyses to improve the bias.

Finally, missing and existing data are adjusted with a weighted contribution from the NCAR reanalysis precipitation fields.

More detail, from NOAA source (https://www.cpc.ncep.noaa.gov/products/global_precip/html/wpage.cmap.html):

First, the random error is reduced by linearly combining the satellite estimates using the maximum likelihood method, in which case the linear combination coefficients are inversely proportional to the square of the local random error of the individual data sources. Over global land areas the random error is defined for each time period and grid location by comparing the data source with the rain gauge analysis over the surrounding area. Over oceans, the random error is defined by comparing the data sources with the rain gauge observations over the Pacific atolls.

Information about the technical and scientific quality

CMAP has been shown to represent a suppressed annual cycle amplitude and low precipitation over land compared to other products.

Limitations and strengths for application in North Canada

Quality of the analysis is highly dependent on the amount and type of input data, improving where there are high gauge densities. There is no inclusion of AIRS/TOVS satellite observations (increase high latitude observations) nor is there adjustment for undercatch in gauge measurements.

Generally, greater uncertainty with increasing latitude; poorest quality in polar regions.

While CMAP and GPCP are valuable because of their long record, it is likely that more recently developed datasets are more accurate for the common periods of record, due to greater uniformity of input data sources and more advanced satellite-derived products.

References to documents describing the methodology and/or the dataset

Xie, P., Arkin P.A., Janowiak J.E. (2007) CMAP: The CPC Merged Analysis of Precipitation. In: Levizzani V., Bauer P., Turk F.J. (eds) Measuring Precipitation From Space. Advances In Global Change Research, vol 28. Springer, Dordrecht. https://doi.org/10.1007/978-1-4020-5835-6_25

Xie, P., and P. A. Arkin, 1997: Global Precipitation: A 17-Year Monthly Analysis Based on Gauge Observations, Satellite Estimates, and Numerical Model Outputs. Bulletin of the American Meteorological Society, 78(11), 2539–2558. https://doi.org/10.1175/1520-0477(1997)078<2539:gpayma>2.0.co;2

Yin, X. G., A. Gruber, and P. Arkin, 2004: Comparison of the GPCP and CMAP merged gauge-satellite monthly precipitation products for the period 1979–2001. Journal of Hydrometeorology, 5(6), 1207– 1222..

Link to download the data and format of data

Link to download available here: https://psl.noaa.gov/data/gridded/data.cmap.html

Data are in netCDF-4 file format.

Publications including dataset evaluation or comparison with other data in Canada

Anderson, B. T., N. Feldl, and B. R. Lintner, 2018: Emergent Behavior of Arctic Precipitation in Response to Enhanced Arctic Warming. Journal of Geophysical Research: Atmospheres, 123(5), 2704–2717. https://doi.org/10.1002/2017jd026799

Behrangi, A., et al. (2016), Status of high-latitude precipitation estimates from observations and reanalyses, J. Geophys. Res. Atmos., 121, 4468– 4486, doi:10.1002/2015JD024546.

7.2.27 <u>Dataset:</u> Integrated Multi-Satellite Retrievals for the GPM mission (IMERG V5.2 and V6)

Overview

This document provides an overview of the precipitation data from the Integrated Multi-Satellite Retrievals for GPM (IMERG) versions 5.2 and 6. The dataset is a combination of many satellite microwave precipitation estimates, microwave-calibrated infrared (IR) satellite estimates, precipitation gauge analyses, and some other precipitation estimators. The precipitation product is the result of several optimization iterations. The GPM is an international (NASA and Japan Aerospace and Exploration Agency (JAXA)) mission. Updates to the morphing algorithm have been introduced to version 6 (V6) of IMERG.

Provider's contact information

The work on IMERG is being carried out as part of the Global Precipitation Measurement (GPM) mission, an international project of NASA and JAXA.

Dataset Point of Contact:

https://gpm.nasa.gov/contact

Licensing and citation

Cite data as:

Huffman, G.J., E.F. Stocker, D.T. Bolvin, E.J. Nelkin, Jackson Tan, 2021, last updated 2021: Data Sets. NASA/GSFC, Greenbelt, MD, USA, , accessed , [doi: or at <data landing page URL>].

Variable name and units

IMERG output is available in two near-real time formats:

- "Early" multi-satellite product is processed about 4 hours after observation time
- "Late" multi-satellite product is processed about 14 hours after observation time

After the monthly gauge analysis is received :

- “Final” satellite-gauge product is processed about 3.5 months after observation month

We cover only the final satellite-gauge product variables here. For more information, see the IMERG Technical Document.

Name	Description	Units	Frequency
precipitationCal	Merged satellite-gauge precipitation estimate	mm/hr	Monthly

Auxiliary data:

randomError	Random error for merged satellite-gauge precipitation	mm/hr	Monthly
gaugeRelativeWeight	Weighting of gauge precipitation relative to the multi-satellite precipitation	Percent	Monthly
probabilityLiquidPrecipitation	Accumulation-weighted probability of liquid precipitation phase	Percent	Monthly

Spatial coverage and resolution

The spatial resolution is 0.1°x0.1° and has global coverage (though not as much data goes into the estimate for different locations)

Temporal coverage and resolution

The temporal resolution of the IMERG product is 30 minutes. The V5.2 record spans from 1998 to present. The V6 record will span from 2000/06/01 to present and supersedes the V5.2 record.

Information about observations (number, homogeneity)

Most satellite-based precipitation estimates are provided by low-Earth-orbit passive microwave sensors. These provide somewhat limited sampling, so a constellation of similar satellites is combined. Additional information can come from geosynchronous-Earth-orbit infrared (IR) estimates, though these are poor over ice and snow. Gauge analyses are used to provide regionalization and bias correction to satellite estimates.

Satellite overview:

- Core satellites (merged radar-passive microwave imager):
  - TRMM PR-TMI [2014/04-est. 2024/02]
  - GPM DPR-GMI [1998/01-2014/09]
- Microwave constellation:
  - Conically-scanning passive microwave imagers and imager/sounders
    - Aqua AMSR-E [2002/06-2011/10]
    - DMSP F13 SSMI [1998/01-2009/11]
    - DMSP F14 SSMI [1998/01-2008/08]
    - DMSP F15 SSMI [2000/02-2006/08]
    - DMSP F17 SSMIS [2008/03-est. 2019/12]
    - DMSP F17 SSMIS [2010/03-est. 2020/03]
    - DMSP F19 SSMIS [2014/12-2016/02]
    - GCOMW1 AMSR2 [2012/07-est. 2022/05]
    - GOSAT-3 AMSR3 [est. 2022/02-est. 2032/01]
    - GPM GMI [2014/03-est. 2024/02]
    - METOP-SG B1 MWI
    - METOP-SG B2 MWI
    - METOP-SG B3 MWI
    - TRMM TMI
    - WSF-M 1 MIS
    - WSF-M 2 MIS
  - Cross-track-scanning passive microwave sounders
    - JPSS-2 ATMS
    - JPSS-3 ATMS
    - METOP-2/A MHS
    - METOP-1/B MHS

        - METOP-3/C MHS
        - METOP-SG A1 MWS
        - METOP-SG A2 MWS
        - METOP-SG A3 MWS
        - M-T SAPHIR
        - NOAA-15 AMSU
        - NOAA-16 AMSU
        - NOAA-17 AMSU
        - NOAA-18 MHS
        - NOAA-19 MHS
        - NOAA-20 ATMS
        - SNPP ATMS
    - IR/passive microwave sounders
        - Aqua AIRS [2002/02-est.2020/09]
        - NOAA-14 TOVS [1998/01-2005/04]
        - NOAA-20 CrIS [2017/11-est.2022/06]
        - SNPP CrIS [2011/11-est.2021/11]
- Geosynchronous infrared images
    - GMS, MTSat, Himawari Series [Sub-sat. Lon. 140E]
    - GOES-E Series [Sub-sat. Lon. 75W]
    - GOES-W Series [Sub-sat. Lon. 135W]
    - Meteosat prime series [Sub-sat. Lon. 0E]
    - Meteosat repositioned series [Sub-sat. Lon. 63E from Jul 1998, 41E from Oct 2016]

Precipitation gauge analysis

- Full version 2018 from DWD/GPCC [1998/01-2016/12]
- Monitoring Version 6 from DWD/GPCC [2017/01-ongoing]

Methodology

First estimates come from the passive microwave sensors, mainly from brightness temperatures. Estimates are gridded, and then some calibration is done (using the CORRA product and the GPCP V2.3 monthly precipitation estimate). This data is combined into half-hourly fields. Quasi-Lagrangian interpolation is applied to the gridded estimates using motion vectors computed from ancillary data. CPC assembles the zenith-angle-corrected, intercalibrated merged geo-IR fields, and these supplements the morphed precipitation. Note that PMW retrievals traditionally suffer from inaccuracies over frozen surfaces, so some missing data may exist at high latitudes where IR-based estimates have gaps.

The "Final" IMERG precipitation estimate results after calibration with gauge data. The ratio between the monthly accumulation of half-hourly multi-satellite-only fields and the monthly satellite-gauge field is found. Then, this ratio is applied to each half-hourly field of multi-satellite only precipitation estimates.

More details for the newest version can be found in the Algorithm Theoretical Basis Document for V6 of IMERG.

Information about the technical and scientific quality

About 90% of ECCC automatic rain gauge stations do not participate in GPCC and are thus independent validation sources for the IMERG data, which uses GPCC for calibration.

This is not covered here in detail, but there are actually four products provided through IMERG: precipitationCal, precipitationUncal, IRprecipitation, and HQprecipitation. The uncalibrated (precipitationUncal) and calibrated (precipitationCal) estimates only differ in the Final run, where gauge calibration is done as described in the methodology section for precipitationCal. Only the infrared geostationary satellite precipitation data is included in IRprecipitation, and the precipitation extracted from merging high-quality passive microwave sensors only includes microwave data but has significant gaps (HQprecipitation).

PrecipitationCal is considered as the most reliable IMERG precipitation estimate and should generally be used.

IMERG is not intended as a Climate Data Record dataset, so be wary of discontinuities/changes where sensors change, etc.

Limitations and strengths for application in North Canada

Due to small number of reporting sites in North Canada, validation specific to that region is limited.

It is suggested by studies that IMERG tends to overestimate light to moderate precipitations, particularly in the summer.

References to documents describing the methodology and/or the dataset

Algorithm Theoretical Basis Document for IMERG V5.2: https://gpm.nasa.gov/resources/documents/gpm-integrated-multi-satellite-retrievals-gpm-imerg-algorithm-theoretical-basis-

Algorithm Theoretical Basis Document for IMERG v6 – may only be temporarily hosted here : https://docserver.gesdisc.eosdis.nasa.gov/public/project/GPM/IMERG_ATBD_V06.pdf

IMERG V06 Changes to Morphing Algorithm:

Tan, J., G. J. Huffman, D. T. Bolvin, and E. J. Nelkin, 2019: IMERG V06: Changes to the Morphing Algorithm. Journal of Atmospheric and Oceanic Technology 36, 12, 2471-2482, https://doi.org/10.1175/JTECH-D-19-0114.1

Link to download the data and format of data

Direct Download from GPM data access page (http://pmm.nasa.gov/data-access/downloads/gpm) – requires a simple, free, automatic on-line registration

Helpful how-to on reading IMERG data using Python: https://disc.gsfc.nasa.gov/information/howto?title=How%20to%20Read%20IMERG%20Data%20Using%20Python

Data are in a variety of formats: Visualization, GeoTIFF, HDF5, NetCDF, OPeNDAP.

Publications including dataset evaluation or comparison with other data in Canada

Moazami, S., and M. R. Najafi, 2021: A comprehensive evaluation of GPM-IMERG V06 and MRMS with hourly ground-based precipitation observations across Canada. Journal of Hydrology, 594, 125929. https://doi.org/10.1016/j.jhydrol.2020.125929

7.3 Humidity

7.3.1 Dataset: MSC Station Observations – humidity

Overview

This dataset provides in-situ surface observations archived by the Meteorological Service of Canada (MSC). It containes data from the MSC operational observation system as well as from their parteners. Therefore, not all stations are QC or maintained by MSC. The network of stations contains stations with only automatic instruments, and human observing (or manual) stations. Humidity variables are obtained from hourly stations that typically measure more weather variables (e.g., wind or snow on ground).

Provider's contact information

Environment and Climate Change Canada

donneesclimatiquesenligne-climatedataonline@ec.gc.ca

Licensing

Open Government Licence - Canada.

Variable name and units:

Hourly Relative Humidity (%)

Hourly dew point temperature (°C)

Hourly Humidex (unitless)

Spatial coverage and resolution:

Canada, point locations.

Temporal coverage and resolution:

Time period varies per station with data for in the North starting in 1940's or 1950's until present.

The data is available at hourly time steps.

The data will continue to be updated regularly.

Information about observations (number, homogeneity)

The number of active stations changed over time. The following figure from Mekis et al. (2018) is presenting the locations of the surface weather stations across Canada with a Needs Index map in the background as of September 2016.

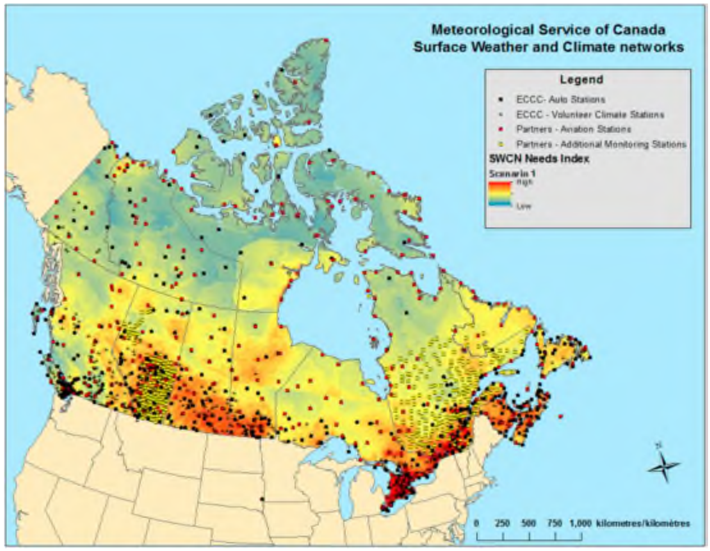


Figure 1. Surface weather stations across Canada, as of September 2016, with a Needs Index map in the background. For further details on station network evolution see Mekis et al. 2018. [Source: Mekis et al., 2018].

Stations over Northern Canda with dew point measurements are the ECCC atomatic stations and stations from the Aviation Monitoring Station network (which include automated and staffed weather stations) operated by NAV CANADA and the Department of National Defence (DND). The ECCC Volunteer Climate Stations provide just temperature and precipitation measurements.

Methodology

Raw and quality-controlled station observations are archived and managed by the MSC's Archive Operations and Climate Services. Observations from different instruments are stored in different formats in the national archive. The methodology, the instruments and the location of instruments have changed in time. Many initialy manual stations were replaced with automatic stations. The following is summarising some information regarding the manual measurements that should be considered when using historic station data.

Relative humidity at manual stations was measured either by a Dewcel remote temperature sensing unit or by psychrometers (e,g. Vaisala HMP 35CF, Vaisala HMP 14C), and derived from the dry bulb temperature and dew point temperature with the aid of psychrometric tables. Currently MSC is using Vaisala HMP 155.

Hourly humidity values are obtained from hourly climate stations. For climate stations operating on a 24-hour basis, before June 1, 1957, the climatological day ended at 1230Z of the following day; from June 1, 1957, to June 30, 1961, the climatological day ended at 1200Z of the following day; since July 1, 1961, the climatological day ends at 0600Z of the following day. In cases where knowing time-of-observation is critical, the best approach is to check the historical inspection reports for the climate station.

MSC is also computing Humidex values using hourly measurements of temperature and humidity. The standard Humidex formula used presently by ECCC is:

Humidex = (air temperature) + h

Where:

h = (0.5555) * (e - 10.0);

e = vapour pressure in hPa (mbar), given by:

e = 6.11 * exp [5417.7530 * ((1/273.16) - (1/dewpoint))]

In this equation, dew point temperature is expressed in Kelvins (temperature in K = temperature in °C + 273.16) and 5417.7530 is a rounded constant based on the molecular weight of water, latent heat of evaporation, and the universal gas constant.

Earlier records have Humidex (and vapour pressure) values computed with another formula. **Consequently, the 1971 Normals used the old formula, and the 1981 Normals used this new formula.**

Information about the technical and scientific quality

This dataset represents Environment and Climate Change Canada's official station observations. Data are subject to change on an on-going basis as MSC is constantly quality controlling (QCing) from ECCC stations. Not all data has the same level of QA/QC (i.e. aviation dat is not QA/QC by MSC but by NAV CANADA).

Careful attention should be accorded if the data from stations is used in climate analyses because abrupt discontinuities to humidity records can be caused by a number of non-climatic factors. Users should be aware about the following factors:

- Canadian conversion algorithms, in the form of psychrometric tables, were refined in the 1960s and the metric system was adopted in 1977. In addition, from the early 1970s psychrometers were replaced by the Dewcel at principal meteorological stations and within the Automated Weather Observation System (AWOS), leading to a decreasing shift in relative humidity at a number of stations. These steps are especially prevalent for stations experiencing cold temperatures during the cold period (van Wijngaarden & Vincent, 2005).
- The change in the observing agency, has also created an artificial positive step in the beginning in the 1990s in 8 MSC hourly stations from the 75 analyzed by Vincent *et al.* (2007).
- At the microscale, the growth of a nearby tree, landscape changes and changes in urban sprawling (i.e. cities and skyscrapers) may affect the local climate through shade and evapotranspiration.
- Changes to the hydrology of an area such as the introduction or cessation of irrigation practises, the construction or draining of a local reservoir and the man-made water sources (i.e dams, treatment plants, pumping stations, lakes/ponds) can effect real changes in humidity.

Limitations and strengths for application in North Canada

It is a challenge to sustain a cost-effective observing system over Norther Canada because of a large part of the teritory is constituted by remote areas (it is hard for technicians to fly to the site for maintenance, and they often have to wait for the thaw). The special climatic conditions produce a large risk of power and telecommunication outages. Concequently, observations in Northern Canada are sparse and records are often incomplete.

Other challenges are related to changes in the observing network, which involves relocation and closure of sites and changes in instruments and practices. In Canada, psychrometers were replaced by dewcel units in the early 1970s and some as late as the 1980s. This change has created an artificial negative step in relative humidity time series because of a positive bias observed in psychometers records in cold climate: psychrometers yield anomalously high values of relative humidity at low temperatures when the wet bulb is coated by ice, while dewcels housed in a sheltered Stevenson screen are less sensitive to icing than other relative humidity sensors and exhibit lower values of relative humidity at very cold temperatures (Déry and Steiglitz, 2002).

A homogeneity assessment of relative humidity and dew point temperatures was carried out by Vincent *et al*. (2007). A significant negative step due to the replacement of the psychrometer by the dewcel was observed for relative humidity at 52 MSC stations. For the dewpoint time series, the step for the introduction of the dewcel was observed at nine MSC stations (mostly located in the northeast). The adjustments for the dewpoint do not have as much impact on the annual national trends but have an important impact on the trend of relative humidity.

Very few significant steps were detected in the specific humidity time series, because in cold temperatures, the specific humidity values are very low and do not vary much (Vincent *et al.,* 2007).

References to documents describing the methodology or/and the dataset

The manual specific for aviation observations/reports (MANOBS): http://publications.gc.ca/collections/collection_2019/eccc/En56-238-2-2018-eng.pdf and http://publications.gc.ca/collections/collection_2019/eccc/En56-238-2-2018-fra.pdf

https://climate.weather.gc.ca/doc/Technical_Documentation.pdf

Link to download the data and format of data:

Only hourly data is available on the CDO/MSC/ECCC database (searchable by location; in CSV format): https://climate.weather.gc.ca/historical_data/search_historic_data_e.html

Publications including dataset evaluation or comparison with other data in northern Canada

Déry, S., and M. Steiglitz, 2002: A note on surface humidity measurements in the cold Canadian environment, Boundary Layer Meteorol., 102, 491–497.

Mekis, E., L.A. Vincent, M.W. Shephard, and X. Zhang, 2015: Observed Trends in Severe Weather Conditions Based on Humidex, Wind Chill, and Heavy Rainfall Events in Canada for 1953–2012, Atmosphere-Ocean, 53:4, 383-397, DOI: 10.1080/07055900.2015.1086970.

van Wijngaarden, W. A. and L.A. Vincent, 2005: Examination of discontinuities in hourly surface relative humidity in Canada during 1953-2003. Journal of Geophysical Research-Atmospheres, 110, D22102, doi:10.1029/2005JD005925.

Vincent, L.A., W.A. van Wijngaarden, and R. Hopkinson, 2007: Surface temperature and humidity trends in Canada for 1953-2005. Journal of Climate, 20, 5100–5113. doi:10.1175/JCLI4293.1

This document provides an overview of the humidity products from the Climate Forecast system reanalysis (CFSR) and its operational extension CFSv2. The CFSR is a third-generation reanalysis product, developed by the National Oceanic and Atmospheric Administration's (NOAA) National Center for Environmental Prediction (NCEP), and it uses a global, high resolution, coupled atmosphere-ocean-land surface-sea ice system. The spatial resolution of the global atmospheric data is ~38 km (T382) and many atmospheric variables are provided at hourly temporal resolution

7.3.2 Dataset: The NOAA NCEP Climate Forecast System Reanalysis (CFSR) and Climate Forecast System Version 2 (CFSv2) - humidity

Overview

This document provides an overview of the humidity products from the Climate Forecast system reanalysis (CFSR) and its operational extension CFSv2. The CFSR is a third-generation reanalysis product, developed by the National Oceanic and Atmospheric Administration's

(NOAA) National Center for Environmental Prediction (NCEP), and it uses a global, high resolution, coupled atmosphere-ocean-land surface-sea ice system. The spatial resolution of the global atmospheric data is ~38 km (T382) and many atmospheric variables are provided at hourly temporal resolution.

Provider's contact information

CFSR is developed by the National Oceanic and Atmospheric Administration's (NOAA) National Center for Environmental Prediction (NCEP).

Contact name: DOC/NOAA/NESDIS/NCEI > National Centers for Environmental Information, NESDIS, NOAA, U.S. Department of Commerce

Contact email: Contact: cfs@noaa.gov

Licensing and citation

CFSR data is freely available

Please reference the following article when using the CFS Reanalysis (CFSR) data:

Saha, S., S. Moorthi, H. Pan, X. Wu, J. Wang, and Coauthors, 2010: The NCEP Climate Forecast System Reanalysis. Bulletin of the American Meteorological Society, 91, 1015–1057, doi:10.1175/2010BAMS3001.1.

For hourly data downloaded from UCAR RDA: **Saha**, S., et al. 2010. NCEP Climate Forecast System Reanalysis (CFSR) Selected Hourly Time-Series Products, January 1979 to December 2010. Research Data Archive at the National Center for Atmospheric Research, Computational and Information Systems Laboratory. https://doi.org/10.5065/D6513W89. Accessed dd mmm yyyy.

For monthly data downloaded from UCAR RDA: **Saha**, S., et al. 2010. NCEP Climate Forecast System Reanalysis (CFSR) Monthly Products, January 1979 to December 2010. Research Data Archive at the National Center for Atmospheric Research, Computational and Information Systems Laboratory. https://doi.org/10.5065/D6DN438J. Accessed dd mmm yyyy.

Please reference the following article when using the CFS Reforecast model or data:

Saha, S., S. Moorthi, X. Wu, J. Wang, S. Nadiga, P. Tripp, D. Behringer, Y. Hou, H. Chuang, M. Iredell, M.Ek, J. Meng, R. Yang, M.P. Mendez, H. van den Dool, Q. Zhang, W. Wang, M. Chen, and E. Becker, 2014: The NCEP Climate Forecast System Version 2, Journal of Climate, 27(6), 2185-2208, doi:10.1175/JCLI-D-12-00823.1.

For hourly data downloaded from UCAR RDA: **Saha**, S., et al. 2011, updated monthly. NCEP Climate Forecast System Version 2 (CFSv2) Selected Hourly Time-Series Products. Research Data Archive at the National Center for Atmospheric Research, Computational and Information Systems Laboratory. https://doi.org/10.5065/D6N877VB. Accessed dd mmm yyyy.

For monthly data downloaded from UCAR RDA: **Saha**, S., et al. 2012. NCEP Climate Forecast System Version 2 (CFSv2) Monthly Products. Research Data Archive at the National Center for Atmospheric Research, Computational and Information Systems Laboratory. https://doi.org/10.5065/D69021ZF. Accessed dd mmm yyyy.

Variable name and units:

The following table summarizes the name of the variables available at NCAR RDA as hourly time series.

Notation (name)	Units
SPF H (Specific humidity) at RDA and Q2 min Flux set of data at NCEI	kg kg-1
R H (Relative humidity)	%

Note: The forecast at the first time step (f00) of 3 minutes constitutes a spin up of the model physics, and IT IS NOT THE ANALYSIS.

Spatial coverage and resolution:

CFSR data, is a global dataset. Humidity variables are provided on the same horizontal regular latitude-longitude grid with a spatial resolution of ~38 km (T382).

Temporal coverage and resolution:

CFSR covers 01Jan1979 - 31Mar2011 period. The product was extended beyond 2011 as an operational real-time product, using a new version: NCEP's Climate Forecast System Version 2 (CFSv2). CFSR humidity products are available at an hourly time resolution and as monthly means.

Information about observations (number, homogeneity)

All available conventional and satellite observations were included in the CFSR. Satellite observations were used in radiance form and were bias corrected with "spin up" runs at full resolution, taking into account variable CO2 concentrations. This procedure enabled smooth transitions of the climate record due to evolutionary changes in the satellite observing system.

It is extremely difficult to assimilate 2 m temperature over land in systems like the CFSR. Therefore, surface temperature from stations is not assimilated in CFSR.

The CFSR uses the NCEP operational observation quality control procedures.

Methodology

The CFSR is a third-generation reanalysis product, and it is using global, high resolution, coupled atmosphere-ocean-land surface-sea ice system. It includes (1) coupling of atmosphere and ocean during the generation of the 6 hour guess field, (2) an interactive sea-ice model, and (3) assimilation of satellite radiances. The CFSR global atmosphere resolution is ~38 km (T382) with 64 levels. The global ocean is 0.25° at the equator, extending to a global 0.5° beyond the tropics, with 40 levels. The global land surface model has 4 soil levels, and the global sea ice model has 3 levels. The CFSR atmospheric model contains observed variations in carbon dioxide (CO2), together with changes in aerosols and other trace gases and solar variations.

Information about the technical and scientific quality

The CSFR products are superior to previous NCEP reanalyses with respect to improved model, finer resolution, advanced assimilation schemes, atmosphere-land-ocean-sea ice coupling, assimilates satellite radiances rather than retrievals, and accounts for changing CO2 and other trace gasses, aerosols, and solar variations.

Known CFSRR data issues are explained in the August 2011 CFSRR Known Issues Technical Document.

Limitations and strengths for application in North Canada

GENERAL KEY STRENGTHS:

- Approaches the horizontal resolution of regional reanalyses like the NARR and Arctic System Reanalysis

GENERAL KEY LIMITATIONS:

- Ocean-atmosphere interactions are not used directly. Rather the information is used for background information. The actual reanalysis is uncoupled.

References to documents describing the methodology or/and the dataset

Saha, S., S. Moorthi, H.-L. Pan, X. Wu, J. Wang, S. Nadiga, P. Tripp, R. Kistler, J. Woollen, D. Behringer, H. Liu, D. Stokes, R. Grumbine, G. Gayno, J. Wang, Y.-T. Hou, H. Chuang, H. H. Juang, J. Sela, M. Iredell, R. Treadon, D. Kleist, P. Van Delst, D. Keyser, J. Derber, M. Ek, J. Meng, H. Wei, R. Yang, S. Lord, H. van den Dool, A. Kumar, W. Wang, C. Long, M. Chelliah, Y. Xue, B. Huang, J. Schemm, W. Ebisuzaki, R. Lin, P. Xie, M. Chen, S. Zhou, W. Higgins, C. Zou, Q. Liu, Y. Chen, Y. Han, L. Cucurull, Ri. W. Reynolds, G. Rutledge, and M. Goldberg, 2010: The NCEP Climate Forecast System Reanalysis. Bulletin of the American Meteorological Society 91, 8, 1015-1058, https://doi.org/10.1175/2010BAMS3001.1.

Saha, S., S. Moorthi, X. Wu, J. Wang, S. Nadiga, P. Tripp, D. Behringer, Y. Hou, H. Chuang, M. Iredell, M.Ek, J. Meng, R. Yang, M.P. Mendez, H. van den Dool, Q. Zhang, W. Wang, M. Chen, and E. Becker, 2014: The NCEP Climate Forecast System Version 2, Journal of Climate, 27(6), 2185-2208, doi:10.1175/JCLI-D-12-00823.1.

Link to download the data and format of data:

The CFSR data (1979 to 2011) are available in GRIB-2 format and can be accessed in multiple ways.
NCEI NOMADS THREDDS Data Server: URL: https://nomads.ncdc.noaa.gov/thredds/cfsr.html
NOAA NOMADS FTP access: URL: ftp://nomads.ncdc.noaa.gov/CFSR/

At UCAR RDA data is grouped as follows:
NCEP Climate Forecast System Version 2 (CFSv2) Monthly Products (ds094.2)
NCEP Climate Forecast System Version 2 (CFSv2) Selected Hourly Time-Series Products (ds094.1)
NCEP Climate Forecast System Reanalysis (CFSR) Monthly Products, January 1979 to December 2010 (ds093.2)
NCEP Climate Forecast System Reanalysis (CFSR) Selected Hourly Time-Series Products, January 1979 to December 2010 (ds093.1)

Publications including dataset evaluation or comparison with other data in Canada

7.3.3 Dataset: NOAA-CIRES-DOE Twentieth Century Reanalysis (20CRv3) - humidity

Overview

This document provides an overview of the 2 m humidity data from Twentieth Century Reanalysis (20CRv3). The 20th Century Reanalysis Project is an effort led by NOAA's Physical Sciences Laboratory (PSL) and CIRES at the University of Colorado, supported by the Department of Energy (DOE), to produce reanalysis datasets spanning the entire 20th century and much of the 19th century. These reanalyses assimilate only surface observations of synoptic pressure into NOAA's Global Forecast System, and prescribed sea surface temperature and sea ice distribution in order to estimate atmospheric variables, from the surface to the top of the atmosphere throughout the 19th and 20th centuries. 20CRv3 is version 3 of the project. For version 3, the ensemble mean and standard deviation for each value were calculated over a set of 80 analyses and short-term forecasts.

Provider's contact information

20CRv3 is developed by the NOAA's Physical Sciences Laboratory (PSL) and CIRES at the University of Colorado, supported by the Department of Energy (DOE).

For help with the dataset please contact

Gilbert P. Compo

CIRES, University of Colorado at Boulder, and Physical Sciences Laboratory, National Oceanic and Atmospheric Administration

gilbert.p.compo at noaa.gov

Laura C. Slivinski

CIRES, University of Colorado at Boulder, and Physical Sciences Laboratory, National Oceanic and Atmospheric Administration

laura.slivinski at noaa.gov

Licensing and citation

20CRv3 data are provided by several collaborative organizations. User registration and agreement to terms and conditions of data service usage are required individually for each organization.

Data at NCAR RDA is licensed under a Creative Commons Attribution 4.0 International Licence.

The following citation should be used for data downloaded from NCAR RDA:

" **Slivinski**, L. C., *et al*. 2019. NOAA-CIRES-DOE Twentieth Century Reanalysis Version 3. Research Data Archive at the National Center for Atmospheric Research, Computational and Information Systems Laboratory. https://doi.org/10.5065/H93G-WS83. Accessed† dd mmm yyyy.

†Please fill in the "Accessed" date with the day, month, and year (e.g., - 5 Aug 2011) you last accessed the data from the RDA. "

The following citation should be used for data downloaded from Physical Sciences Laboratory (PSL) or from National Energy Research Scientific Computing Center (NERSC):

Papers using the NOAA-CIRES-DOE Twentieth Century Reanalysis Project version 3 dataset are requested to include the following text in their acknowledgments: "Support for the Twentieth Century Reanalysis Project version 3 dataset is provided by the U.S. Department of Energy, Office of Science Biological and Environmental Research (BER), by the National Oceanic and Atmospheric Administration Climate Program Office, and by the NOAA Physical Sciences Laboratory."

If you acquire 20th Century Reanalysis V3 data products from PSL, we are asked to acknowledge PSL by including also a text such as *20th Century Reanalysis V3 data provided by the NOAA/OAR/ESRL PSL, Boulder, Colorado, USA, from their Web site at /* in any documents or publications using these data and send a copy of the relevant publications to:

Physical Sciences Laboratory: Data Management

NOAA/ESRL/PSL

325 Broadway

Boulder, CO 80305-3328

psl.data@noaa.gov

Spatial coverage and resolution:

20CRv3 data, is a global dataset. 20CRv3 has a Gaussian T-254 grid (approximately 75 km at the equator).

Variable name and units:

The following table summarizes the 2 m humidity data.

Notation (name)	Units	Organisation (type)
SPFH at NERSC and SHUM at PSL (Specific Humidity at 2 m)	Kg/kg	PSL; NERSC;
RHUM (Relative Humidity at 2 m)	%	PSL; NCAR (Analysis Fields and First Guess Forecast Fields)
QMIN (Minimum Specific Humidity at 2 m)	Kg/kg	PSL; NCAR (First Guess Forecast Fields)
QMAX (Maximum Specific Humidity at 2 m)	Kg/kg	PSL; NCAR (First Guess Forecast Fields)

Temporal coverage and resolution:

On PSL website, 20CRv3.SI is available for years 1836-1980 and 20CRv3.MO is available for years 1981-2015 (the only differences between these two versions are the prescribed sea surface temperatures and dates of availability):

- 3-hourly values for 1836/01/01 0Z to 2015/12/31 21Z.
- Daily average values for 1836/01/01 to 2015/12/31.
- Monthly values for 1836/01 to 2015/12 (Combined SI-MO).

At NCAR RDA, 20CRv3 is available from:

- 1835/12/31 18Z to 2016/01/01 0Z (Yearly Time Series 3-Hourly Analysis Fields (Gaussian T-254))
- 1806/12/31 18Z to 2015/12/31 12Z (Yearly Time Series 3-Hourly First Guess Forecast Fields (Gaussian T-254))
- 1806/12/31 21Z to 2015/12/31 15Z (Yearly Time Series 6-Hourly Analysis Fields (Gaussian T-254))

The data is updated on an irregular base.

Information about observations (number, homogeneity)

These reanalyses assimilate only surface observations of synoptic pressure. Boundary conditions of pentad sea surface temperature and monthly sea ice concentration and time-varying solar, volcanic, and carbon dioxide radiative forcings are prescribed.

The surface pressure observations: ISPD version 4.7, made available through international cooperation facilitated by the Atmospheric Circulation Reconstructions over the Earth (ACRE) initiative and working groups of the Global Climate Observing System and World Climate Research Program.

Sea Ice Concentration Boundary Condition: monthly HadISST2.3 sea ice (Slivinski *et al*., 2019; Titchner & Rayner 2014; Walsh *et al*., 2015)

Sea Surface Temperature Boundary Condition: prior to 1981(20CRv3.SI): 8 members of pentad interpolated to daily Simple Ocean Data Assimilation with Sparse Input (SODAsi) version 3 (SODAsi.3, Giese *et al*., 2016) seasonally adjusted to the 1981-2010 HadISST2.2 climatology. Regions where sea ice was ever indicated in HadISST2.3 are filled with: HadISST2.2 daily (1963+); HadISST2.1 monthly interpolated to daily (1850-1962); or the 1861–1891 HadISST2.1 climatology (1849 and earlier). **1981 and later (20CRv3.MO)**: 8 members of pentad interpolated to daily HadISST2.2 sea surface temperatures.

Methodology

20CRv3 assimilates only surface observations of synoptic pressure into an 80-member the coupled Global Forecast System land-atmospheric model with prescribed sea surface temperatures and sea ice concentration. A coupled one-dimensional thermodynamic sea-ice model is also used. Boundary conditions of pentad sea surface temperature and monthly sea ice concentration and time-varying solar, volcanic, and carbon dioxide radiative forcings are prescribed.

Forecast model: 20CRv3 uses the atmospheric model from the NCEP Global Forecast System v14.0.1 coupled with the Noah land surface model and 2.5-layer thermodynamic sea ice model (Compo *et al*., (2011). The forecast system is run at a resolution of T254 (approximately 75 km at the equator) with 64 vertical levels up to .3 mb and it has 80 individual ensemble members.

Assimilation model: The data assimilation algorithm is the Ensemble Square Root Filter (Whitaker and Hamill 2002) with 4D Incremental Analysis Update (4D-IAU; Bloom *et al*., 1996, Lei & Whitaker 2016). The snow relaxes to a monthly climatology (Saha *et al*., 2010) over 60 days.

Streams: Every 5th year a stream is produced for a continuous 5 year period. Stream years are 1835, 1840, ... , 2005, 2010. Stream year 2010 will be extended beyond 2015.

Information about the technical and scientific quality

There are three previous versions of the reanalysis: V1, V2, and V2c. Several adjustments were made to the model prior to implementation in the 20CRv3 system. Updates to the parameterizations are described in Saha *et al.* (2010) and include revised solar radiation transfer, boundary layer vertical diffusion, cumulus convection, and gravity wave drag parameterizations. In addition, the cloud liquid water is a prognostic quantity with a simple cloud microphysics parameterization. Another important improvement is in the resolution and ensemble size. Previous 20CR versions were using a 56-member ensemble with a coarser spatial resolution (T62 28 levels), while the 20CRv3 is using 80 ensemble members with a finer spatial resolution (T254 64 levels). 20CRv3 also assimilates a larger set of observations, and includes an improved data assimilation system relative to its predecessor 20CRv2c.

Observations are first grossly tested for quality control: if the observation is outside the range 850 and 1090 hPa, or if the absolute difference between the observation and the first guess value is greater than 3.2 times the square root of the sum of the forecast ensemble variance and the observation error variance, the observation is rejected. (Slivinski *et al*., 2018). They are then subject to adaptive quality control and adaptive localization control.

Limitations and strengths for application in North Canada

Key Strengths: Length of record and estimates of uncertainty

Key Limitations: As with all reanalyses, users should take care in interpreting long-term trends - inconsistencies between 20CR and other data have been reported, especially on a regional scale.

References to documents describing the methodology or/and the dataset

Compo, G.P., J.S. Whitaker, P.D. Sardeshmukh, N. Matsui, R.J. Allan, X. Yin, B.E. Gleason, R.S. Vose, G. Rutledge, P. Bessemoulin, S. Brönnimann, M. Brunet, R.I. Crouthamel, A.N. Grant, P.Y. Groisman, P.D. Jones, M. Kruk, A.C. Kruger, G.J. Marshall, M. Maugeri, H.Y. Mok, Ø. Nordli, T.F. Ross, R.M. Trigo, X.L. Wang, S.D. Woodruff, and S.J. Worley, 2011: The Twentieth Century Reanalysis Project. Quarterly Journal of the Royal Meteorological Society, 137(654), 1-28, DOI: 10.1002/qj.776.

Slivinski, L. C.,G. P. Compo, P.D. Sardeshmukh, J. S. Whitaker, C. McColl, R. J. Allan, P. Brohan, X. Yin, C. A. Smith, L. J. Spencer, R. S. Vose, M. Rohrer, R. P. Conroy, D. C. Schuster, J. J. Kennedy, L. Ashcroft, S. Brönnimann, M. Brunet, D. Camuffo, R. Cornes, T. A. Cram, F. Domínguez-Castro, J. E. Freeman, J. Gergis, E. Hawkins, P. D. Jones, H. Kubota, T. C. Lee, A. M. Lorrey, J. Luterbacher, C. J. Mock, R. K. Przybylak, C. Pudmenzky, V. C. Slonosky, B. Tinz, B. Trewin, X. L. Wang, C. Wilkinson, K. Wood, and P. Wyszyński , 2021: An Evaluation of the Performance of the Twentieth Century Reanalysis Version 3. Journal of Climate 34, 4, 1417-1438, https://doi.org/10.1175/JCLI-D-20-0505.1

Link to download the data and format of data:

20CRv3 data are available at several organizations.

At NOAA/PSL, the ensemble mean and the ensemble uncertainty files are available in netCDF4 format: https://psl.noaa.gov/data/gridded/data.20thC_ReanV3.monolevel.html

At National Center for Atmospheric Research (NCAR), the ensemble mean and the ensemble uncertainty files are available in netCDF4 format: https://rda.ucar.edu/datasets/ds131.3/

At NERSC Science Gateway, data for every member of 20CRv3 are available in netCDF4 format: https://portal.nersc.gov/project/20C_Reanalysis/

Publications including dataset evaluation or comparison with other data in Canada

7.3.4 *Dataset: Modern-Era Retrospective analysis for Research and Applications, Version 2 (MERRA-2) - humidity*

Overview

This document provides an overview of the humidity data from the Modern-Era Retrospective analysis for Research and Applications, Version 2 (MERRA-2). MERRA-2 represents a third-generation atmospheric global reanalysis produced by the Global Modeling and Assimilation Office (GMAO) at NASA. It begins in 1980 and it replaces the original MERRA reanalysis (Rienecker *et al*., 2011) using an upgraded version of the Goddard Earth Observing System Model, Version 5 (GEOS-5) data assimilation system. Alongside the meteorological data assimilation using a modern satellite database, MERRA-2 includes an interactive analysis of aerosols that feed back into the circulation, uses NASA's observations of stratospheric ozone and temperature, and takes steps towards representing cryogenic processes by including a representation of ice sheets over Greenland and Antarctica.

Provider's contact information

MERRA-2 is developed by the Global Modeling and Assimilation Office (GMAO) and produced through NASA's Modeling, Analysis and Prediction (MAP) program.

Data Download questions should go to the GES DISC help email: gsfc-help-disc@lists.nasa.gov

Science questions regarding MERRA-2 data be emailed to: merra-questions@lists.nasa.gov

When contacting these emails, provide specific information and links to where you have attempted the data downloads. They also ask you to familiarize yourself with the existing documentation first (MERRA-2: http://gmao.gsfc.nasa.gov/reanalysis/MERRA-2/docs/)

Licensing and citation

MERRA-2 data is freely available from the Goddard Earth Sciences (GES) Data Information Services center (DISC). Note that each MERRA-2 data collection has a citable DOI, that should be used in peer-reviewed publications.

Citing MERRA-2 data has 2 steps for a full citation:

(5) First pick the correct variable here.
(6) When you click on the correct variable, it will take you to a second webpage with tabs that you can click that include: (1) documentation papers you need to cite, and (2) the correct variable citation information. You need both types of citation.

Variable name and units:

Specific humidity is available as instantaneous values for every hour. Monthly means of instantaneous diagnostics have also been computed.

inst1_2d_asm_Nx collection of data contains basic assimilated fields from IAU corrector provided on a single level as hourly instantaneous values.

instM_2d_asm_Nx collection of data contains basic assimilated fields from IAU corrector provided on a single level as monthly means of the instantaneous values.

tavg1_2d_slv_Nx collection of data contains Single-Level Diagnostics as 1 hour time means.

tavgM_2d_lnd_Nx collection of data contains monthly time average data of Single-Level Diagnostics

Each time-averaged collection consists of a continuous sequence of data averaged over the indicated interval and time stamped with the central time of the interval. For hourly data, for example, these times are 00:30 GMT, 01:30 GMT, 02:30 GMT, etc. Monthly files represent averages for the calendar months, accounting for leap years.

Name	Description	Units	Collection of data
QV2M	2 m specific humidity	kg kg-1	inst1_2d_asm_Nx; instM_2d_asm_Nx; tavg1_2d_slv_Nx; tavgM_2d_slv_Nx
QV10M	10 m specific humidity	kg kg-1	inst1_2d_asm_Nx; instM_2d_asm_Nx; tavg1_2d_slv_Nx; tavgM_2d_slv_Nx

More broadly, **MERRA-2 File Specification** document has a comprehensive list of datasets available, as well as description of the horizontal and vertical grids.

Spatial coverage and resolution:

MERRA-2 data, is a global dataset. All variables are provided on the same horizontal regular latitude-longitude grid that has 576 points in the longitudinal direction and 361 points in the latitudinal direction, corresponding to a resolution of 0.625°×0.5°.

Temporal coverage and resolution:

MERRA-2 data, is available from 1980 to present.

2 m data is available at hourly and monthly time step as instantaneous value.

MERRA-2 data, is updated on a monthly base (each new month is available approximately between the 15th and 20th of the next month.).

Information about observations (number, homogeneity)

Like any other climate variable from a reanalysis product, temperature is potentially influenced by all observations assimilated into the product. MERRA-2 assimilates conventional and satellite-based observations.

Conventional observations include surface, upper air, and aircraft measurements. **From land based surface meteorology stations, only surface pressure is assimilated in MERRA and MERRA-2**. 2 m temperature from surface observations is not assimilated in MERRA-2. Radiosonde stations may contribute to the lower level analysis (T, Qv, U, V). Likewise, commercial aircraft can provide lower level data on the ascent and descent (T, U, V). There are also wind profilers (U,V). Over ocean, ships and buoys may provide PS, T, Qv, U and V.

Spaceborne observations include satellite radiances and retrieved measurements of the temperature and moisture fields, and satellite observations of wind (derived retrievals of surface and upper-air wind). Spaceborne observations represent the majority of the global observing system, and the percentage of the global observing system that is measured from space increases from 62% in Jan 1980 to 88% in Dec 2014. Modern hyperspectral radiance and microwave observations, along with GPS-Radio Occultation and NASA ozone datasets are now assimilated in MERRA-2.

See the MERRA-2 Observations Tech Memo for more details.

Methodology

Like any other reanalysis, MERRA-2 data is strongly influenced by the data assimilation methodology. MERRA-2 is currently being produced with the GMAO/GEOS-5 Data Assimilation System Version 5.12.4, which incorporates the Global Statistical Interpolation (GSI) analysis scheme of Wu *et al.* (2002). The system utilizes a revised version of the GEOS global atmospheric model (Molod *et al*., 2014). MERRA-2 is intended to replace the MERRA reanalysis product (which was created with GEOS-5.2.0). Details of the MERRA-2 system, including the major changes from the MERRA system, are summarized in the companion GMAO Office Note No. 10. The major motivation for replacing MERRA with MERRA-2 is the fact that the MERRA data assimilation system was frozen in 2008 and is not capable of ingesting several important new data types as the newer microwave sounders and hyperspectral infrared radiance instruments. The GEOS-5 system actively assimilates roughly 2×10^6 observations for each analysis, including about 7.5×10^5 AIRS radiance data. The input stream is roughly twice this volume, but because of the large volume, the data are thinned commensurate with the analysis grid to reduce the computational burden. Data are also rejected from the analysis through quality control procedures.

There is a fundamental change between MERRA and MERRA-2 over land surfaces. Soil moisture in MERRA-2 is initialized using a separate observation-based precipitation product (variable PRECTOTCORR in "flx" collections). This approach improves the representation of land surface properties and runoff, and is similar to the soil moisture initialization scheme developed for MERRA-Land (Reichle *et al*., 2011; Reichle, 2012; Reichle and Liu, 2014). The forcing precipitation is primarily based on gauge observations at low and midlatitudes, and gradually tapers to the MERRA-2 modelled precipitation over a zonal range from 42.5° to 62.5° latitude. The forcing precipitation is entirely composed of the MERRA-2 modelled precipitation poleward of 62.5°.

MERRA-2 is produced as four production Streams, each of the first three covering approximately a third of the MERRA-2 period, with the fourth stream starting within a couple years of real time. Initial conditions for the four MERRA-2 streams were derived from MERRA with a subsequent single year spin-up period, which has not been released in MERRA-2.

Information about the technical and scientific quality

MERRA-2 replaces the original NASA MERRA reanalysis (Rienecker *et al.,* 2011) using an upgraded version of the data assimilation system, and of the forecast model. It is accompanied by extensive technical documentation (see section below on reference to s describing the methodology or/and the dataset). It incorporates observations from the more recent satellite instruments, uses observation-corrected precipitation forcing for the land surface, includes stratospheric ozone products and assimilates interactive aerosols and observed time varying emissions.

A webpage is provided with FAQ answers here: https://gmao.gsfc.nasa.gov/reanalysis/MERRA-2/FAQ/#

Limitations and strengths for application in North Canada

Key general limitations:

- Discontinuities occur in the sea ice and SST boundary condition fields that affect certain time series analysis
- Discontinuities associated with major observing system variations do occur

References to documents describing the methodology or/and the dataset

MERRA-2 Overview: The Modern-Era Retrospective Analysis for Research and Applications, Version 2 (MERRA-2), Gelaro, *et al*., 2017, J. Clim., doi: 10.1175/JCLI-D-16-0758.1

The American Meteorological Society has a special collection of articles relevant to MERRA-2. This collection, coordinated by Mike Bosilovich, is available at http://journals.ametsoc.org/collection/MERRA2.

There are several MAO Technical Memoranda that document and evaluate different aspects of the MERRA-2 system aspects of the MERRA-2 system:

#43, Bosilovich et al. – MERRA-2: Initial Evaluation of the Climate

#45, Randles et al. – The MERRA-2 Aerosol Assimilation

#46, McCarty et al. – MERRA-2 Input Observations: Summary and Assessment

Description of the observation corrected precipitation process used in MERRA-2:

Reichle, R., Q. Liu, R. Koster, C. Draper, S. Mahanama, and G. Partyka, 2017: Land Surface Precipitation in MERRA-2. *J. Clim.* doi:10.1175/JCLI-D-16-0570.1 Link.

Description of the GEOS-5 model changes between the MERRA and MERRA-2 systems:

Molod, A., L. Takacs, M. Suarez, and J. Bacmeister, 2015: Development of the GEOS-5 atmospheric general circulation model: evolution from MERRA to MERRA-2, *Geosci. Model Dev.*, 8, 1339-1356, doi:10.5194/gmd-8-1339-2015. Link.

Description of the mass constraint used in MERRA-2:

Takacs, L.L., M. Suarez, and R. Todling, 2015: Maintaining Atmospheric Mass and Water Balance Within Reanalysis. *NASA/TM–2014-104606*, Vol. 37 Document.

Link to download the data and format of data:

The MERRA-2 data are available online through the Goddard Earth Sciences (GES) Data and Information Services Center (DISC) (http://disc.sci.gsfc.nasa.gov/mdisc/). All MERRA-2 data are organized into file collections that contain fields with common characteristics. 2 m and 10 m specific humidity can be found in the following collections:

MERRA-2 inst1_2d_asm_Nx: contains basic assimilated fields from IAU corrector provided on a single level as hourly instantaneous values.

MERRA-2 instM_2d_asm_Nx: contains basic assimilated fields from IAU corrector provided on a single level as monthly means of the instantaneous values.

MERRA-2 tavg1_2d_lnd_Nx: 1-Hourly time averaged data containing Land Surface Diagnostics

MERRA-2 tavgM_2d_lnd_Nx: Monthly time average data containing Land Surface Diagnostics.

MERRA-2 data files are provided in netCDF-4 format. Due to the size of the MERRA-2 archive, most product collections are compressed with a GRIB like method that is invisible to the user. This method does degrade the precision of the data, but every effort has been made to ensure that differences between the product and the original, non-degraded data are not scientifically meaningful.

Publications including dataset evaluation or comparison with other data in Canada

7.3.5 Dataset: The Japanese 55-year Reanalysis (JRA-55) - humidity

Overview

This document provides an overview of the 2 m humidity data from JRA-55. JRA-55 is a third-generation reanalysis developed by Japanese Meteorological Agency (JMA). It spans the 1958 to present period and represents an update of the previous Japanese 25-year Reanalysis (JRA-25). The analysis period starts in 1958, when regular radiosonde observation began on a global basis. Many of the deficiencies of JRA-25 are alleviated in JRA-55 because the Data Assimilation (DA) system used for the project featured a variety of improvements.

Provider's contact information

JRA-55 is developed by the Japanese Meteorological Agency (JMA). Contact JMA at the email address below with any questions on JRA-55:

Climate Prediction Division, Global Environment and Marine Department,

Japan Meteorological Agency,

Email: jra@met.kishou.go.jp

Contact DIAS Office at the email address below with any questions on JRA-55 stored at DIAS:

DIAS Office

Japan Agency for Marine-Earth Science and Technology

Email: dias-office@diasjp.net

Licensing and citation

The intellectual property rights of the datasets belong exclusively to JMA.

JRA-55 data are provided by collaborative organizations that are separate entities from JMA. User registration and agreement to terms and conditions of data service usage are required individually for each organization. Data at NCAR RDA is licensed under a Creative Commons Attribution 4.0 International Licence.

Individual users should provide JMA (jra@met.kishou.go.jp) with a copy of their scientific or technical papers, publications, press releases or other communications regarding these datasets. The source of the products should be duly acknowledged in scientific or technical

papers, publications, press releases or other communications regarding the products. This includes information on the provider of data and of the collaborative organizations from where the data was downloaded.

Example for data downloaded from DIAS Office:

" In this study, the Japanese 55-year Reanalysis (JRA-55) provided by the Japan Meteorological Agency (JMA) was utilized. This dataset was also collected and provided under the Data Integration and Analysis System (DIAS), which was developed and operated by a project supported by the Ministry of Education, Culture, Sports, Science and Technology. "

Example for downloaded from NCAR RDA:

Japan Meteorological Agency/Japan. 2013, updated monthly. JRA-55: Japanese 55-year Reanalysis, Daily 3-Hourly and 6-Hourly Data. Research Data Archive at the National Center for Atmospheric Research, Computational and Information Systems Laboratory. https://doi.org/10.5065/D6HH6H41. Accessed† dd mmm yyyy.

†Please fill in the "Accessed" date with the day, month, and year (e.g., - 5 Aug 2011) you last accessed the data from the RDA.

Spatial coverage and resolution:

JRA-55 is a global dataset. Data is available at two spatial resolutions: (1) data on pressure levels at 1.25 degree spatial resolution and (2) data on model TL319L60 grid (~55 km) that was processed to a regular latitude-longitude Gaussian grid (320 latitudes by 640 longitudes, nominally 0.5625 degrees) and is available on NCAR RDA.

Variable name and units:

The following table summarizes the humidity variables available at NCAR RDA a regular latitude-longitude Gaussian grid (320 latitudes by 640 longitudes, nominally 0.5625 degree).

Notation (name)	Units	Dataset product
2 m Relative humidity	%	JRA-55 **3-Hourly** Model Resolution 2-Dimensional **Instantaneous Diagnostic Fields (fcst_surf)** JRA-55 **6-Hourly** Model Resolution Surface **Analysis Fields (anl_surf)**
2 m Specific humidity	Kg kg-1	JRA-55 **3-Hourly** Model Resolution 2-Dimensional **Instantaneous Diagnostic Fields (fcst_surf)**

		JRA-55 **6-Hourly** Model Resolution **Surface Analysis Fields (anl_surf)**

Temporal coverage and resolution:

JRA-55 covers 1958 to the present period. Humidity fields are available as Instantaneous Diagnostic Fields and from the Surface Analysis. The Diagnostic fields are available at 3h time step, while the Analysis Fields are available just at 6h time steps.

Monthly statistics are computed as averages and variances for the whole month using only six-hourly data for analyzed and instantaneous forecast fields.

The data is updated on a monthly basis.

Information about observations (number, homogeneity)

Most of the observational data employed in JRA-55 are those used in JRA-25. Additionally, newly reprocessed METEOSAT and GMS data were supplied by EUMETSAT and MSC/JMA respectively. The table below summarizes the conventional data assimilate in JRA-55. From 1958 to 2002, JRA-55 is using the same conventional data as ECMWF ERA-40 reanalysis.

Table 1. Conventional data assimilated in JRA-55

Obs type	Parameter	Level
SYNOP	P	surface
SHIP	P	surface
BUOY	P	surface
Upper-level	T	~100 hPa
Upper-level	T	100~1000 hPa
Upper-level	u	~100 hPa
Upper-level	u	100~1000 hPa
Upper-level	Rh	100~1000 hPa
Aircraft	u	100~1000 hPa
Profiler (US)	u	100~1000 hPa

Quality control of conventional data is basically the same as the one used for JRA-25, and it includes a climatological check, track check, removal of duplicates, consistency check and gross error check.

For satellite radiances, tropospheric temperature, and humidity channels are only used in clear sky conditions and channels sensitive to the ground are excluded over land and sea ice because surface temperature and emissivity estimates over those regions are not very reliable.

The analysis of screen-level variables (2 m temperatures, 2 m relative humidities, and 10 m winds) is performed separately from the atmospheric analysis component. These variables are analyzed with a univariate 2-dimensional optimal interpolation (2D-OI).

Methodology

JRA-55 has been produced with the TL319 version of the Japan Meteorological Agency (JMA) operational data assimilation system (as of December 2009), which features numerous improvements made since the Japanese 25-year Reanalysis (JRA-25). These include a revised longwave radiation scheme, 4D-Var and variational bias correction for satellite radiances. It also incorporates several newly available observational datasets produced as a result of ongoing efforts to improve quality of past observations, including homogenization of radiosonde temperature observations (Haimberger *et al.* 2008, 2012) and reprocessing of satellite data at major meteorological satellite centers.

The analysis of screen-level variables (2 m temperatures, 2 m relative humidities and 10 m winds) is performed separately with a univariate 2-dimensional optimal interpolation (2D-OI). Land surface analysis fields are generated by driving an offline version of the JMA Simple Biosphere (SiB) model with forcing fields from the atmospheric model. Snow depth analysis fields are generated once a day with 2D-OI using SYNOP snow depth observations. First-guess fields are derived for each grid point using (A) snow depth of the land surface analysis and (B) satellite snow covers. Satellite snow covers are retrieved in the 0.25° × 0.25° latitude/longitude grid from microwave imager radiances.

The forecast model used for JRA-55 is based on the TL319 spectral resolution version of the JMA global spectral model (GSM) as of December 2009 (JMA 2007, 2013b), which has been extensively improved since JRA-25.

The reanalysis period was divided into two streams (A002, B002) which have been producing three discontinuities: at 00 UTC on 1 July 1958, 00 UTC on 1 September 1980, and 00 UTC on 1 October 1992. JRA-55 is presently operated on a near-real-time basis and provides monthly updates for the data.

Information about the technical and scientific quality

One important achievement in JRA-55 is the increase in the model resolution (T319L60 vs T106L40 in JRA-25). Among the improvements in the product are reduced biases in stratospheric temperature and Amazonian rainfall, and greater temporal consistency of the temperature analysis. Some notable biases persist, including a dry bias in the upper and middle troposphere, and a warm bias in the upper troposphere. The impacts of changes in the observing system on the forecast error are generally more evident in the Southern Hemisphere than the Northern Hemisphere.

The data is updated on a monthly basis. JMA provide a webpage where the issues with jRA-55 are described: JRA-55 Quality Issues

Limitations and strengths for application in North Canada

GENERAL KEY STRENGTHS:

- Longest-running full observing system reanalysis with 4DVar

GENERAL KEY LIMITATIONS:

- Generally, great caution is needed when hydrological variables from reanalyses are used, especially for model diagnostic variables such as precipitation and evaporation. (From NCAR climate Data Guide: '' Due to the practice of observational correction for forecasts (also known as analysis increment), the energy balance is not exactly preserved in reanalysis. The introduction of analysis increment also creates an artificial sink or source in the water budget, which in turn leads to spin up issues (in which precipitation is insufficient immediately after the start of forecasts and then gradually increases) or spin-down issues (the reverse) with the hydrological cycle. (Bosilovich *et al*., 2011; Trenberth *et al*., 2011).''
- Dry bias in upper and middle troposphere and in regions of deep convection
- The impact of changes in observing systems is particularly apparent for July 2006, when Global Navigation Satellite System-Radio Occultation (GNSS-RO) refractivity data were introduced into JRA-55.

References to documents describing the methodology or/and the dataset

Kobayashi, S., Y. Ota, Y. Harada, A. Ebita, M. Moriya, H. Onoda, K. Onogi, H. Kamahori, C. Kobayashi, H. Endo, K. Miyaoka, and K. Takahashi, 2015: The JRA-55 Reanalysis: General specifications and basic characteristics. Journal of the Meteorological Society of Japan. Ser. II, 93(1), 5-48, doi:10.2151/jmsj.2015-001.

Harada, Y., H. Kamahori, C. Kobayashi, H. Endo, S. Kobayashi, Y. Ota, H. Onoda, K. Onogi, K. Miyaoka, and K. Takahashi, 2016: The JRA-55 Reanalysis: Representation of atmospheric circulation and climate variability, J. Meteor. Soc. Japan, 94, 269-302, doi:10.2151/jmsj.2016-015.

Link to download the data and format of data:

The JRA-55 data are available in GRIB-2 format and can be accessed from the following organizations:

DIAS: Data Integration & Analysis System (data from 1958 to 2012, on a grid of approx. 1.25 deg.) : http://search.diasjp.net/en/dataset/JRA55

NCAR: National Center for Atmospheric Research (USA) (data from 1958 to present, on both spatial grids):

- Daily, 3-Hourly and 6-Hourly Data http://rda.ucar.edu/datasets/ds628.0/
- Monthly Means and Variances http://rda.ucar.edu/datasets/ds628.1/
- Near Real-Time Data http://rda.ucar.edu/datasets/ds628.8/
- Near Real-Time Data -- Monthly Means and Variances http://rda.ucar.edu/datasets/ds628.9/

Publications including dataset evaluation or comparison with other data in Canada

7.3.6 Dataset: NCAR Arctic System Reanalysis, Version 2 (ASRv2) - humidity

Overview

This document provides an overview of near-surface humidity products of ASRv2. ASRv2 is a multi-agency, university-led regional reanalysis product that covers the Arctic. It is produced using high-resolution versions of the Polar Weather Forecast Model (PWRF) and the WRF-VAR and High Resolution Land Data Assimilation (HRLDAS) systems that have been optimized for the Arctic. The final version, which has 15 km horizontal resolution and spans 2000-2016 period, is available online through the NCAR's RDA.

Provider's contact information

ASRv2 is produced by Polar Meteorology Group, Byrd Polar & Climate Research Center, the Ohio State University **and is available at NCAR CISL RDA.**

RDA NCAR User support manager schuster@ucar.edu.

Licensing

Licence: This data are licensed under Creative Commons Attribution 4.0 International Licence (Licence agreement information can be found here)

Dataset citable as: National Center for Atmospheric Research/University Corporation for Atmospheric Research, and Polar Meterology Group/Byrd Polar and Climate Research Center/The Ohio State University. 2017. Arctic System Reanalysis version 2. Research Data Archive at the National Center for Atmospheric Research, Computational and Information Systems Laboratory. https://doi.org/10.5065/D6X9291B , https://rda.ucar.edu/datasets/ds631.1/

Bromwich, D., L. Bai, K. Hines, S. Wang, Z. Liu, H. Lin, Y. Kuo, and M. Barlage, 2012: Arctic System Reanalysis (ASR) Project. Research Data Archive at the National Center for Atmospheric Research, Computational and Information Systems Laboratory.

Variable name and units:

ASRv2 provides 2 products kind, analysis and forecast. The table below provide details on near-surface humidity products from ASRv2.

Name (parameter)	Units	Dataset

Q2M (Q Vapor at 2 m)	kg kg-1	ASRv2.0 2D surface analysis ASRv2.0 2D surface forecast
RH2M (Relative Humidity at 2 m)	%	ASRv2.0 2D surface analysis ASRv2.0 2D surface forecast

Spatial coverage and resolution:

Geographical Coverage: 15kmx15km (at 60 N) oriented 175 W (720x720 North Polar Stereographic).

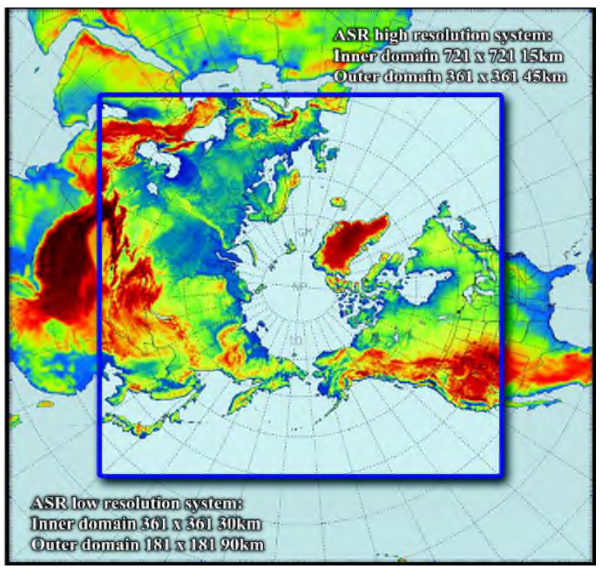


Figure 1. ASR domain (from http://polarmet.osu.edu/ASR/)

Temporal coverage and resolution:

ASRv2 10 m humidity products are available from 2000 to 2016 as **3-hourly** subsets and monthly means.

Methodology

ASRv2 provides a high resolution description of the atmosphere-sea ice-land surface system of the Arctic. It is using the polar version of the Weather Research and Forecasting (WRF) model version 3.6.0. It uses the 3DVAR technique and the High Resolution Land Data Assimilation (HRLDAS) data assimilation systems that have been optimized for the Arctic.

A full description of ASRv2 is presented in the Bulletin of the American Meteorological Society (PDF).

Observations data in ASRv2

The observations data used in ASRv2 (Figure 2) includes synoptic surface observations (black dots), METARs (purple plus signs), ship observations (royal blue dots), buoys (navy-blue dots), radiosondes (purple asterisks), global positioning system refractivity observations (red dots), wind profiler (yellow dots), aviation in-flight weather reports (green dots), QuikSCAT sea surface winds (orange dots), and satellite atmospheric motion vectors (aqua dots).

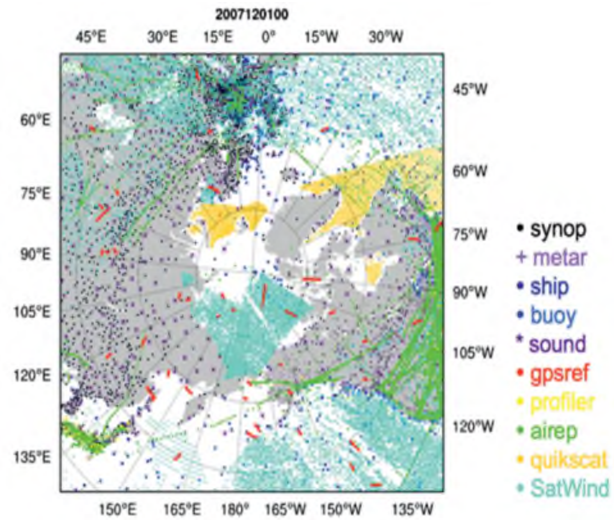


Figure 2. Sample distribution of observations

Information about the technical and scientific quality

New features in ASRv2 compared to ASRv1 are higher horizontal resolution, updated model physics including sub-grid scale cloud fraction interaction with radiation, and a dual outer loop routine for more accurate data assimilation.

The following document compares near-surface variables from ASRv1, ASRv2, and ERAI to observations from ~4500 surface stations provided by the National Centers for Environmental Information (https://www.ncdc.noaa.gov/) for the period December 2006-November 2007: **http://polarmet.osu.edu/ASR/asr_v2_table.pdf**

Presently there are plans to update ASRv2. The updated version will use the latest version of WRF and WRFDA, a more advanced data assimilation procedure, implement Morrison microphysics with a specified variable aerosol concentration, change to Noah-MP land surface model, incorporate a thermodynamic sea ice model, and increase the horizontal resolution to at least 10 km with ~ 100 vertical levels. This version will be known as ASRv3. Plans are to conduct a reanalysis of the MOSAiC drift period (fall 2019 - fall 2020) and it will be available through NCAR.

Limitations and strengths for application in North Canada

References to documents describing the methodology or/and the dataset

Bromwich, D., Y.-H. Kuo, M. Serreze, J. Walsh, L.S. Bai, M. Barlage, K. Hines, and A. Slater, 2010: Arctic System Reanalysis: Call for community involvement. Eos, Transactions American Geophysical Union, 91(2), 13-14, https://doi.org/10.1029/2010EO020001

Online technical description: **https://rda.ucar.edu/datasets/ds631.0/#!docs**

Link to download the data and format of data:

Data Access: NCAR/RDA

ASRv2 is available in NetCDF formats

Link to download 3 hourly and monthly data on RDA:

3 hourly data surface analysis from 2000 to 2016

3 hourly data surface forecast from 2000 to 2016

ASR 15 km monthly means of analysis products

ASR 15 km monthly means of forecast products

Publications including dataset evaluation or comparison with other data in Canada

Bromwich, D.H., A.B. Wilson, L. Bai, G.W.K. Moore, and P. Bauer, 2016: A comparison of the regional Arctic System Reanalysis and the global ERA-Interim Reanalysis for the Arctic. Q. J. R. Meteorol. Soc., 142, 644-658. https://doi.org/10.1002/qj.2527

Bromwich, D.H., K.M. Hines, and L.-S. Bai, 2009: Development and testing of Polar WRF: 2. Arctic Ocean. J. Geophys. Res., 114, D08122. https://doi.org/10.1029/2008JD010300

Smirnova, J., and P. Golubkin, 2017: Comparing polar lows in atmospheric reanalyses: Arctic System Reanalysis versus ERA-Interim. Mon. Wea. Rev., 145, 2375-2383, https://doi.org/10.1175/MWR-D-16-0333.1

Avila-Diaz, A., D.H. Bromwich, A.B. Wilson, F. Justino, S.-H. Wang, 2021: Climate extremes across the North American Arctic in modern reanalyses. J. Climate, , 34, 2385–2410, https://doi.org/10.1175/JCLI-D-20-0093.1

Chanona, M., and S. Waterman, 2020: Temporal Variability of Internal Wave-Driven Mixing in Two Distinct Regions of the Arctic Ocean. J. Geophys. Res. Oceans, 125, https://doi.org/10.1029/2020JC016181

Edel, L., C. Claud, C. Genthon, C. Palerme, N. Wood, T. L'Ecuyer, and D. Bromwich, 2020: Arctic snowfall from CloudSat observations and reanalyses. J. Clim., 33, 2093-2109, https://doi.org/10.1175/JCLI-D-19-0105.1

Kaiser-Weiss, A.K., M. Borsche, D. Niermann, F. Kaspar, C. Lussana, F.A. Isotta, E. van den Besselaar, G. van der Schrier, and P. Undén, 2019: Added value of regional reanalyses for climatological applications. Environ. Res. Commun., 1, https://doi.org/10.1088/2515-7620/ab2ec3

Gutjahr, O., and G. Heinemann, 2018: A model-based comparison of extreme winds in the Arctic and around Greenland. Int. J. Clmatol., 38, 5272-5292, https://doi.org/10.1002/joc.5729

Rabatel, M., P. Rampal, A. Carrassi, L. Bertino, and C. K. Jones, 2018: Impact of rheology on probabilistic forecasts of sea ice trajectories: Application for search and rescue operations in the Arctic. Cryosphere, 12, 935-953, https://doi.org/10.5194/tc-12-935-2018

Kohnemann, S.H., G. Heinemann, D.H. Bromwich, and O. Gutjahr, 2017: Extreme warming in the Kara Sea and Barents Sea during the winter period 2000-16. J. Clim., 30, 8913-8927, https://doi.org/10.1175/JCLI-D-16-0693.1

Kolstad, E.W., 2017: Higher ocean wind speeds during marine cold air outbreaks. Quarterly J. Roy. Meteor. Soc., 143, 2084-2092, https://doi.org/10.1002/qj.3068

Rampal, P., S. Bouillon, E. Ólason, and M. Morlighem, 2016: neXtSIM: a new Lagrangian sea ice model. The Cryosphere, 10, 1055-1073, https://doi.org/10.5194/tc-10-1055-2016

Wang, F., W. Li, and S. Wang, 2016: Polar cyclone identification from 4D climate data in a knowledge-driven visualization system. Climate, 4, https://doi.org/10.3390/cli4030043

7.3.7 *__Dataset__: NCEP North American Regional Reanalysis (NARR) - humidity*

Overview

This document focuses on humidity data from NARR. NARR is a regional reanalysis covering the North America using a Northern Lambert Conformal Conic grid with an approximately 0.3 degrees (32 km) spatial resolution at the lowest latitude. Dataset was originally produced at NOAA's National Center for Atmospheric Prediction (NCEP), and detailed description is provided at https://psl.noaa.gov/data/gridded/data.narr.html#detail with online Analysis and Plotting Tools at https://psl.noaa.gov/cgi-bin/data/getpage.pl.

Provider's contact information

Physical Sciences Laboratory: Data Management

NOAA/ESRL/PSL

325 Broadway

Boulder, CO 80305-3328

psl.data@noaa.gov.

Licensing

This work is licensed under a Creative Commons Attribution 4.0 International Licence.

There are no restrictions for the use of data.

If the data are taken from PSD, the providers ask that the data is acknowledged by including text such as NCEP Reanalysis data provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, from their Web site at http://www.esrl.noaa.gov/psd/ in any documents or publications using these data.

If the data are taken from NCAR, the citation should include the following: National Centers for Environmental Prediction/National Weather Service/NOAA/U.S. Department of Commerce. 2005, updated monthly. NCEP North American Regional Reanalysis (NARR). Research Data Archive at the National Center for Atmospheric Research, Computational and Information Systems Laboratory. https://rda.ucar.edu/datasets/ds608.0/. Accessed dd mmm yyyy.

Variable name and units:

The variables are divided into three sections: Pressure level, Monolevel (surface and others) and Subsurface. Humidity related variables are available in the list of Monolevel variables and they are the output of the analysis and first guess forecast:

Specific humidity [kg/kg] at 2 m, 10 m, 30 m

Relative humidity [%] at 2 m

Table with variables available in NetCDF format at NOAA

Variable	Statistic	Level	Download File
Relative Humidity at 2 m	3-hourly value	2 m	rhum.2m.yyyy.nc
Relative Humidity at 2 m	Daily Mean	2 m	rhum.2m.yyyy.nc
Relative Humidity at 2 m	Monthly Mean	2 m	rhum.2m.mon.mean.nc
Relative Humidity at 2 m	Long-term Monthly Mean	2 m	rhum.2m.mon.ltm.nc
Specific Humidity at 2 m	3-hourly value	2 m	shum.2m.yyyy.nc
Specific Humidity at 2 m	Daily Mean	2 m	shum.2m.yyyy.nc
Specific Humidity at 2 m	Monthly Mean	2 m	shum.2m.mon.mean.nc
Specific Humidity at 2 m	Long-term Monthly Mean	2 m	shum.2m.mon.ltm.nc

Values labelled 3 hourly values are output at that exact time (no averaging).

For a complete list of model output variables, see NCEP's variable list. Details for Monolevel variables are provided on https://psl.noaa.gov/data/gridded/data.narr.monolevel.html .

Spatial coverage and resolution:

The data is available for all of North America at an approximate 0.3 degrees (32 km) spatial resolution at the lowest latitude, on a Northern Lambert Conformal Conic grid. Corners of this grid are 1.000001N, 145.5 W; 0.897945N, 68.32005W; 46.3544N, 2.569891W; 46.63433N, 148.6418E. A page describing the coverage along with information on reading the projection is available.

Temporal coverage and resolution:

Data is available as 3h values, Daily and Monthly means for the period 1979/01/01 to 2021/05/31.

Information about observations

The data that are assimilated in order to initialize the model are temperatures, winds, and moisture from radiosondes as well as pressure data from surface observations. Also included in this dataset are dropsondes, pibals, aircraft temperatures and winds, satellite radiance (a measure of heat) from polar (orbiting Earth) satellites, and cloud-drift winds from geostationary (fixed at one location viewing Earth) satellites. The sources of observations are summarized in the table below.

Dataset	Details	Source
Precipitation	Continental United States: comes from a 1/8-degree gauge dataset analyzed using PRISM and a least-squares distance-weighting algorithm. Canada and Mexico: comes from 1-degree gauge datasets and is disaggregated using NCEP R2 hourly precipitation weighting factors. Over oceans (<42.5°N): comes from the Climate Prediction Center (CPC) CMAP (CPC Merged Analysis of Precipitation), a merged combination of satellite and gauge precipitation. It is using a 15-degree “blending belt” between 27.5 and 42.5 N, with no CMAP north of 42.5 N.	NCEP/CPC,Canada, Mexico
TOVS-1B radiances	Temperature, precipitable water over ocean	NESDIS

NCEP Surface	Wind, moisture	GR
TDL Surface	Pressure, wind, moisture	NCAR
COADS (ships/buoys)	Pressure, wind, moisture	NCEP/EMC
Air Force Snow	Snow depth (The Air Force Weather Agency snow depth is estimated daily by merging satellite-derived snow cover data with daily snow depth reports from ground stations.)	COLA and NCEP/EMC
SST	1-degree Reynolds, with Great Lakes SSTs	NCEP/EMC, GLERL
Sea and lake ice	Contains data on Canadian lakes, Great Lakes	NCEP/EMC, GLERL, Ice Services Canada
Tropical cyclones	Locations used for blocking of CMAP Precipitation	Lawrence Livermore National Laboratory

The following figure presents sample distributions of surface assimilated data.

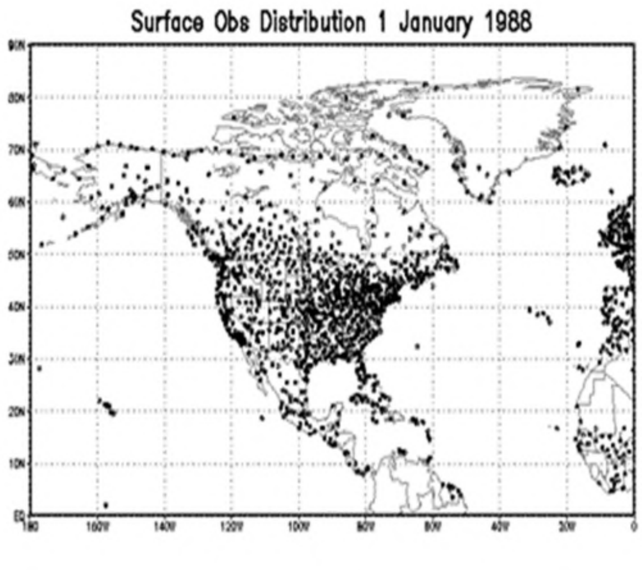


Figure 1. Sample distribution of surface observations

Methodology

The NARR project is an extension of the NCEP Global Reanalysis which is run over the North American Region. The NARR model uses a high-resolution NCEP Eta Model (32 km/45 layer) together with the Regional Data Assimilation System (RDAS) using a 3DVAR method, and it is one of the few reanalysis that assimilates precipitation along with other variables, also over Canada this feature is much reduced comparable to the US. It is using the ETA / NOAH land surface model and it is assimilating snow depths from US Air Force daily snow depth analysis.

For more information, please refer to the publication in the references section below.

Information about the technical and scientific quality

The improvements in the model/assimilation have resulted in a dataset with substantial improvements in the accuracy of temperature, winds and precipitation compared to the NCEP-DOE Global Reanalysis 2 (the parent global reanalysis). Wind improvement is especially greatest in the upper troposphere in winter. The 10 m winds improved greatly in winter, a little bit in summer. Relative humidity also improved in both analysis and first guess forecast.

Precipitation over Canada: the number of gauge observations is insufficient to do better than the model is doing.

Tests on assimilation of 2 m land surface station air temperatures, in NARR proved to be harmful in the sense of making the first guess considerably worse, throughout the troposphere. Consequently, 2 m land surface station air temperatures are not assimilated by NARR.

Useful information can be found at NCEP's NARR FAQ page: http://www.emc.ncep.noaa.gov/mmb/rreanl/faq.html

Data is updated on a monthly base.

Limitations and strengths for application in North Canada

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References to documents describing the methodology or/and the dataset

Mesinger, F., G. DiMego, E. Kalnay,K. Mitchell, P. C. Shafran, W. Ebisuzaki, D. Jović, J. Woollen, E. Rogers, E. H. Berbery, M. B. Ek, Y. Fan, R. Grumbine, W. Higgins, H. Li, Y. Lin, G. Manikin, D. Parrish, and W. Shi, 2006: North American Regional Reanalysis. Bulletin of the American Meteorological Society, 87(3), 343-360, doi:10.1175/BAMS-87-3-343.

Link to download the data and format of data:

NARR is available through NOAA ftp page, UCAR and from NCDC page.

NOAA: ftp://ftp.cdc.noaa.gov/Datasets/NARR/ (NetCDF standard format; the data are divided by variable and year and month into separate files; Missing data is flagged with a value of 9.96921e+36f.)

NCDC: https://www.ncdc.noaa.gov/data-access/model-data/model-datasets/north-american-regional-reanalysis-narr (GRIB format)

UCAR: https://rda.ucar.edu/datasets/ds608.0/ (GRIB format)

Publications including dataset evaluation or comparison with other data in northern Canada

7.3.8 *Dataset: North American Precipitation and Land Surface Reanalysis - Regional Deterministic Reforecast System (RDRS) - humidity*

Overview

This document focuses on humidity data from RDRSv2. RDRSv2 is a precipitation and surface reanalysis developed at the Canadian Centre for Meteorological and Environmental Prediction (CCMEP) of Environment and Climate Change Canada (ECCC). It provides various forecasted meteorological variables obtained with the Regional Deterministic Reforecast System (RDRS) two-way coupled with the Canadian Land Data Assimilation System (CaLDAS) and Precipitation Analysis (CaPA), and it is initialized and driven by ERA-Interim reanalysis. Results are provided at a spatial resolution of 10 km across North America. Data is currently available for the period of 1980-2017.

Provider's contact information

Data developed by the Canadian Centre for Meteorological and Environmental Prediction (CCMEP) of Environment and Climate Change Canada (ECCC)

Electronic Mail Address of the provider: The Canadian Surface Prediction Archive (caspar.data@uwaterloo.ca)

Licensing

The end-user licence for Environment and Climate Change Canada's data servers specifies the conditions of use of this data.

The Canadian Surface Prediction Archive Terms of Service

Variable name and units:

Relative humidity and specific humidity are available as **predicted values** at hourly time steps for two levels: 1.5 metres, and ~40 metres in elevation.

Variable	Variable long name	Unit	Level
RDRS_v2_P_HR_1.5m	Relative humidity (fraction)	[-]	1.5m
RDRS_v2_P_HR_09944	Relative humidity (fraction)	[-]	~40 m

RDRS_v2_P_HU_1.5m	Specific humidity	[kg/kg]	1.5m
RDRS_v2_P_HU_09944	Specific humidity	[kg/kg]	~40 m

Information about other variables available for download can be found on CaSPAr data portal.

Spatial coverage and resolution:

The data is available for all of North America at an approximate 10 km x 10 km spatial resolution on a rotated pole grid.

Temporal coverage and resolution:

RDRSv2 is available for the period of 1980-2017. Data is available at **hourly time** steps.

Information about observations (number, homogeneity)

RDRSv2 is initialized and driven by ERA-Interim reanalysis and rely only on surface observations and no remote sensing observations, such as satellite or radar data. Observations were taken from ECCC's operational and climate data archives and include temperature and dew point temperature. The Integrated Surface Data (ISD, DS463.3) is used in the version v2.1 for the years prior to 2000. Table 3 from Gasset *et al.* (2021) summarizes the surface observation datasets used in the assimilation processes.

Table 3. Surface networks and variables used by CaLDAS and CaPA.

Network	Domain covered	Availability at CCMEP	Variables used by CaLDAS	Variables used by CaPA-6h	Variables used by CaPA-24h
METAR	North America	1992-present	T, T_d	$P, T, \|\|U\|\|$	$P, T, \|\|U\|\|$
SWOB	North America	2013-present	T, T_d, S_d	Not used	$P, T, \|\|U\|\|$
SYNOP	North America	1992-present	T, T_d, S_d	$P, T, \|\|U\|\|$	$P, T, \|\|U\|\|$
AdjDlyRS	Canada	1980-present	Not used	Not used	P
RMCQ	Province of Quebec	2011-present	Not used	Not used	$P, T, \|\|U\|\|$
SHEF	USA	1998-present	Not used	Not used	$P, T, \|\|U\|\|$

T: temperature, T_d: dew point temperature, S_d: snow depth, P: total precipitation, $||U||$: wind speed

Figure 1 from Lespinas *et al.* (2010) is presenting the spatial distribution of the meteorological stations assimilated by CaPA and geographical limits of the Canadian terrestrial ecozones.

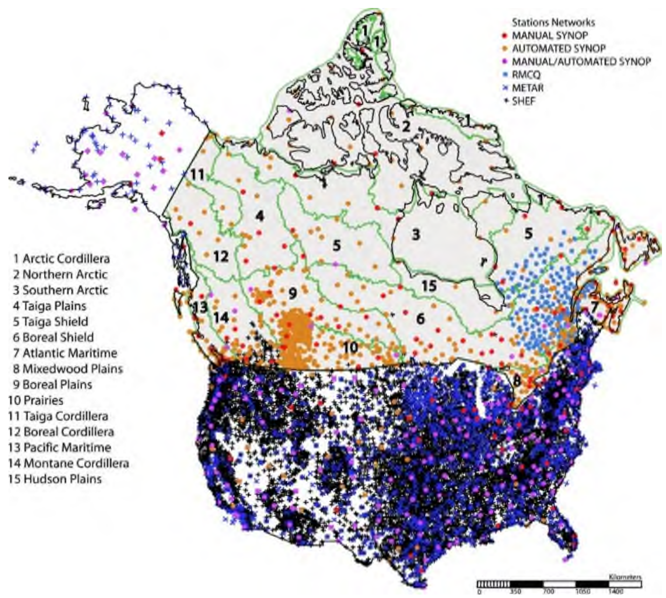

Figure 1. Spatial distribution of the meteorological stations assimilated by CaPA. Source: Journal of Hydrometeorology 16, 5; 10.1175/JHM-D-14-0191.1)

Supplementary information relevant for precipitation, soil moisture and snow: The 24 h a posteriori precipitation analysis, CaPA-24, is also using the Adjusted Daily Rain and Snow (AdjDlyRS) observations dataset (Wang *et al*., 2017). AdjDlyRS data features 3346 stations that are mainly manual stations from the Canadian synoptic network, and are known as the most reliable observations (they were adjusted for systematic errors, and in particular undercatch and evaporation caused by wind effects, gauge-specific wetting loss, as well as for trace precipitation amounts.).

Methodology

ERA-Interim reanalysis is first used to initialize the atmospheric conditions of the Global Deterministic Reforecast System (GDRS) at a spatial resolution of 39 km. Additional surface conditions are input via the GEM-Surf model, which is also initialized by ERA-Interim. The GDRS output is then dynamically downscaled to 10 km using the RDRS. These finer resolution outputs are two-way coupled with the Canadian Land Data Assimilation System (CaLDAS) and Precipitation Analysis (CaPA) system (this means that outputs from RDRS is used to drive both the CaLDAS and CaPA system, and these results are then fed back into RDRS). This coupling results in significantly improved near-surface atmospheric and land-surface predictions.

Both GDRS and RDRS are based on the latest stable version of the Global Environment Multiscale (GEM v4.8-LTS) model and they are both using the same geophysical fields (i.e. orography, vegetation characteristics, soil thermal and hydraulic coefficients, glaciers fraction) as the corresponding forecast operational versions. The coupling with CaLDAs and CaPA allows for combining surface observations of temperature, humidity, snow depth and precipitation with the first guess provided by the RDRS. CaLDAS uses a one-dimensional Ensemble Kalman Filter (EnKF) to estimate soil moisture and soil temperature, and an optimal interpolation (OI) scheme to estimate snow depth. CaPA combines precipitation observations with a background field obtained from the short-term reforecast provided by the RDRS through an OI method. CaPA also serves to provide CaLDAS with 6-h precipitation analysis.

For more information, please refer to the publication in the references section below.

Information about the technical and scientific quality

Version 2 was evaluated and compared to the operational numerical weather prediction system (RDPS) over the period of 2010-2017. Gasset *et al*. (2021) mentions that the RDRS improves upon RDPS in most regions and for most variables, notably for Alaska and the Canadian Arctic, as well as Western USA.

In general, reanalyses often do not assimilate any observations of precipitation and of the land-surface state, but instead only provide short-term forecasts of these variables. RDRS do assimilate precipitation observations through the coupling with CaPA. Gasset *et al*. (2021) mentions that the coupling approach of the GDRS, RDRS, CaLDAS, and CaPA demonstrates significant improvements in the surface layer compared to the results obtained without coupling.

Strict quality control procedures are in place in CaPA to avoid the assimilation of biased observations, and in particular wind-induced undercatch of solid precipitation (based on a temperature analysis, different wind speed thresholds are used depending on the network, the type of gauge and whether the station is manned or automated).

In Gasset *et al*. (2021), short-term absolute temperature, dew point temperature, and wind speed forecasts from RDRSv2 were compared to observations from synoptic stations across North America. Results indicate that these data may be suitable in driving other environmental models. Likewise, a preliminary streamflow modelling study has also demonstrated that the RDRSv2 has some skill in driving hydrological models to predict runoff into Lake Erie, suggesting that the RDRSv2 may be useful for hydrological purposes.

Internal analyses at ECCC showed that RDRSv2 has good skill in estimating relative humidity in southeast Canada. However, no analysis was performed for northern Canada.

Data is available in netCDF format on CaSPAr data portal. Two scientific papers accompany the dataset, one detailing CaSPAr and the other detailing the RDRSv2 dataset. It is expected that the data will be updated regularly.

Limitations and strengths for application in North Canada

RDRSv2 is initialized and driven by ERA-Interim, a reanalysis dataset that has been since superseded by ERA5. The pending data for the years 1980-1999 and 2018 will continue to use ERA-Interim, and tests are currently being conducted to determine the suitability and impacts of switching to another dataset. Furthermore, a bug that was identified during the development of the 2000-2017 reanalysis data: snow depth was expressed in metres in the code whereas it is supposed to be expressed in centimetres. It was verified that while biases and other errors for snow depth itself wasn't heavily impacted, snow density and snow water equivalent demonstrated significant differences. As such, these two fields are not distributed for 2000-2017 in version 2 release. The error is corrected in version 2.1 and will be available for download soon.

References to documents describing the methodology or/and the dataset

Gasset, N., V. Fortin, M. Dimitrijevic, M. Carrera, B. Bilodeau, R. Muncaster, É.,Gaborit, G. Roy, N. Pentcheva, M. Bulat, X. Wang, R. Pavlovic, F. Lespinas, and D. Khedhaouiria, 2021: A 10 km North American Precipitation and Land Surface Reanalysis Based on the GEM Atmospheric Model. Hydrology and Earth System Sciences, 25(9), 4917-4945, https://doi.org/10.5194/hess-25-4917-2021

Link to download the data and format of data:

The data can be accessed through the CaSPAr data catalogue as well as directly from their data portal:

Data catalogue: **https://github.com/julemai/CaSPAr/wiki/Available-products**

Data portal: **https://caspar-data.ca/caspar (NetCDF)**

Publications including dataset evaluation or comparison with other data

Mai, J., B.A. Tolson, H. Shen, É. Gaborit, V. Fortin, N. Gasset, H. Awoye, T. A. Stadnyk, L. M. Fry, E. A. Bradley, F. Seglenieks, A. G. T. Temgoua, D. G. Princz, S. Gharari, A. Haghnegahdar, M. E. Elshamy, S. Razavi, M. Gauch, J. Lin, X. Ni, Y. Yuan, M. McLeod, N. B. Basu, R. Kumar, O. Rakovec, L. Samaniego, S. Attinger, N. K. Shrestha, P. Daggupati, T. Roy, S. Wi, T. Hunter, J. R. Craig, and A. Pietroniro, 2021: Great Lakes Runoff Intercomparison Project Phase 3: Lake Erie (GRIP-E), Journal of Hydrologic Engineering, 26(9), 05021020-1-19. https://doi.org/10.1061/(ASCE)HE.1943-5584.0002097

Reference for CaPA:

Mahfouf, J.-F., B. Brasnett, and S. Gagnon, 2007: A Canadian precipitation analysis (CaPA) project: Description and preliminary results, Atmosphere-Ocean, 45(1), 1-17, DOI: 10.3137/ao.v450101.

Fortin, V., G. Roy, T. Stadnyk, K. Koenig, N. Gasset, and A. Mahidjiba, 2018: Ten Years of Science Based on the Canadian Precipitation Analysis: A CaPA System Overview and Literature Review, Atmosphere-Ocean, 56(3), 178-196, DOI: 10.1080/07055900.2018.1474728.

Lespinas, F., V. Fortin, G. Roy, P. Rasmussen, and T. Stadnyk, 2015: Performance Evaluation of the Canadian Precipitation Analysis (CaPA), Journal of Hydrometeorology, 16(5), 2045-2064. Retrieved May 26, 2021, from

https://journals.ametsoc.org/view/journals/hydr/16/5/jhm-d-14-0191_1.xml

7.3.9 *Dataset: NOAA-CIRES-DOE Twentieth Century Reanalysis (20CRv3) - humidity*

Overview

This document provides an overview of the 2 m humidity data from Twentieth Century Reanalysis (20CRv3). The 20th Century Reanalysis Project is an effort led by NOAA's Physical Sciences Laboratory (PSL) and CIRES at the University of Colorado, supported by the Department of Energy (DOE), to produce reanalysis datasets spanning the entire 20th century and much of the 19th century. These reanalyses assimilate only surface observations of synoptic pressure into NOAA's Global Forecast System, and prescribed sea surface temperature and sea ice distribution in order to estimate atmospheric variables, from the surface to the top of the atmosphere throughout the 19th and 20th centuries. 20CRv3 is version 3 of the project. For version 3, the ensemble mean and standard deviation for each value were calculated over a set of 80 analyses and short-term forecasts.

Provider's contact information

20CRv3 is developed by the NOAA's Physical Sciences Laboratory (PSL) and CIRES at the University of Colorado, supported by the Department of Energy (DOE).

For help with the dataset please contact

Gilbert P. Compo

CIRES, University of Colorado at Boulder, and Physical Sciences Laboratory, National Oceanic and Atmospheric Administration

gilbert.p.compo at noaa.gov

Laura C. Slivinski

CIRES, University of Colorado at Boulder, and Physical Sciences Laboratory, National Oceanic and Atmospheric Administration

laura.slivinski at noaa.gov

Licensing and citation

20CRv3 data are provided by several collaborative organizations. User registration and agreement to terms and conditions of data service usage are required individually for each organization.

Data at NCAR RDA is licensed under a Creative Commons Attribution 4.0 International Licence.

The following citation should be used for data downloaded from NCAR RDA:

" **Slivinski**, L. C., et al. 2019. NOAA-CIRES-DOE Twentieth Century Reanalysis Version 3. Research Data Archive at the National Center for Atmospheric Research, Computational and Information Systems Laboratory. https://doi.org/10.5065/H93G-WS83. Accessed† dd mmm yyyy.

†Please fill in the "Accessed" date with the day, month, and year (e.g., - 5 Aug 2011) you last accessed the data from the RDA. "

The following citation should be used for data downloaded from Physical Sciences Laboratory (PSL) or from National Energy Research Scientific Computing Center (NERSC):

Papers using the NOAA-CIRES-DOE Twentieth Century Reanalysis Project version 3 dataset are requested to include the following text in their acknowledgments: "Support for the Twentieth Century Reanalysis Project version 3 dataset is provided by the U.S. Department of Energy, Office of Science Biological and Environmental Research (BER), by the National Oceanic and Atmospheric Administration Climate Program Office, and by the NOAA Physical Sciences Laboratory."

If you acquire 20th Century Reanalysis V3 data products from PSL, we are asked to acknowledge PSL by including also a text such as *20th Century Reanalysis V3 data provided by the NOAA/OAR/ESRL PSL, Boulder, Colorado, USA, from their Web site at /* in any documents or publications using these data and send a copy of the relevant publications to:

Physical Sciences Laboratory: Data Management

NOAA/ESRL/PSL

325 Broadway

Boulder, CO 80305-3328

psl.data@noaa.gov

Spatial coverage and resolution:

20CRv3 data, is a global dataset. 20CRv3 has a Gaussian T-254 grid (approximately 75 km at the equator).

Variable name and units:

The following table summarizes the 2 m humidity data.

Notation (name)	Units	Organisation (type)

SPFH at NERSC and SHUM at PSL (Specific Humidity at 2 m)	Kg/kg	PSL; NERSC;
RHUM (Relative Humidity at 2 m)	%	PSL; NCAR (Analysis Fields and First Guess Forecast Fields)
QMIN (Minimum Specific Humidity at 2 m)	Kg/kg	PSL; NCAR (First Guess Forecast Fields)
QMAX (Maximum Specific Humidity at 2 m)	Kg/kg	PSL; NCAR (First Guess Forecast Fields)

Temporal coverage and resolution:

On PSL website, 20CRv3.SI is available for years 1836-1980 and 20CRv3.MO is available for years 1981-2015 (the only differences between these two versions are the prescribed sea surface temperatures and dates of availability):

- 3-hourly values for 1836/01/01 0Z to 2015/12/31 21Z.
- Daily average values for 1836/01/01 to 2015/12/31.
- Monthly values for 1836/01 to 2015/12 (Combined SI-MO).

At NCAR RDA, 20CRv3 is available from:

- 1835/12/31 18Z to 2016/01/01 0Z (Yearly Time Series 3-Hourly Analysis Fields (Gaussian T-254))
- 1806/12/31 18Z to 2015/12/31 12Z (Yearly Time Series 3-Hourly First Guess Forecast Fields (Gaussian T-254))
- 1806/12/31 21Z to 2015/12/31 15Z (Yearly Time Series 6-Hourly Analysis Fields (Gaussian T-254))

The data is updated on an irregular base.

Information about observations (number, homogeneity)

These reanalyses assimilate only surface observations of synoptic pressure. Boundary conditions of pentad sea surface temperature and monthly sea ice concentration and time-varying solar, volcanic, and carbon dioxide radiative forcings are prescribed.

The surface pressure observations: ISPD version 4.7, made available through international cooperation facilitated by the Atmospheric Circulation Reconstructions over the Earth (ACRE) initiative and working groups of the Global Climate Observing System and World Climate Research Program.

Sea Ice Concentration Boundary Condition: monthly HadISST2.3 sea ice (Slivinski *et al*., 2019; Titchner & Rayner 2014; Walsh *et al*., 2015)

Sea Surface Temperature Boundary Condition: prior to 1981(20CRv3.SI): 8 members of pentad interpolated to daily Simple Ocean Data Assimilation with Sparse Input (SODAsi) version 3 (SODAsi.3, Giese *et al*., 2016) seasonally adjusted to the 1981-2010 HadISST2.2 climatology. Regions where sea ice was ever indicated in HadISST2.3 are filled with: HadISST2.2 daily (1963+); HadISST2.1 monthly interpolated to daily (1850-1962); or the 1861–1891 HadISST2.1 climatology (1849 and earlier). **1981 and later (20CRv3.MO)**: 8 members of pentad interpolated to daily HadISST2.2 sea surface temperatures.

Methodology

20CRv3 assimilates only surface observations of synoptic pressure into an 80-member the coupled Global Forecast System land-atmospheric model with prescribed sea surface temperatures and sea ice concentration. A coupled one-dimensional thermodynamic sea-ice model is also used. Boundary conditions of pentad sea surface temperature and monthly sea ice concentration and time-varying solar, volcanic, and carbon dioxide radiative forcings are prescribed.

<u>Forecast model</u>: 20CRv3 uses the atmospheric model from the NCEP Global Forecast System v14.0.1 coupled with the Noah land surface model and 2.5-layer thermodynamic sea ice model (Compo *et al*., (2011). The forecast system is run at a resolution of T254 (approximately 75 km at the equator) with 64 vertical levels up to .3 mb and it has 80 individual ensemble members.

<u>Assimilation model</u>: The data assimilation algorithm is the Ensemble Square Root Filter (Whitaker and Hamill 2002) with 4D Incremental Analysis Update (4D-IAU; Bloom et al., 1996, Lei & Whitaker 2016). The snow relaxes to a monthly climatology (Saha *et al*., 2010) over 60 days.

<u>Streams</u>: Every 5th year a stream is produced for a continuous 5 year period. Stream years are 1835, 1840, ... , 2005, 2010. Stream year 2010 will be extended beyond 2015.

Information about the technical and scientific quality

There are three previous versions of the reanalysis: V1, V2, and V2c. Several adjustments were made to the model prior to implementation in the 20CRv3 system. Updates to the parameterizations are described in Saha *et al.* (2010) and include revised solar radiation transfer, boundary layer vertical diffusion, cumulus convection, and gravity wave drag parameterizations. In addition, the cloud liquid water is a prognostic quantity with a simple cloud microphysics parameterization. Another important improvement is in the resolution and ensemble size. Previous 20CR versions were using a 56-member ensemble with a coarser spatial resolution (T62 28 levels), while the 20CRv3 is using 80 ensemble members with a finer spatial resolution (T254 64 levels). 20CRv3 also assimilates a larger set of observations and includes an improved data assimilation system relative to its predecessor 20CRv2c.

Observations are first grossly tested for quality control: if the observation is outside the range 850 and 1090 hPa, or if the absolute difference between the observation and the first guess value is greater than 3.2 times the square root of the sum of the forecast ensemble variance and the observation error variance, the observation is rejected. (Slivinski *et al*., 2018). They are then subject to adaptive quality control and adaptive localization control.

Limitations and strengths for application in North Canada

Key Strengths: Length of record and estimates of uncertainty

Key Limitations: As with all reanalyses, users should take care in interpreting long-term trends - inconsistencies between 20CR and other data have been reported, especially on a regional scale.

References to documents describing the methodology or/and the dataset

Compo, G.P., J.S. Whitaker, P.D. Sardeshmukh, N. Matsui, R.J. Allan, X. Yin, B.E. Gleason, R.S. Vose, G. Rutledge, P. Bessemoulin, S. Brönnimann, M. Brunet, R.I. Crouthamel, A.N. Grant, P.Y. Groisman, P.D. Jones, M. Kruk, A.C. Kruger, G.J. Marshall, M. Maugeri, H.Y. Mok, Ø. Nordli, T.F. Ross, R.M. Trigo, X.L. Wang, S.D. Woodruff, and S.J. Worley, 2011: The Twentieth Century Reanalysis Project. Quarterly Journal of the Royal Meteorological Society, 137(654), 1-28, DOI: 10.1002/qj.776.

Slivinski, L. C.,G. P. Compo, P.D. Sardeshmukh, J. S. Whitaker, C. McColl, R. J. Allan, P. Brohan, X. Yin, C. A. Smith, L. J. Spencer, R. S. Vose, M. Rohrer, R. P. Conroy, D. C. Schuster, J. J. Kennedy, L. Ashcroft, S. Brönnimann, M. Brunet, D. Camuffo, R. Cornes, T. A. Cram, F. Domínguez-Castro, J. E. Freeman, J. Gergis, E. Hawkins, P. D. Jones, H. Kubota, T. C. Lee, A. M. Lorrey, J. Luterbacher, C. J. Mock, R. K. Przybylak, C. Pudmenzky, V. C. Slonosky, B. Tinz, B. Trewin, X. L. Wang, C. Wilkinson, K. Wood, and P. Wyszyński , 2021: An Evaluation of the Performance of the Twentieth Century Reanalysis Version 3. Journal of Climate 34, 4, 1417-1438, https://doi.org/10.1175/JCLI-D-20-0505.1

Link to download the data and format of data:

20CRv3 data are available at several organizations.

At NOAA/PSL, the ensemble mean and the ensemble uncertainty files are available in netCDF4 format: https://psl.noaa.gov/data/gridded/data.20thC_ReanV3.monolevel.html

At National Center for Atmospheric Research (NCAR), the ensemble mean and the ensemble uncertainty files are available in netCDF4 format: https://rda.ucar.edu/datasets/ds131.3/

At NERSC Science Gateway, data for every member of 20CRv3 are available in netCDF4 format: https://portal.nersc.gov/project/20C_Reanalysis/

Publications including dataset evaluation or comparison with other data in Canada

7.4 Wind

7.4.1 Dataset: MSC Station Observations – wind

Overview

This dataset provides in-situ surface observations archived by the Meteorological Service of Canada (MSC). It containes data from the MSC operational observation system as well as from theirparteners. Therefore, not all stations are QC or maintained by MSC. The network of stations containes stations with only automatic instruments, and human observing (or manual) stations.

Provider's contact information

Environment and Climate Change Canada

donneesclimatiquesenligne-climatedataonline@ec.gc.ca

Licensing

Open Government Licence - Canada.

Variable name and units:

Direction of Maximum Gust (10s deg)

Speed of Maximum Gust (km/h)

Hourly wind speed/direction (km/h)

Spatial coverage and resolution:

Canada, point locations.

Temporal coverage and resolution:

Time period varies per station with data for in the North starting in 1940's or 1950's until present.

The data is available at the hourly, daily and monthly time step.

The data will continue to be updated regularly.

Information about observations (number, homogeneity)

The number of active stations changed over time. The following figure from Mekis et al. (2018) is presenting the locations of the surface weather stations across Canada with a Needs Index map in the background as of September 2016.

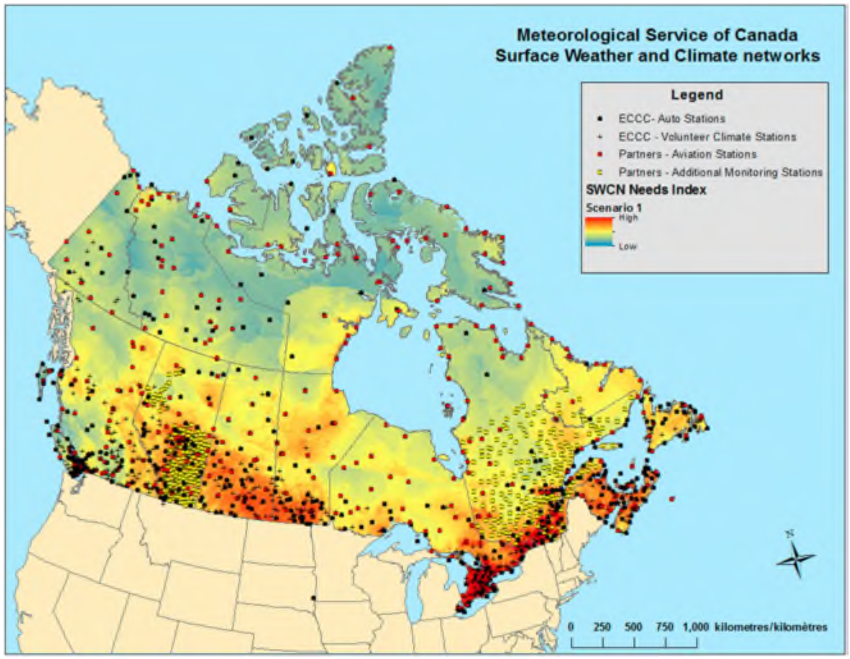

Figure 1. Surface weather stations across Canada, as of September 2016, with a Needs Index map in the background. For further details on station network evolution see Mekis et al. 2018. [Source: Mekis et al., 2018].

Stations over Northern Canda with wind measurements are the ECCC atomatic stations and stations from the Aviation Monitoring Station network (which include automated and staffed weather stations) operated by NAV CANADA and the Department of National Defence (DND). The ECCC Volunteer Climate Stations provide just temperature and precipitation measurements.

Methodology

Raw and quality-controlled station observations are archived and managed by the MSC's Archive Operations and Climate Services. Observations from different instruments are stored in different formats in the national archive. The methodology, the instruments and the location of instruments have changed in time. Many of initialy manual stations were replaced with automatic stations. The following is summarising some information regarding the manual measurements that should be considered when using historic station data.

Wind speed is usually observed at 10 metres above the ground. It represents the average speed during the one- or two-minute period ending at the time of observation for aviation station. For Aviation Weather Reports, a one-minute mean of wind direction and speed was used until the late 1980s. The wind speed now represents the average speed during the two-minute period ending at the time of observation, for Aviation stations. The only historical 10-minute mean wind data are winds from the synoptic reports. Synoptic reports are only created four times a day: 12z, 18z, 00z, 06z.

Some stations are equipped with a standard type U2A anemometer, taking one minute or (since 1985) two-minute mean speeds values at each observation. At other wind-measuring sites, values are usually obtained from autographic records of U2A or 45B anemometers. Averaging periods at these sites may vary from one minute to an hour. The current standard at automated stations is the RM Young.

In observing, wind speed is measured in nautical miles per hour and converted to kilometres per hour. The extreme gust speed is the instantaneous peak wind observed from the anemometer dials, or abstracted from a continuous chart recording. A value of zero (0) denotes a calm or no wind.

Conversion factors: 1 nautical mile = 1852 m or 1.852 km

Therefore: 1 knot = 1.852 km/h and 1 km/h = 0.54 knot.

Wind directions measured by U2A's are recorded to the nearest ten degrees, while those from the 45B are provided to 8 points of the compass. All wind directions are defined as the direction from which the wind blows with respect to true or geographic north. For example, an easterly wind is blowing from the east, not toward the east. A wind direction observation represents the average direction over the two-minute period ending at the time of observation. Certain sites measure only the wind. The daily climate sites typically don’t measure the wind.

Information about the technical and scientific quality

This dataset represents Environment and Climate Change Canada’s official station observations. Data are subject to change on an on-going basis as MSC is constantly QCing the data from ECCC stations. Not all data has the same level of QA/QC (i.e. aviation dat is not QA/QC by MSC but by NAV CANADA).

Limitations and strengths for application in North Canada

It is a challenge to sustain a cost-effective observing system over Norther Canada because of a large part of the teritory is constituted by remote areas (it is hard for technicians to fly to the site for maintenance, and they often have to wait for the thaw). The special climatic conditions produce a large risk of power and telecommunication outages, and anemometer to freeze due to cold temperature or freezing rain. Concequently, observations in Nortehrn Canada are sparse and records are often incomplete.

References to documents describing the methodology or/and the dataset

The manual specific for aviation observations/reports (MANOBS): http://publications.gc.ca/collections/collection_2019/eccc/En56-238-2-2018-eng.pdf and http://publications.gc.ca/collections/collection_2019/eccc/En56-238-2-2018-fra.pdf

https://climate.weather.gc.ca/doc/Technical_Documentation.pdf

Link to download the data and format of data:

Hourly, Daily and Monthly

Database searchable by location for CSV via CDO/MSC/ECCC: https://climate.weather.gc.ca/historical_data/search_historic_data_e.html

Only Hourly:

Map based extraction tool for GeoJSON and CSV on CCCS/ECCC: https://climate-change.canada.ca/climate-data/#/hourly-climate-data

Note: Only a subset of the total stations is shown due to size limitations. The priorities for inclusion are as follows: (1) Station is currently operational, (2) Stations with long periods of record, (3) Stations that are co-located with the categories above and supplement the period of record. For additional stations not included, go to CDO/MSC/ECCC.

Only Daily

Map based extraction tool for GeoJSON and CSV on CCCS/ECCC: https://climate-change.canada.ca/climate-data/#/daily-climate-data

CSV via MSC/ECCC: https://dd.weather.gc.ca/climate/observations/daily/

Note: Only a subset of the total stations is shown due to size limitations. The priorities for inclusion are as follows: (1) Station is currently operational, (2) Stations with long periods of record, (3) Stations that are co-located with the categories above and supplement the period of record. For additional stations not included, go to CDO/MSC/ECCC.

Only Monthly

Map based extraction tool for GeoJSON and CSV on CCCS/ECCC: https://climate-change.canada.ca/climate-data/#/monthly-climate-summaries

CSV via MSC: https://dd.weather.gc.ca/climate/observations/monthly/

Provincial and territory observation summaries in XML format for the last month are available on the MSC Datamart

Publications including dataset evaluation or comparison with other data in northern Canada

There are no publications that evaluate station data specifically on northern Canada. The following papers are providing general discussions on the issues with wind records at stations in Canada for climate analysis.

Wan, H., X. L. Wang, V. R. Swail, 2010: Homogenization and trend analysis of Canadian near-surface wind speeds. Journal of Climate. 23, 1209-1225.

7.4.2 *Dataset: MSC Climate Normals – wind*

Overview

This dataset provides Climate Normals at the in-situ surface observations archived by the Meteorological Service of Canada (MSC), which containes data from the MSC operational observation system as well as from their parteners. The Climate Normals summarize or describe the average climatic conditions of a particular location over a period of 30 years, and they are based on Canadian climate stations with at least 15 years of data in the 30-year period. At the completion of each decade, Environment and Climate Change Canada updates its Climate Normals for as many locations and as many climatic characteristics as possible. MSC is QC the Normals but the QC of the data used in the Normal computation is done by the owers of the sites.

Provider's contact information

Environment and Climate Change Canada

donneesclimatiquesenligne-climatedataonline@ec.gc.ca

Licensing

Open Government Licence - Canada.

Variable name and units:

Maximum Hourly Speed (km/h)

Direction of Maximum Hourly Speed

Mean of hourly wind speed (km/h)

Most frequently occurring wind direction (deg true)

Direction of extreme of hourly wind speed (deg true)

Maximum wind gust (km/h)

Days with wind ≥ 28 knots

Days with wind ≥ 34 knots

Note: The number of available variables differs from station to station and from period to period.

Spatial coverage and resolution:

Canada, point locations.

Temporal coverage and resolution:

The data is presented as 30-year average and has a decadal time step: 1941-1970, 1951-1980, 1961-1990, 1971-2000 and 1981-2010 periods.

The data will continue to be updated every decade.

Information about observations (number, homogeneity)

The number of active stations changed over time. The following figure from Mekis et al. (2018) is presenting the locations of the surface weather stations across Canada with a Needs Index map in the background as of September 2016.

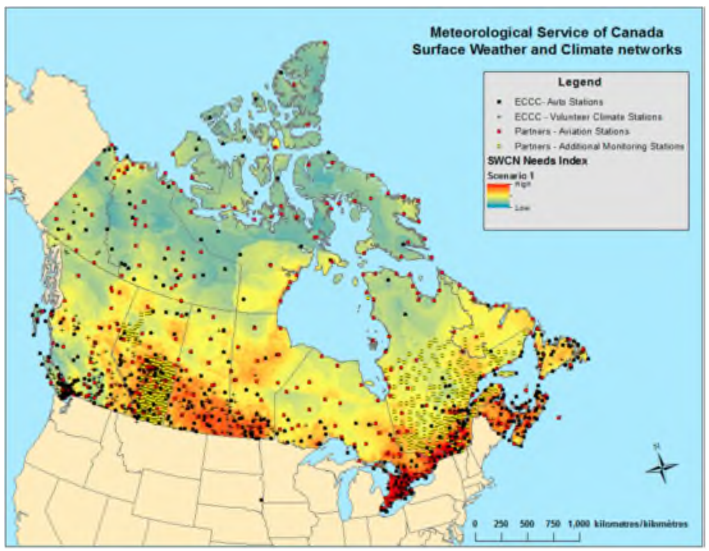

Figure 1. Surface weather stations across Canada, as of September 2016, with a Needs Index map in the background. For further details on station network evolution see Mekis et al. 2018. [Source: Mekis et al., 2018].

Stations over Northern Canda with wind measurements are the ECCC atomatic stations and stations from the Aviation Monitoring Station network (which include automated and staffed weather stations) operated by NAV CANADA and the Department of National Defence (DND). The ECCC Volunteer Climate Stations provide just temperature and precipitation measurements.

The following table presents the number of stations per region in the Northen Canada for the 1981-2010 normals (the number varies with the period of the record).

Region	No. stations with data for at least one wind variables available for 1981-2010
Yukon	10 (BEAVER CREEK A; BLANCHARD RIVER; BURWASH A; DAWSON A; FARO A; MAYO A; OLD CROW A; TESLIN A; WATSON LAKE A; WHITEHORSE A)
NWT	11 (FORT LIARD A; FORT MCPHERSON A; FORT SIMPSON A; FORT SMITH A; HAY RIVER A; INUVIK A; NORMAN WELLS A; SACHS HARBOUR A; TUKTOYAKTUK A; ULUKHAKTOK A; YELLOWKNIFE A)
Nunavut	24 (ALERT; ARVIAT A; BAKER LAKE A; CAMBRIDGE BAY A; CAPE DORSET A; CHESTERFIELD INLET A; CLYDE A; CORAL HARBOUR A; EUREKA A; GJOA HAVEN A; HALL BEACH A; IGLOOLIK; IGLOOLIK A; IQALUIT A; KUGAARUK A; KUGLUKTUK A; LUPIN A; NANISIVIK A; POND INLET A; RANKIN INLET A; REPULSE BAY A; RESOLUTE CARS; TALOYOAK A; WHALE COVE A)
North Quebec	3 (LA GRANDE RIVIERE A; KUUJJUARAPIK A; KUUJJUAQ A)
Labrador	4 (CARTWRIGHT; GOOSE A; MAKKOVIK A; NAIN A; WABUSH LAKE A)

Methodology

The MSC computation has evolved with the time. For wind, (1) the normal are computed over a 30 year period of consecutive records, starting January 1st and ending December 31st, (2) use 90% hourly completeness (including just days with at least one hourly wind speed), (3) the total is divided by total hours available in the month to get monthly values. Normal values were calculated as the mean for each month from all the individual months in the period of 30 years that sufficiently fulfilled the requirement.

Any extreme elements use all available values no matter the completeness.

Information about the technical and scientific quality

Only Normals for temperature and precipitation (not wind Normals) are computed using WMO standards (they are classified as "A Class" stations).

MSC is QC the Normals but the QC of the data used in the Normal computation is done by the owers of the sites.

Wind speed and direction are greatly affected by proximity to the ground and by the presences of obstacles such as hills, buildings and trees. It tends to increase in speed and veer with height above ground. For meteorological purposes, the standard exposure of anemometer cups is at a height of 10 metres above the ground surface.

Limitations and strengths for application in North Canada

It is a challenge to sustain a cost-effective observing system over Norther Canada because of a large part of the teritory is constituted by remote areas (it is hard for technicians to fly to the site for maintenance, and they often have to wait for the thaw). The special climatic conditions produce a large risk of power and telecommunication outages and it is common for the anemometer to freeze for a period of time if the temperature is too cold or in freezing rain conditions. Concequently, observations in Nortehrn Canada are sparse and records are often incomplete. Therefore, apart from any uncertainty due to site, instrument, or observing program changes, or general representativeness of the observing site with the surrounding region, the normals for most locations will have some uncertainty due to the fact that the observations are not complete for the 30-year period.

The number of available variables differs from station to station and from period to period.

References to documents describing the methodology or/and the dataset

https://climate.weather.gc.ca/doc/Canadian_Climate_Normals_1981_2010_Calculation_Information.pdf

https://climate.weather.gc.ca/doc/Canadian_Climate_Normals_1971_2000_Calculation_Information.pdf

https://climate.weather.gc.ca/doc/Canadian_Climate_Normals_1961_1990_Calculation_Information.pdf

https://drive.google.com/open?id=1OLqRySaAdJSpajkEGmOAHd7zKR2FW72s

https://drive.google.com/open?id=1M2W8t7bG1JmseLEgm90G8O7hAc718RBD

Link to download the data and format of data:

Most recent Normals (1981-2010):

GeoJSON and CSV on CCCS/ECCC: https://climate-change.canada.ca/climate-data/#/climate-normals

CSV via MSC: https://dd.weather.gc.ca/climate/observations/normals/

CSV via ClimateData.ca: https://climatedata.ca/explore/variable/?var=weather-stations

Note: A smaller number of stations qualify for Normals compared to earlier Normals decadal publications.

For all Normals periods:

CSV via CDO/MSC/ECCC: https://climate.weather.gc.ca/climate_normals/index_e.html.

Publications including dataset evaluation or comparison with other data in northern Canada

Information not available.

7.4.3 *Dataset: Adjusted and homogenized Canadian climate data (AHCCD) – Historical and Homogenized surface wind speeds for Canada*

Overview

Adjusted and homogenized Canadian climate data (AHCCD) consist of monthly, seasonal and annual means of wind speed at a standard 10m level for more than 150 locations in Canada. The data at stations incorporate adjustments (derived from statistical procedures) to the original historical station data to account for discontinuities from non-climatic factors, such as instrument changes or station relocation. Daily observations from nearby sites were often merged into a single record to create a long-time series

Provider's contact information

Environment and Climate Change Canada

Contact cccs-ccsc@ec.gc.ca for information related to monthly, seasonal and annual data.

Licensing

Open Government Licence - Canada.

The end-user licence for Environment and Climate Change Canada's data servers specifies the conditions of use of this data.

Variable name and units:

Wind speed (km/h)

Spatial coverage and resolution:

Canada, point location.

Temporal coverage and resolution:

Time period varies per station with data for most stations in the North starting in 50's and ending in 2014.

The data is available at **monthly, seasonal and annual** time steps.

Information about observations (number, homogeneity)

The following table presents the number of stations per region and variable:

Region	Wind
Yukon	18
NWT	31
Nunavut	40
North Quebec	15
Labrador	8

The figure below shows the position of stations in northern Canada.

Methodology

The AHCCD station data are derived from observations made at the weather stations from the Meteorological Service of Canada (MSC) and use the same ID as MSC stations; this allows users to compare the raw station data to homogenized and adjusted data. The AHCCD dataset was developed for use in climate research, including climate change studies that needs long-term data records. Over long periods, meteorological records are subject to changes (e.g., site exposure, location, instrumentation, observer, and observing procedures) that are not related to climate. These non-climatic changes were detected and removed in AHCCD using statistical procedures.

There are two steps used to homogenize surface wind speeds. First, metadata and logarithmic wind profile are used to adjust hourly wind speeds measured at non-standard height to the standard 10m level. Then, the monthly mean wind speed series are derived from the anemometer height adjusted hourly wind speeds and tested for homogeneity by a statistic inhomogeneity model based on regression models (Wang, 2008), using homogeneous monthly mean geotropic wind speed series as reference series (which were derived from homogenized hourly sea level pressure data recorded at Canadian and US stations). Series of annual and seasonal mean were tested separately for homogeneity using neighbour observations as a reference series.

The methodology involves the identification of inhomogeneities in the wind speed series, which are often non-climatic steps due to station alterations including changes in anemometer height, in site exposure, location, instrumentation, anemometer type, or a combination of the above. Monthly adjustments were derived from the results of statistical tests/modelling, and the monthly mean wind speeds were adjusted to the most recent segment (Wan *et al*., 2010). Whenever possible, the main causes of the identified inhomogeneities from statistical tests were retrieved through metadata database.

Information about the technical and scientific quality

The dataset is accompanied by a technical documentation and a scientific paper. A new updated version is in work and will be available in 2022.

Limitations and strengths for application in North Canada

The data constitute the longest records at stations that were adjusted to eliminate non-climatic shifts and take into account the change in observing time. Data availability over most of the Canadian Arctic is restricted to the mid-1950s to 2014. This dataset is usually used to validate other historical datasets estimated using various models or methodologies.

The major limitation for applications in the North is the number restrained of locations with a record. As any data at stations, it has missing values, which may vary by variable, station and time. The missing values in daily records were taken into account when monthly, seasonal and annual data was developed (see methodology section).

References to documents describing the methodology or/and the dataset

Wan, H., X. L. Wang, V. R. Swail, 2010: Homogenization and trend analysis of Canadian near-surface wind speeds. Journal of Climate. 23, 1209-1225.

Technical documentation: http://crd-data-donnees-rdc.ec.gc.ca/CDAS/products/AHCCD/Wind_Documentation.doc

Link to download the data and format of data:

For monthly, seasonal and annual data:

https://climate-change.canada.ca/climate-data/#/adjusted-station-data (GeoJSON and CSV on CCCS/ECCC webpage)

http://crd-data-donnees-rdc.ec.gc.ca/CDAS/products/AHCCD/ (.txt on CRD/ECCC webpage)

On MSC Datamart at https://dd.weather.gc.ca/climate/ahccd/geojson/historical/ (GeoJSON)

Publications including dataset evaluation or comparison with other data in northern Canada.

This dataset is usually used as reference in the evaluation of climate variables from other datasets.

7.4.4 *<u>Dataset</u>: ECMWF 5th Generation Atmospheric Reanalysis (ERA 5) - wind*

Overview

This document provides an overview of single-level wind products of ERA5, in the context of the larger ERA5 dataset. As background, ERA5 is the 5th generation of the global atmospheric reanalysis (the latest – it replaces the ERA-Interim reanalysis) produced by the Copernicus Climate Change Service at ECMWF, covering the period from January 1950 to present. It provides hourly data on many atmospheric, land-surface and sea-state parameters together with estimates of uncertainty.

Provider's contact information

ERA5 is produced by the Copernicus Climate Change Service (C3S) at ECMWF.

Copernicus User support (copernicus-support@ecmwf.int (external to C3S)).

Licensing

Licence: Copernicus (Licence agreement information can be found here or here).

Dataset citable as: Copernicus Climate Change Service (C3S) (2017): ERA5: Fifth generation of ECMWF atmospheric reanalyses of the global climate . Copernicus Climate Change Service Climate Data Store (CDS), date of access. https://cds.climate.copernicus.eu/cdsapp#!/home

Variable name and units:

Single-level wind of ERA5 over northern Canada is the main focus of this document. The parameter description is provided in the table below.

Name	Units	Description
100 m u-component of wind	m s-1	This parameter is the eastward component of the 100 m wind. It is the horizontal speed of air moving towards the east, at a height of 100 metres above the surface of the Earth, in metres per second. Care should be taken when comparing model parameters with observations, because observations are often local to a particular point in space and time, rather than representing averages over a model grid box. This parameter can be combined with the northward component to give the speed and direction of the horizontal 100 m wind.

100 m v-component of wind	m s-1	This parameter is the northward component of the 100 m wind. It is the horizontal speed of air moving towards the north, at a height of 100 metres above the surface of the Earth, in metres per second. Care should be taken when comparing model parameters with observations, because observations are often local to a particular point in space and time, rather than representing averages over a model grid box. This parameter can be combined with the eastward component to give the speed and direction of the horizontal 100 m wind.
10 m u-component of neutral wind	m s-1	This parameter is the eastward component of the "neutral wind", at a height of 10 metres above the surface of the Earth. The neutral wind is calculated from the surface stress and the corresponding roughness length by assuming that the air is neutrally stratified. The neutral wind is slower than the actual wind in stable conditions, and faster in unstable conditions. The neutral wind is, by definition, in the direction of the surface stress. The size of the roughness length depends on land surface properties or the sea state.
10 m u-component of wind	m s-1	This parameter is the eastward component of the 10m wind. It is the horizontal speed of air moving towards the east, at a height of ten metres above the surface of the Earth, in metres per second. Care should be taken when comparing this parameter with observations, because wind observations vary on small space and time scales and are affected by the local terrain, vegetation and buildings that are represented only on average in the ECMWF Integrated Forecasting System (IFS). This parameter can be combined with the V component of 10m wind to give the speed and direction of the horizontal 10m wind.
10 m v-component of neutral wind	m s-1	This parameter is the northward component of the "neutral wind", at a height of 10 metres above the surface of the Earth. The neutral wind is calculated from the surface stress and the corresponding roughness length by assuming that the air is neutrally stratified. The neutral wind is slower than the actual wind in stable conditions, and faster in unstable conditions. The neutral wind is, by definition, in the direction of the surface stress. The size of the roughness length depends on land surface properties or the sea state.
10 m v-component of wind	m s-1	This parameter is the northward component of the 10m wind. It is the horizontal speed of air moving towards the north, at a height of ten metres above the surface of the Earth, in metres per second. Care should be taken when comparing this parameter with observations, because wind observations vary

		on small space and time scales and are affected by the local terrain, vegetation and buildings that are represented only on average in the ECMWF Integrated Forecasting System (IFS). This parameter can be combined with the U component of 10m wind to give the speed and direction of the horizontal 10m wind.
10 m wind gust since previous post-processing	m s-1	Maximum 3 second wind at 10 m height as defined by WMO. Parametrization represents turbulence only before 01/10/2008; thereafter effects of convection are included. The 3 s gust is computed every time step and the maximum is kept since the last post processing.
Instantaneous 10 m wind gust	m s-1	This parameter is the maximum wind gust at the specified time, at a height of ten metres above the surface of the Earth. The WMO defines a wind gust as the maximum of the wind averaged over 3 second intervals. This duration is shorter than a model time step, and so the ECMWF Integrated Forecasting System (IFS) deduces the magnitude of a gust within each time step from the time-step-averaged surface stress, surface friction, wind shear and stability. Care should be taken when comparing model parameters with observations, because observations are often local to a particular point in space and time, rather than representing averages over a model grid box.

Hourly and **monthly** subsets are available at the links below:

- hourly data on single levels from 1950 to 1978,
- hourly data on single levels from 1979 to present,
- monthly averaged data on single levels from 1950 to 1978,
- monthly averaged data on single levels from 1979 to present,

The monthly data is pre-calculated as monthly-mean averages from hourly data.

Spatial coverage and resolution:

Wind in ERA5, like all ERA5 data, is a global dataset. The atmospheric data is available on a regular latitude-longitude grid at 0.25° x 0.25° resolution (converted from native reduced-Gaussian grid resolution of approximately 31 km x 31 km), and on 37 pressure levels.

Temporal coverage and resolution:

Wind in ERA5, like all ERA5 data, is available from 1950 to present (split into two entries: primary from 1979 onwards and a back extension from 1950-1978). The back extension is a preliminary version that has been released in 2020, and an updated version (that corrects some issues in the tropics) will appear around the end of 2021.

The data is available as hourly and monthly data.

Wind in ERA5, like all ERA5 data, is updated daily with a latency of about 5 days in an early product and with a final release 2 to 3 months later.

Information about observations (number, homogeneity)

ERA5's data assimilation uses observations for all geophysical quantities from about 0.75 million observations per day in 1979 and about 24 Million in 2018. The 2D-OI uses surface observations at 'screen level'. The online technical documentation provides tables with the satellite and in-situ observations used as input into ERA5.

The satellite measurements used in ERA5 are: temperature, humidity, ozone, column water vapour, cloud liquid water, precipitation, ocean surface wind speed, wind vector, soil moisture, wave height.

The in-situ data is provided by WMO WIS and consists in measurements for: surface pressure, temperature, humidity, wind, wind profiles and snow depth. Figure 4 from Hersbach et al. (2020) presents the conventional observations assimilated per day in ERA5 during the period 1979–2018.

ERA5 assimilates rain rates from ground-based radar–gauge composite observations from 2009, and snow cover (NH only) from NOAA/NESDIS IMS.

The time evolving nature of the assimilated observations means that caution should be employed when using ERA5 to evaluate long-term variability and trends.

Methodology

Like any other climate variable from a reanalysis product, ERA5 wind is strongly influenced by the data assimilation methodology. ERA5 is produced using 4D-Var data assimilation with the ECMWF's Integrated Forecast System (IFS) model (CY41R2). The forecast model has 137 hybrid sigma/pressure (model) levels in the vertical, with the top level at 0.01 hPa. The IFS is coupled to a land-surface model and an ocean wave model. The model uses as boundary conditions the sea surface temperature, the sea ice cover, the greenhouse gases, the aerosols, and the total solar irradiance. Climate variables are offered from the atmospheric model, the surface model and the wave model.

The ERA5 dataset contains one (31 km) high resolution realization (HRES) and a reduced resolution 10-member ensemble (EDA). The model time step is 12 minutes for the HRES and 20 minutes for the Ensemble Data Assimilation (EDA), though occasionally these numbers are adjusted to cope with instabilities. Climate variables result from analyses and short (18 hours) forecasts, initialized twice daily from analyses at 06 and 18 UTC. Most of climate variables from the analyses are also available from the forecasts. However, there are several climate variables from forecast, e.g., mean rates and accumulations, that are not available from the analyses. More information on the differences between analysis, forecast, instantaneous, accumulated and mean rate parameters are provided on https://confluence.ecmwf.int/pages/viewpage.action?pageId=85402030.

The ERA5 atmospheric analysis is based on a hybrid incremental 4-dimensional variational data assimilation (4D-Var) system including variational bias correction (VarBias). The method finds the best estimate of the state of the atmosphere/land/surface ocean within an assimilation time window, given a background forecast valid at the start of the window and observations falling within that window. The 4D-Var data assimilation uses 12 hour windows from 09 UTC to 21 UTC and 21 UTC to 09 UTC (the following day).

Uncertainty estimate: An uncertainty estimate is sampled by a 10-member lower-resolution Ensemble Data Assimilation (EDA) which provides background-error estimates for the deterministic HRES 4D-Var Data Assimilation system. The analysis method is the same for each EDA member and follows that of the HRES. Each member (except the control) is run with different random perturbations added to the observations. Likewise, the model physical tendencies are perturbed in the short forecasts that link subsequent analysis windows. Ensemble mean and spread have been pre-computed for convenience. Such uncertainty estimates are closely related to the information content of the available observing system which has evolved considerably over time. They also indicate flow-dependent sensitive areas. To facilitate many climate applications, monthly-mean averages have been pre-calculated too, though monthly means are not available for the ensemble mean and spread.

A strength of reanalysis (including ERA5) is the use of a consistent assimilation/forecast methodology throughout the analysis cycle. Thus, even though the observations assimilated are evolving in time (see above), the data assimilation approach can be considered fixed throughout the products analysis period, which adds to the homogeneity of the dataset.

Information about the technical and scientific quality

ERA5 wind represents one of the products of the latest global atmospheric reanalysis produced by Copernicus Climate Change Service at ECMWF. It is archived at a shorter (hourly) time step, has a finer spatial resolution, uses a more advanced assimilation system and includes more sources of data than previous versions. It is accompanied by extensive technical documentation and two principal scientific documentation papers. A list of ‘known issues’ is maintained at the online documentation (https://confluence.ecmwf.int/display/CKB/ERA5%3A+data+documentation#ERA5:datadocumentation-Knownissues).

A prerelease quality control revealed some problems affecting the performance in the tropics (tropical cyclones are too intense) and that the deep soil moisture tends to be too dry for the 1950-1978 dataset. A new version of the data should gradually become available by late 2021. This issue will be of little direct relevance to ERA5 wind in Canada’s north, but the user should be aware of the reason for this update.

Information on model improvement: The forecast model of the ERA5 is the IFS Cycle 41r2. In the ten-year period between ERA-Interim (Cy31r2) and ERA5 (Cy41r2), many significant improvements have been made to the representation of atmospheric physical processes (see Section 4 of Hersbach *et al.* (2020)). ERA5 wind will be influenced by several changes to ERA5’s land-surface model and parameterization schemes. ERA5’s HTESSEL land surface scheme (Balsamo *et al.*, 2015) accounts for seasonally varying monthly vegetation maps specified from a MODIS-based satellite dataset. In addition, an enhanced snowpack parameterization allows a more realistic timing of runoff and terrestrial water storage variations and a better match of the albedo to satellite products. The chosen parameterization for lakes (FLake), allows consideration of both subgrid and resolved water bodies, which is potentially relevant for the lake-enriched Canadian sub-Arctic. This series of changes contributes to significant improvements in the soil moisture and land surface fluxes consistency, which allowed for the usage of satellite data in ERA5 to analyze soil moisture. This will influence the surface energy budget. Some important improvements in the wave model include: an updated model bathymetry with a more recent version of ETOPO2 and a revised unresolved bathymetry scheme. Some of these changes will also affect coastal regions as well as better accounting for wave propagation along coastlines and better modelling of the impact of previously unresolved features like islands and narrow embayments.

Limitations and strengths for application in North Canada

ERA5 is a new atmospheric reanalysis and there are not available scientific evaluations of the dataset dedicated specifically to northern Canada. However, it should be noted that in northern Canada, there are currently no sub-daily records over a long historical period for many weather stations. Reanalyses data with hourly output cover this gap and, with suitable investigation and calibration (downscaling), could be valuable resources.

As for all gridded data, care should be taken when comparing 10m wind with observations, because wind observations vary on small space and time scales and are affected by the local terrain, vegetation and buildings that are represented only on average in the reanalyses.

Also, as mentioned above, changes in the amounts and types of observational data that are assimilated may produce artificial trends or variability in reanalysis variables. **For ERA5 this has been observed for wind in the boundary layer** (Hersbach *et al.*, 2020).

Up to once or twice per year, the analyzed near-surface (e.g., 10 m) winds in ERA5 suffer from a problem of extremely large wind speeds; the largest speeds seen so far are of order 300 ms −1.

References to documents describing the methodology or/and the dataset

Hersbach, H., B. Bell, P. Berrisford, G. Biavati, A. Horányi, J. Muñoz Sabater, J. Nicolas, C. Peubey, R. Radu, I. Rozum, D. Schepers, A. Simmons, C. Soci, D. Dee, and J-N. Thépaut, 2018: ERA5 hourly data on single levels from 1979 to present. Copernicus Climate Change Service (C3S) Climate Data Store (CDS). (Accessed on < 29-Apr-2019 >), https://doi.org/10.24381/cds.adbb2d47

Hersbach, H., B .Bell, P. Berrisford, S. Hirahara, A. Horányi, J. Muñoz-Sabater, J. Nicolas, C. Peubey, R. Radu, D. Schepers, A. Simmons, C. Soci, S. Abdalla, X. Abellan, G. Balsamo, P. Bechtold, G. Biavati, J. Bidlot, M. Bonavita, G. Chiara, P. Dahlgren, D. Dee, M. Diamantakis, R. Dragani, J. Flemming, R. Forbes, M. Fuentes, A. Geer, L. Haimberger, S. Healy, R.J. Hogan, E. Hólm, M. Janisková, S. Keeley, P. Laloyaux, P. Lopez, C. Lupu, G. Radnoti, P. Rosnay, I. Rozum, F. Vamborg, S. Villaume, and J.-N. Thépaut, 2020: The ERA5 global reanalysis. Quarterly Journal of the Royal Meteorological Society, 146(730), 1999–2049. https://doi.org/10.1002/qj.3803.

Online technical documentation: https://confluence.ecmwf.int/display/CKB/ERA5%3A+data+documentation

Link to download the data and format of data:

Data Access: Copernicus | NCAR | ECMWF

ERA5 is available in GRIB1 and NetCDF formats

Link to download hourly and monthly data on Copernicus:

- hourly data on single levels from 1950 to 1978,
- hourly data on single levels from 1979 to present,
- hourly data on pressure levels from 1950 to 1978,
- hourly data on pressure levels from 1979 to present,
- monthly averaged data on single levels from 1950 to 1978,
- monthly averaged data on single levels from 1979 to present,
- monthly averaged data on pressure levels from 1950 to 1978,
- monthly averaged data on pressure levels from 1979 to present.

Publications including dataset evaluation or comparison with other data in Canada

Tarek, M., F.P. Brissette, and R. Arsenault, 2020: Evaluation of the ERA5 reanalysis as a potential reference dataset for hydrological modelling over North America. Hydrology and Earth System Sciences, 24(5), 2527-2544. (It compares ERA5 and ERA-Interim with stations in US and Canada south of 60° latitude).

Sheridan, S.C., C.C. Lee, and E.T. Smith, 2019: A comparison between station observations and reanalysis data in the identification of extreme temperature events. Geophysical Research Letters, 47(15), e2020GL088120. (It compares observations, ERA5, ERA5-LAND, and NARR, in the United States and Canada- only a very small number of stations are in North Canada).

Betts, A.K., D.Z. Chan, and R.L. Desjardins, 2019: Near-surface biases in ERA5 over the Canadian Prairies. Frontiers in Environmental Science, 7 (129). (ERA5 is compared with hourly data for 4 stations in Saskatchewan, Canada).

Cao, B., X. Quan, N. Brown, E. Stewart-Jone, and S. Gruber, 2019: GlobSim (v1.0): deriving meteorological time series for point locations from multiple global reanalyses. Geosci. Model Dev., 12, 4661–4679, https://doi.org/10.5194/gmd-12-4661-2019 (2 m temperature from ERA5 is compared with ERA-Interim, JRA-55 and MERRA-2 at a site located near the north shore of Lac de Gras in the Northwest Territories, Canada)

7.4.5 <u>Dataset</u>: The NOAA NCEP Climate Forecast System Reanalysis (CFSR) and Climate Forecast System Version 2 (CFSv2) - wind

Overview

This document provides an overview of the 10 m wind from the Climate Forecast system reanalysis (CFSR) and its operational extension CFSv2. The CFSR is a third generation reanalysis product, developed by the National Oceanic and Atmospheric Administration's (NOAA) National Center for Environmental Prediction (NCEP), and it is using a global, high resolution, coupled atmosphere-ocean-land surface-sea ice system. The spatial resolution of the global atmospheric data is ~38 km (T382) and many atmospheric variables are provided at hourly temporal resolution.

Provider's contact information

CFSR is developed by the National Oceanic and Atmospheric Administration's (NOAA) National Center for Environmental Prediction (NCEP).

Contact name: DOC/NOAA/NESDIS/NCEI > National Centers for Environmental Information, NESDIS, NOAA, U.S. Department of Commerce

Contact email: Contact: cfs@noaa.gov

Licensing and citation

CFSR data is freely available

Please reference the following article when using the CFS Reanalysis (CFSR) data:

Saha, S., S. Moorthi, H. Pan, X. Wu, J. Wang, and Coauthors, 2010: The NCEP Climate Forecast System Reanalysis. Bulletin of the American Meteorological Society, 91, 1015–1057, doi:10.1175/2010BAMS3001.1.

For hourly data downloaded from UCAR RDA: **Saha**, S., et al. 2010. NCEP Climate Forecast System Reanalysis (CFSR) Selected Hourly Time-Series Products, January 1979 to December 2010. Research Data Archive at the National Center for Atmospheric Research, Computational and Information Systems Laboratory. https://doi.org/10.5065/D6513W89. Accessed dd mmm yyyy.

For monthly data downloaded from UCAR RDA: **Saha**, S., et al. 2010. NCEP Climate Forecast System Reanalysis (CFSR) Monthly Products, January 1979 to December 2010. Research Data Archive at the National Center for Atmospheric Research, Computational and Information Systems Laboratory. https://doi.org/10.5065/D6DN438J. Accessed dd mmm yyyy.

Please reference the following article when using the CFS Reforecast model or data:

Saha, S., S. Moorthi, X. Wu, J. Wang, S. Nadiga, P. Tripp, D. Behringer, Y. Hou, H. Chuang, M. Iredell, M.Ek, J. Meng, R. Yang, M.P. Mendez, H. van den Dool, Q. Zhang, W. Wang, M. Chen, and E. Becker, 2014: The NCEP Climate Forecast System Version 2, Journal of Climate, 27(6), 2185-2208, doi:10.1175/JCLI-D-12-00823.1.

For hourly data downloaded from UCAR RDA: Saha, S., et al. 2011, updated monthly. NCEP Climate Forecast System Version 2 (CFSv2) Selected Hourly Time-Series Products. Research Data Archive at the National Center for Atmospheric Research, Computational and Information Systems Laboratory. https://doi.org/10.5065/D6N877VB. Accessed dd mmm yyyy.

For monthly data downloaded from UCAR RDA: Saha, S., et al. 2012. NCEP Climate Forecast System Version 2 (CFSv2) Monthly Products. Research Data Archive at the National Center for Atmospheric Research, Computational and Information Systems Laboratory. https://doi.org/10.5065/D69021ZF. Accessed dd mmm yyyy.

Variable name and units:

The following table summarizes the name of the variables available at NCAR RDA as hourly time series.

Notation (name)	Units
WND10M (u and v at 10 m) : instantaneous (The 2 Wind variable has the zonal component (U) and meridional component (V) interspersed one after the other)	m s-1

Note: The forecast at the first time step (f00) of 3 minutes constitutes a spin up of the model physics, and IT IS NOT THE ANALYSIS.

Spatial coverage and resolution:

CFSR data, is a global dataset. 10 m wind is provided on a horizontal regular latitude-longitude grid with a spatial resolution of ~38 km (T382).

Temporal coverage and resolution:

CFSR is covering 01Jan1979 - 31Mar2011 period. The product was extended beyond 2011 as an operational real-time product, using a new version: NCEP's Climate Forecast System Version 2 (CFSv2). CFSR 10 m wind is available at an hourly time resolution and as monthly means.

Information about observations (number, homogeneity)

All available conventional and satellite observations were included in the CFSR. Satellite observations were used in radiance form and were bias corrected with "spin up" runs at full resolution, taking into account variable CO2 concentrations. This procedure enabled smooth transitions of the climate record due to evolutionary changes in the satellite observing system.

It is extremely difficult to assimilate 2 m temperature over land in systems like the CFSR. Therefore, surface temperature from stations is not assimilated in CFSR.

The CFSR uses the NCEP operational observation quality control procedures.

Methodology

The CFSR is a third generation reanalysis product, and it is using global, high resolution, coupled atmosphere-ocean-land surface-sea ice system. It includes (1) coupling of atmosphere and ocean during the generation of the 6 hour guess field, (2) an interactive sea-ice model, and (3) assimilation of satellite radiances. The CFSR global atmosphere resolution is ~38 km (T382) with 64 levels. The global ocean is 0.25° at the equator, extending to a global 0.5° beyond the tropics, with 40 levels. The global land surface model has 4 soil levels and the global sea ice model has 3 levels. The CFSR atmospheric model contains observed variations in carbon dioxide (CO2), together with changes in aerosols and other trace gases and solar variations.

Information about the technical and scientific quality

The CSFR products are superior to previous NCEP reanalyses with respect to: improved model, finer resolution, advanced assimilation schemes, atmosphere-land-ocean-sea ice coupling, assimilates satellite radiances rather than retrievals, and accounts for changing CO2 and other trace gasses, aerosols, and solar variations.

Known CFSRR data issues are explained in the August 2011 CFSRR Known Issues Technical Document.

Limitations and strengths for application in North Canada

GENERAL KEY STRENGTHS:

- Approaches the horizontal resolution of regional reanalyses like the NARR and Arctic System Reanalysis

GENERAL KEY LIMITATIONS:

- Ocean-atmosphere interactions are not used directly. Rather the information is used for background information. The actual reanalysis is uncoupled.

References to documents describing the methodology or/and the dataset

Saha, S., S. Moorthi, H.-L. Pan, X. Wu, J. Wang, S. Nadiga, P. Tripp, R. Kistler, J. Woollen, D. Behringer, H. Liu, D. Stokes, R. Grumbine, G. Gayno, J. Wang, Y.-T. Hou, H. Chuang, H. H. Juang, J. Sela, M. Iredell, R. Treadon, D. Kleist, P. Van Delst, D. Keyser, J. Derber, M. Ek, J. Meng, H. Wei, R. Yang, S. Lord, H. van den Dool, A. Kumar, W. Wang, C. Long, M. Chelliah, Y. Xue, B. Huang, J. Schemm, W. Ebisuzaki, R. Lin, P. Xie, M. Chen, S. Zhou, W. Higgins, C. Zou, Q. Liu, Y. Chen, Y. Han, L. Cucurull, Ri. W. Reynolds, G. Rutledge, and M. Goldberg, 2010: The NCEP Climate Forecast System Reanalysis. Bulletin of the American Meteorological Society 91, 8, 1015-1058, https://doi.org/10.1175/2010BAMS3001.1

Saha, S., S. Moorthi, X. Wu, J. Wang, S. Nadiga, P. Tripp, D. Behringer, Y. Hou, H. Chuang, M. Iredell, M.Ek, J. Meng, R. Yang, M.P. Mendez, H. van den Dool, Q. Zhang, W. Wang, M. Chen, and E. Becker, 2014: The NCEP Climate Forecast System Version 2, Journal of Climate, 27(6), 2185-2208, doi:10.1175/JCLI-D-12-00823.1.

Link to download the data and format of data:

The CFSR data (1979 to 2011) are available in GRIB-2 format and can be accessed in multiple ways.

NCEI NOMADS THREDDS Data Server: URL: https://nomads.ncdc.noaa.gov/thredds/cfsr.html

NOAA NOMADS FTP access: URL: ftp://nomads.ncdc.noaa.gov/CFSR/

At UCAR RDA data is grouped as follows:

NCEP Climate Forecast System Version 2 (CFSv2) Monthly Products (ds094.2)

NCEP Climate Forecast System Version 2 (CFSv2) Selected Hourly Time-Series Products (ds094.1)

NCEP Climate Forecast System Reanalysis (CFSR) Monthly Products, January 1979 to December 2010 (ds093.2)

NCEP Climate Forecast System Reanalysis (CFSR) Selected Hourly Time-Series Products, January 1979 to December 2010 (ds093.1)

Publications including dataset evaluation or comparison with other data in Canada

7.4.6 *Dataset: Modern-Era Retrospective analysis for Research and Applications, Version 2 (MERRA-2) - wind*

Overview

This document provides an overview of the wind data from the Modern-Era Retrospective analysis for Research and Applications, Version 2 (MERRA-2). MERRA-2 represents a third generation atmospheric global reanalysis produced by the Global Modeling and Assimilation Office (GMAO) at NASA. It begins in 1980 and it replaces the original MERRA reanalysis (Rienecker et al., 2011) using an upgraded version of the Goddard Earth Observing System Model, Version 5 (GEOS-5) data assimilation system. Alongside the meteorological data assimilation using a modern satellite database, MERRA-2 includes an interactive analysis of aerosols that feed back into the circulation, uses NASA's observations of stratospheric ozone and temperature, and takes steps towards representing cryogenic processes by including a representation of ice sheets over Greenland and Antarctica.

Provider's contact information

MERRA-2 is developed by the Global Modeling and Assimilation Office (GMAO) and produced through NASA's Modeling, Analysis and Prediction (MAP) program.

Data Download questions should go to the GES DISC help email: gsfc-help-disc@lists.nasa.gov

Science questions regarding MERRA-2 data be emailed to: merra-questions@lists.nasa.gov

When contacting these emails, provide specific information and links to where you have attempted the data downloads. They also ask you to familiarize yourself with the existing documentation first (MERRA-2: http://gmao.gsfc.nasa.gov/reanalysis/MERRA-2/docs/)

Licensing and citation

MERRA-2 data is freely available from the Goddard Earth Sciences (GES) Data Information Services center (DISC). Note that each MERRA-2 data collection has a citable DOI, that should be used in peer-reviewed publications.

Citing MERRA-2 data has 2 steps for a full citation:

(7) First pick the correct variable here.
(8) When you click on the correct variable, it will take you to a second webpage with tabs that you can click that include: (1) documentation papers you need to cite, and (2) the correct variable citation information. You need both types of citation.

Variable name and units:

2 m, 10 m and 50 m wind are available as instantaneous values for every hour. Monthly means of instantaneous diagnostics have also been computed.

inst1_2d_asm_Nx collection of data contains basic assimilated fields from IAU corrector provided on a single level as hourly instantaneous values.

instM_2d_asm_Nx collection of data contains basic assimilated fields from IAU corrector provided on a single level as monthly means of the instantaneous values.

inst1_2d_lfo_Nx collection of data contains Land Surface Forcings data as hourly instantaneous values.

tavg1_2d_flx_Nx collection of data contains Surface Flux Diagnostics as hourly time averages.

tavg1_2d_slv_Nx collection of data contains Single-Level Diagnostics as 1 hour time means.

tavgM_2d_lnd_Nx collection of data contains monthly time average data of Single-Level Diagnostics

Each time-averaged collection consists of a continuous sequence of data averaged over the indicated interval and time stamped with the central time of the interval. For hourly data, for example, these times are 00:30 GMT, 01:30 GMT, 02:30 GMT, etc. Monthly files represent averages for the calendar months, accounting for leap years.

Name	Description	Units	Collection of data
U2M	2 m eastward wind	m s-1	inst1_2d_asm_Nx; instM_2d_asm_Nx; tavg1_2d_slv_Nx; tavgM_2d_slv_Nx
U10M	10 m eastward wind	m s-1	inst1_2d_asm_Nx; instM_2d_asm_Nx; tavg1_2d_slv_Nx; tavgM_2d_slv_Nx
U50M	50 m eastward wind	m s-1	inst1_2d_asm_Nx;

			instM_2d_asm_Nx; tavg1_2d_slv_Nx; tavgM_2d_slv_Nx
V2M	2 m northward wind	m s-1	inst1_2d_asm_Nx; instM_2d_asm_Nx; tavg1_2d_slv_Nx; tavgM_2d_slv_Nx
V10M	10 m northward wind	m s-1	inst1_2d_asm_Nx; instM_2d_asm_Nx; tavg1_2d_slv_Nx; tavgM_2d_slv_Nx
V50M	50 m northward wind	m s-1	inst1_2d_asm_Nx; instM_2d_asm_Nx; tavg1_2d_slv_Nx; tavgM_2d_slv_Nx
SPEEDLML	surface wind speed	m s-1	inst1_2d_lfo_Nx
SPEEDMAX	Maximum surface wind speed	m s-1	tavg1_2d_flx_Nx

More broadly, **MERRA-2 File Specification** document has a comprehensive list of datasets available, as well as description of the horizontal and vertical grids.

Spatial coverage and resolution:

MERRA-2 data, is a global dataset. All variables are provided on the same horizontal regular latitude-longitude grid that has 576 points in the longitudinal direction and 361 points in the latitudinal direction, corresponding to a resolution of 0.625° × 0.5°.

Temporal coverage and resolution:

MERRA-2 data, is available from 1980 to present.

2 m, 10 m and 50 m wind data is available at hourly and monthly time step as instantaneous value.

MERRA-2 data, is updated on a monthly base (each new month is available approximately between the 15th and 20th of the next month.).

Information about observations (number, homogeneity)

Like any other climate variable from a reanalysis product, wind is potentially influenced by all observations assimilated into the product. MERRA-2 assimilates conventional and satellite-based observations.

Conventional observations include surface, upper air, and aircraft measurements. **From land based surface meteorology stations, only surface pressure is assimilated in MERRA and MERRA-2**. Radiosonde stations may contribute to the lower level analysis (T, Qv, U, V). Likewise, commercial aircraft can provide lower level data on the ascent and descent (T, U, V). There are also wind profilers (U,V). Over ocean, ships and buoys may provide PS, T, Qv, U and V.

Spaceborne observations include satellite radiances and retrieved measurements of the temperature and moisture fields, and satellite observations of wind (derived retrievals of surface and upper-air wind). Spaceborne observations represent the majority of the global observing system, and the percentage of the global observing system that is measured from space increases from 62% in Jan 1980 to 88% in Dec 2014. Modern hyperspectral radiance and microwave observations, along with GPS-Radio Occultation and NASA ozone datasets are now assimilated in MERRA-2.

See the MERRA-2 Observations Tech Memo for more details.

Methodology

Like any other reanalysis, MERRA-2 data is strongly influenced by the data assimilation methodology. MERRA-2 is currently being produced with the GMAO/GEOS-5 Data Assimilation System Version 5.12.4, which incorporates the Global Statistical Interpolation (GSI) analysis scheme of Wu *et al*. (2002). The system utilizes a revised version of the GEOS global atmospheric model (Molod *et al.,* 2014). MERRA-2 is intended to replace the MERRA reanalysis product (which was created with GEOS-5.2.0). Details of the MERRA-2 system, including the major changes from the MERRA system, are summarized in the companion GMAO Office Note No. 10. The major motivation for replacing MERRA with MERRA-2 is the fact that the MERRA data assimilation system was frozen in 2008 and is not capable of ingesting several important new data types as the newer microwave sounders and hyperspectral infrared radiance instruments. The GEOS-5 system actively assimilates roughly 2×10^6 observations for each analysis, including about 7.5×10^5 AIRS radiance data. The input stream is roughly twice this volume, but because of the large volume, the data are thinned commensurate with the analysis grid to reduce the computational burden. Data are also rejected from the analysis through quality control procedures.

There is a fundamental change between MERRA and MERRA-2 over land surfaces. Soil moisture in MERRA-2 is initialized using a separate observation-based precipitation product (variable PRECTOTCORR in “flx” collections). This approach improves the representation of land surface properties and runoff, and is similar to the soil moisture initialization scheme developed for MERRA-Land (Reichle *et al*., 2011; Reichle, 2012; Reichle and Liu, 2014). The forcing precipitation is primarily based on gauge observations at low and midlatitudes, and gradually tapers to the MERRA-2 modelled precipitation over a zonal range from 42.5° to 62.5° latitude. The forcing precipitation is entirely composed of the MERRA-2 modelled precipitation poleward of 62.5°.

MERRA-2 is produced as four production Streams, each of the first three covering approximately a third of the MERRA-2 period, with the fourth stream starting within a couple years of real time. Initial conditions for the four MERRA-2 streams were derived from MERRA with a subsequent single year spin-up period, which has not been released in MERRA-2.

Information about the technical and scientific quality

MERRA-2 replaces the original NASA MERRA reanalysis (Rienecker *et al*., 2011) using an upgraded version of the data assimilation system, and of the forecast model. It is accompanied by extensive technical documentation (see section below on reference to s describing the methodology or/and the dataset). It incorporates observations from the more recent satellite instruments, uses observation-corrected precipitation forcing for the land surface, includes stratospheric ozone products and assimilates interactive aerosols and observed time varying emissions.

A webpage is provided with FAQ answers here: https://gmao.gsfc.nasa.gov/reanalysis/MERRA-2/FAQ/#

Limitations and strengths for application in North Canada

Key general limitations: Discontinuities associated with major observing system variations do occur

References to documents describing the methodology or/and the dataset

MERRA-2 Overview: The Modern-Era Retrospective Analysis for Research and Applications, Version 2 (MERRA-2), Gelaro, *et al*., 2017, J. Clim., doi: 10.1175/JCLI-D-16-0758.1

The American Meteorological Society has a special collection of articles relevant to MERRA-2. This collection, coordinated by Mike Bosilovich, is available at http://journals.ametsoc.org/collection/MERRA2.

There are several MAO Technical Memoranda that document and evaluate different aspects of the MERRA-2 system aspects of the MERRA-2 system:

#43, Bosilovich et al. – MERRA-2: Initial Evaluation of the Climate

#45, Randles et al. – The MERRA-2 Aerosol Assimilation

#46, McCarty et al. – MERRA-2 Input Observations: Summary and Assessment

Description of the observation corrected precipitation process used in MERRA-2:

Reichle, R., Q. Liu, R. Koster, C. Draper, S. Mahanama, and G. Partyka, 2017: Land Surface Precipitation in MERRA-2. *J. Clim.* doi:10.1175/JCLI-D-16-0570.1 Link.

Description of the GEOS-5 model changes between the MERRA and MERRA-2 systems:

Molod, A., Takacs, L., Suarez, M., and Bacmeister, J., 2015: Development of the GEOS-5 atmospheric general circulation model: evolution from MERRA to MERRA-2, *Geosci. Model Dev.*, 8, 1339-1356, doi:10.5194/gmd-8-1339-2015. Link.

Description of the mass constraint used in MERRA-2:

Takacs, L. L., M. Suarez, and R. Todling, 2015: Maintaining Atmospheric Mass and Water Balance Within Reanalysis. *NASA/TM–2014-104606*, Vol. 37 Document.

Link to download the data and format of data:

The MERRA-2 data are available online through the Goddard Earth Sciences (GES) Data and Information Services Center (DISC) (http://disc.sci.gsfc.nasa.gov/mdisc/). All MERRA-2 data are organized into file collections that contain fields with common characteristics. 2 m temperature and skin temperature can be found in the following collections:

MERRA-2 inst1_2d_asm_Nx: contains basic assimilated fields from IAU corrector provided on a single level as hourly instantaneous values.

MERRA-2 instM_2d_asm_Nx: contains basic assimilated fields from IAU corrector provided on a single level as monthly means of the instantaneous values.

MERRA-2 tavg1_2d_lnd_Nx: 1-Hourly time averaged data containing Land Surface Diagnostics

MERRA-2 tavgM_2d_lnd_Nx: Monthly time average data containing Land Surface Diagnostics.

MERRA-2 data files are provided in netCDF-4 format. Due to the size of the MERRA-2 archive, most product collections are compressed with a GRIB like method that is invisible to the user. This method does degrade the precision of the data, but every effort has been made to ensure that differences between the product and the original, non-degraded data are not scientifically meaningful.

Publications including dataset evaluation or comparison with other data in Canada

7.4.7 *<u>Dataset</u>: The Japanese 55-year Reanalysis (JRA-55) - wind*

Overview

This document provides an overview of the 10m wind data from JRA-55. JRA-55 is a third-generation reanalysis developed by Japanese Meteorological Agency (JMA). It is spanning 1958 to present period and represent an update of the previous Japanese 25-year Reanalysis (JRA-25). The analysis period starts in 1958, when regular radiosonde observation began on a global basis. Many of the deficiencies of JRA-25 are alleviated in JRA-55 because the Data Assimilation (DA) system used for the project featured a variety of improvements.

Provider's contact information

JRA-55 is developed by the Japanese Meteorological Agency (JMA). Contact JMA at the email address below with any questions on JRA-55:

Climate Prediction Division, Global Environment and Marine Department,

Japan Meteorological Agency,

Email: jra@met.kishou.go.jp

Contact DIAS Office at the email address below with any questions on JRA-55 stored at DIAS:

DIAS Office

Japan Agency for Marine-Earth Science and Technology

Email: dias-office@diasjp.net

Licensing and citation

The intellectual property rights of the datasets belong exclusively to JMA.

JRA-55 data are provided by collaborative organizations that are separate entities from JMA. User registration and agreement to terms and conditions of data service usage are required individually for each organization. Data at NCAR RDA is licensed under a Creative Commons Attribution 4.0 International Licence.

Individual users should provide JMA (jra@met.kishou.go.jp) with a copy of their scientific or technical papers, publications, press releases or other communications regarding these datasets. The source of the products should be duly acknowledged in scientific or technical

papers, publications, press releases or other communications regarding the products. This includes information on the provider of data and of the collaborative organizations from where the data was downloaded.

Example for data downloaded from DIAS Office:

" In this study, the Japanese 55-year Reanalysis (JRA-55) provided by the Japan Meteorological Agency (JMA) was utilized. This dataset was also collected and provided under the Data Integration and Analysis System (DIAS), which was developed and operated by a project supported by the Ministry of Education, Culture, Sports, Science and Technology. "

Example for downloaded from NCAR RDA:

Japan Meteorological Agency/Japan. 2013, updated monthly. JRA-55: Japanese 55-year Reanalysis, Daily 3-Hourly and 6-Hourly Data. Research Data Archive at the National Center for Atmospheric Research, Computational and Information Systems Laboratory. https://doi.org/10.5065/D6HH6H41. Accessed† dd mmm yyyy.

†Please fill in the "Accessed" date with the day, month, and year (e.g., - 5 Aug 2011) you last accessed the data from the RDA.

Spatial coverage and resolution:

JRA-55 data, is a global dataset. Data is available at two spatial resolutions: (1) data on pressure levels at 1.25 degree spatial resolution and (2) data on model TL319L60 grid (~55 km) that was processed to a regular latitude-longitude Gaussian grid (320 latitudes by 640 longitudes, nominally 0.5625 degrees) and is available on NCAR RDA.

Variable name and units:

The following table summarizes the 10 m wind variables available at NCAR RDA a regular latitude-longitude Gaussian grid (320 latitudes by 640 longitudes, nominally 0.5625 degree).

Notation (name)	Units	Dataset product
10 m Maximum wind speed	m s-1	JRA-55 **3-Hourly** Model Resolution 2-Dimensional **Minimum-Maximum Diagnostic Fields (minmax_surf)**
10 m u-component of wind	m s-1	JRA-55 **3-Hourly** Model Resolution 2-Dimensional **Instantaneous Diagnostic Fields (fcst_surf)** JRA-55 **6-Hourly** Model Resolution **Surface Analysis Fields (anl_surf)**

10 m v-component of wind	m s-1	JRA-55 **3-Hourly** Model Resolution 2-Dimensional **Instantaneous Diagnostic Fields (fcst_surf)** JRA-55 **6-Hourly** Model Resolution **Surface Analysis Fields (anl_surf)**

Maximum wind speed, shown in the table, is produced every three hours and it is computed from the beginning of forecasts up to three hours for 00 - 03, 06 - 09, 12 - 15 and 18 - 21 UTC, and from three to six hours for 03 - 06, 09 - 12, 15 - 18 and 21 - 24 UTC. Dates in file name indicate the end of the valid time. This field is produced for daily data, but not for monthly statistics.

Temporal coverage and resolution:

JRA-55 is covering 1958 to present period. The Instantaneous Diagnostic fields are available at 3h time step, while the Surface Analysis Fields are available just at 6h time step.

Monthly statistics are computed as averages and variances for the whole month using only six-hourly data for analyzed and instantaneous forecast fields.

The data is updated on a monthly base.

Information about observations (number, homogeneity)

Most of the observational data employed in JRA-55 are those used in JRA-25. Additionally, newly reprocessed METEOSAT and GMS data were supplied by EUMETSAT and MSC/JMA respectively. The table below summarizes the conventional data assimilate in JRA-55. From 1958 to 2002, JRA-55 is using the same conventional data as ECMWF ERA-40 reanalysis.

Table 1. Conventional data assimilated in JRA-55

Obs type	Parameter	Level
SYNOP	*P*	surface
SHIP	*P*	surface
BUOY	*P*	surface
Upper-level	*T*	~100 hPa
Upper-level	*T*	100~1000 hPa
Upper-level	*u*	~100 hPa
Upper-level	*u*	100~1000 hPa
Upper-level	*Rh*	100~1000 hPa
Aircraft	*u*	100~1000 hPa
Profiler (US)	*u*	100~1000 hPa

Quality control of conventional data is basically the same as the one used for JRA-25, and it includes a climatological check, track check, removal of duplicates, consistency check and gross error check.

The analysis of screen-level variables (2 m temperatures, 2 m relative humidities and 10 m winds) is performed separately from the atmospheric analysis component. These variables are analyzed with a univariate 2-dimensional optimal interpolation (2D-OI). Temperature and wind observations from islands are not used because they are not necessarily representative at the grid scale of JRA-55. Determining whether an observation is from an island is based on the 0.25-degree resolution land cover data; consequently, observations from the coast are also excluded.

Methodology

JRA-55 has been produced with the TL319 version of the Japan Meteorological Agency (JMA) operational data assimilation system (as of December 2009), which features numerous improvements made since the Japanese 25-year Reanalysis (JRA-25). These include a revised longwave radiation scheme, 4D-Var and variational bias correction for satellite radiances. It also incorporates several newly available observational datasets produced as a result of ongoing efforts to improve quality of past observations, including homogenization of radiosonde temperature observations (Haimberger *et al.,* 2008, 2012) and reprocessing of satellite data at major meteorological satellite centers.

The analysis of screen-level variables (2 m temperatures, 2 m relative humidities and 10 m winds) is performed separately with a univariate 2-dimensional optimal interpolation (2D-OI). Land surface analysis fields are generated by driving an offline version of the JMA Simple Biosphere (SiB) model with forcing fields from the atmospheric model. Snow depth analysis fields are generated once a day with 2D-OI using SYNOP snow depth observations. First-guess fields are derived for each grid point using (A) snow depth of the land surface analysis and (B) satellite snow covers. Satellite snow covers are retrieved in the 0.25° × 0.25° latitude/longitude grid from microwave imager radiances.

The forecast model used for JRA-55 is based on the TL319 spectral resolution version of the JMA global spectral model (GSM) as of December 2009 (JMA 2007, 2013b), which has been extensively improved since JRA-25.

The reanalysis period was divided into two streams (A002, B002) which have been producing three discontinuities: at 00 UTC on 1 July 1958, 00 UTC on 1 September 1980, and 00 UTC on 1 October 1992. JRA-55 is presently operated on a near-real-time basis and provides monthly updates for the data.

Information about the technical and scientific quality

One important realization in jRA-55 is the increase in the model resolution (T319L60 vs T106L40 in JRA-25). Among the improvements in the product are reduced biases in stratospheric temperature and Amazonian rainfall, and greater temporal consistency of the temperature analysis. Some notable biases persist, including a dry bias in the upper and middle troposphere, and a warm bias in the upper troposphere. The impacts of changes in the observing system on the forecast error are generally more evident in the Southern Hemisphere than the Northern Hemisphere.

The data is updated on a monthly base. JMA provide a webpage where the issues with JRA-55 are described: JRA-55 Quality Issues

Limitations and strengths for application in North Canada

GENERAL KEY STRENGTHS:

- Longest-running full observing system reanalysis with 4DVar

GENERAL KEY LIMITATIONS:

- Excessive precipitation is observed over the tropics.
- Dry bias in upper and middle troposphere and in regions of deep convection
- Time-varying warm bias in the upper troposphere.
- Tropical cyclone strength analyzed in JRA-55 exhibits unrealistic trends.

- The impact of changes in observing systems is particularly apparent for July 2006, when Global Navigation Satellite System-Radio Occultation (GNSS-RO) refractivity data were introduced into JRA-55.

References to documents describing the methodology or/and the dataset

Kobayashi, S., Y. Ota, Y. Harada, A. Ebita, M. Moriya, H. Onoda, K. Onogi, H. Kamahori, C. Kobayashi, H. Endo, K. Miyaoka, and K. Takahashi, 2015: The JRA-55 Reanalysis: General specifications and basic characteristics. Journal of the Meteorological Society of Japan. Ser. II, 93(1), 5-48, doi:10.2151/jmsj.2015-001.

Harada, Y., H. Kamahori, C. Kobayashi, H. Endo, S. Kobayashi, Y. Ota, H. Onoda, K. Onogi, K. Miyaoka, and K. Takahashi, 2016: The JRA-55 Reanalysis: Representation of atmospheric circulation and climate variability, J. Meteor. Soc. Japan, 94, 269-302, doi:10.2151/jmsj.2016-015.

Link to download the data and format of data:

The JRA-55 data are available in GRIB-2 format and can be accessed from the following organizations:

DIAS: Data Integration & Analysis System (data from 1958 to 2012, on a grid of approx. 1.25 deg.):

http://search.diasjp.net/en/dataset/JRA55

NCAR: National Center for Atmospheric Research (USA) (data from 1958 to present, on both spatial grids):

- Daily, 3-Hourly and 6-Hourly Data http://rda.ucar.edu/datasets/ds628.0/
- Monthly Means and Variances http://rda.ucar.edu/datasets/ds628.1/
- Near Real-Time Data http://rda.ucar.edu/datasets/ds628.8/
- Near Real-Time Data -- Monthly Means and Variances http://rda.ucar.edu/datasets/ds628.9/

Publications including dataset evaluation or comparison with other data in Canada

7.4.8 *<u>Dataset</u>: The NCAR Arctic System Reanalysis (ASRv2) - wind*

Overview

This document provides an overview of near-surface wind products of ASRv2. ASRv2 is a multi-agency, university-led regional reanalysis product that covers the Arctic. It is produced using high-resolution versions of the Polar Weather Forecast Model (PWRF) and the WRF-VAR and High Resolution Land Data Assimilation (HRLDAS) systems that have been optimized for the Arctic. The final version, which has 15 km horizontal resolution and spans 2000-2016 period, is available online through the NCAR's RDA.

Provider's contact information

ASRv2 is produced by Polar Meteorology Group, Byrd Polar & Climate Research Center, the Ohio State University **and is available at NCAR CISL RDA.**

RDA NCAR User support manager schuster@ucar.edu.

Licensing

Licence: This data are licensed under Creative Commons Attribution 4.0 International Licence (Licence agreement information can be found here)

Dataset citable as: National Center for Atmospheric Research/University Corporation for Atmospheric Research, and Polar Meterology Group/Byrd Polar and Climate Research Center/The Ohio State University. 2017. Arctic System Reanalysis version 2. Research Data Archive at the National Center for Atmospheric Research, Computational and Information Systems Laboratory. https://doi.org/10.5065/D6X9291B , https://rda.ucar.edu/datasets/ds631.1/

Bromwich, D., L. Bai, K. Hines, S. Wang, Z. Liu, H. Lin, Y. Kuo, and M. Barlage, 2012: Arctic System Reanalysis (ASR) Project. Research Data Archive at the National Center for Atmospheric Research, Computational and Information Systems Laboratory.

Variable name and units:

ASRv2 provides 2 products kind, analysis and forecast. The table below provide details on near-surface wind products from ASRv2.

Name (parameter)	Units	dataset
U10M (x-grid relative wind component at 10 M)	m s-1	ASRv2.0 2D surface analysis

		ASRv2.0 2D surface forecast
V10M (y-grid relative wind component at 10 M)	m s-1	ASRv2.0 2D surface analysis ASRv2.0 2D surface forecast
U10E (Earth-relative zonal wind at 10 M)	m s-1	ASRv2.0 2D surface analysis ASRv2.0 2D surface forecast
V10E (Earth-relative meridional wind at 10 M)	m s-1	ASRv2.0 2D surface analysis ASRv2.0 2D surface forecast

Spatial coverage and resolution:

Geographical Coverage: 15kmx15km (at 60 N) oriented 175 W (720x720 North Polar Stereographic).

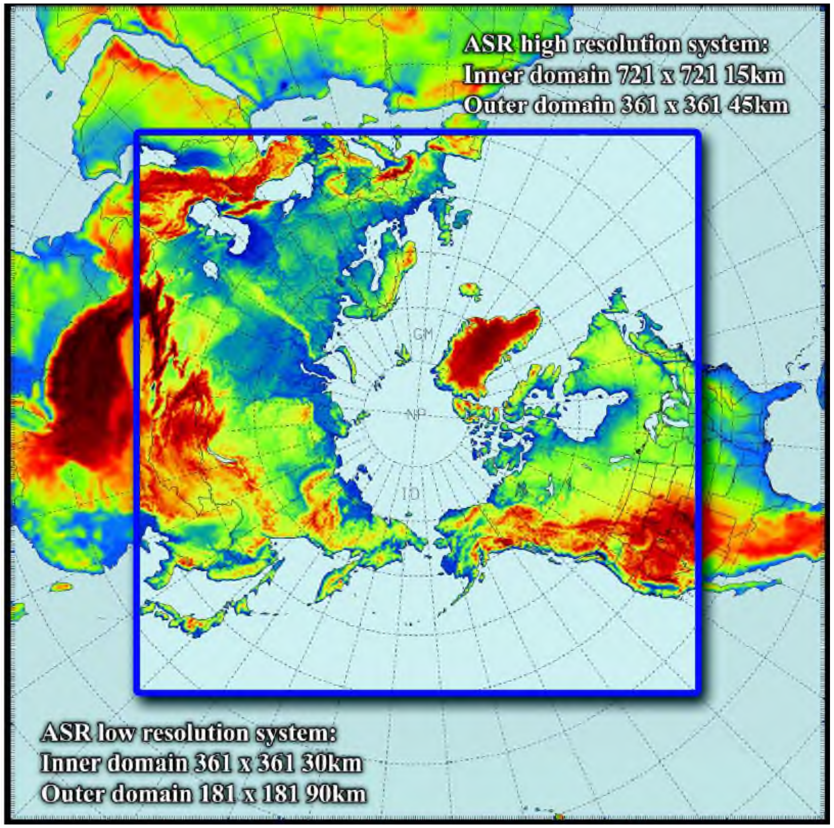

Figure 1. ASR domain (from http://polarmet.osu.edu/ASR/)

Temporal coverage and resolution:

ASRv2 10 m wind products are available from 2000 to 2016 as **3-hourly** subsets and monthly means.

Methodology

ASRv2 provides a high resolution description of the atmosphere-sea ice-land surface system of the Arctic. It is using the polar version of the Weather Research and Forecasting (WRF) model version 3.6.0. It uses the 3DVAR technique and the High Resolution Land Data Assimilation (HRLDAS) data assimilation systems that have been optimized for the Arctic.

A full description of ASRv2 is presented in the Bulletin of the American Meteorological Society (PDF).

Observations data in ASRv2

The observations data used in ASRv2 (Figure 2) includes synoptic surface observations (black dots), METARs (purple plus signs), ship observations (royal blue dots), buoys (navy-blue dots), radiosondes (purple asterisks), global positioning system refractivity observations (red dots), wind profiler (yellow dots), aviation in-flight weather reports (green dots), QuikSCAT sea surface winds (orange dots), and satellite atmospheric motion vectors (aqua dots).

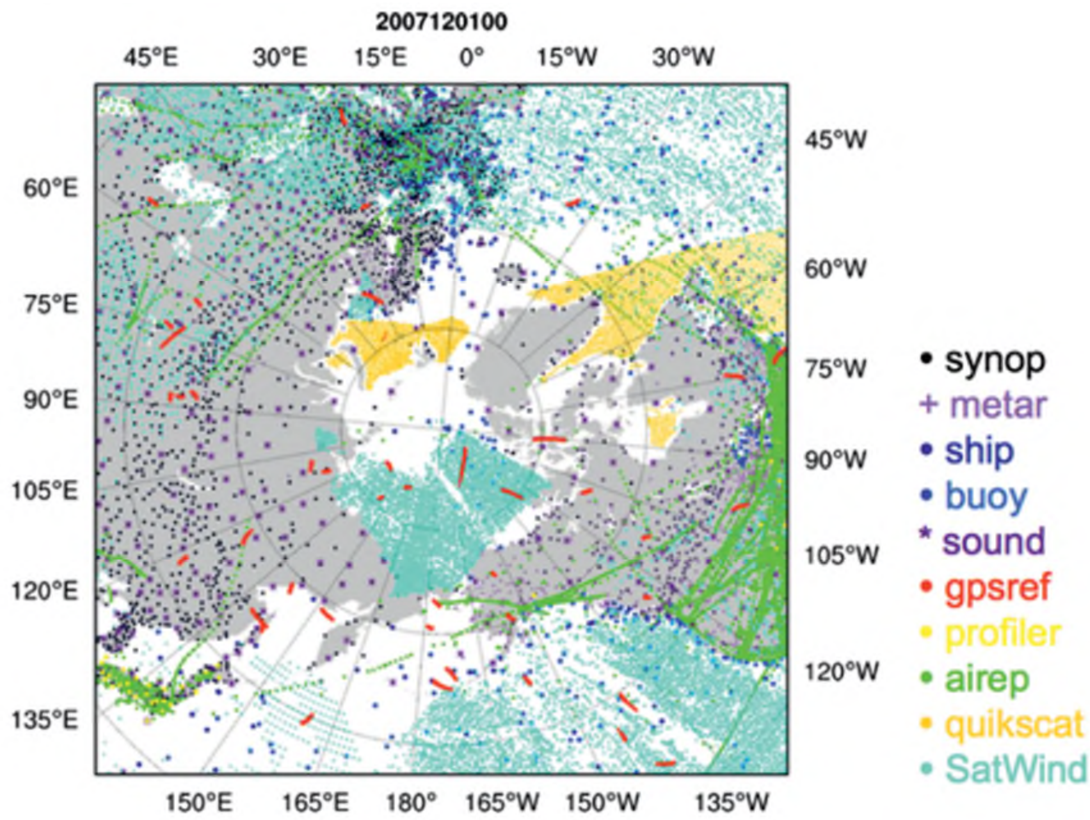

Figure 2. Sample distribution of observations

Information about the technical and scientific quality

New features in ASRv2 compared to ASRv1 are higher horizontal resolution, updated model physics including sub-grid scale cloud fraction interaction with radiation, and a dual outer loop routine for more accurate data assimilation.

The following document compares near-surface variables from ASRv1, ASRv2, and ERAI to observations from ∼4500 surface stations provided by the National Centers for Environmental Information (https://www.ncdc.noaa.gov/) for the period December 2006-November 2007: **http://polarmet.osu.edu/ASR/asr_v2_table.pdf**

For 10 m Wind Speed is mentioned: ''Annual mean 10 m wind speed biases are smaller in the ASR products compared to ERAI, though a positive (negative) bias is demonstrated by ASRv2 (ASRv1). There is quite an improvement in RMSE and correlation between ERAI and ASRv2, where ASRv2 captures two thirds of the variance. As we describe in Bromwich et al. (2016*), the improvements in near-surface wind are tied to the finer resolution in ASR and the improved skill in capturing local wind effects near complex terrain. ASRv1 wind fields have been shown to be well represented, including wind related to topographically forced wind events (Moore *et al*., 2016*) and Arctic cyclones (Tilinina *et al*., 2014*). Though analysis continues, these results suggest that local wind effects are even better captured by ASRv2.''

Presently there are plans to update ASRv2. The updated version will use the latest version of WRF and WRFDA, a more advanced data assimilation procedure, implement Morrison microphysics with a specified variable aerosol concentration, change to Noah-MP land surface model, incorporate a thermodynamic sea ice model, and increase the horizontal resolution to at least 10 km with ~ 100 vertical levels. This version will be known as ASRv3. Plans are to conduct a reanalysis of the MOSAiC drift period (fall 2019 - fall 2020) and it will be available through NCAR.

Limitations and strengths for application in North Canada

The following notes are general observations provided at https://climatedataguide.ucar.edu/climate-data/arctic-system-reanalysis-asr :

Key Strengths: Excellent reproduction of near-surface and tropospheric variables; for example, ASRv2 captures two thirds of the 3-hourly wind speed variance in surface observations, outperforming ASRv1 and ERA-Interim; The high-resolution topography and land surface resolve well the fine-scale processes such as topographically forced winds and polar low

Key Limitations: A dry bias is still present during the cooler months in ASRv2.

References to documents describing the methodology or/and the dataset

Bromwich, D., Y.-H. Kuo, M. Serreze, J. Walsh, L.S. Bai, M. Barlage, K. Hines, and A, Slater, 2010: Arctic System Reanalysis: Call for community involvement. EOS Trans. AGU, 91, 13-14. https://doi.org/10.1029/2010EO020001

Online technical description: **https://rda.ucar.edu/datasets/ds631.0/#!docs**

Link to download the data and format of data:

Data Access:NCAR/RDA

ASRv2 is available in NetCDF formats

Link to download 3 hourly and monthly data on RDA:

3 hourly data surface analysis from 2000 to 2016

3 hourly data surface forecast from 2000 to 2016

ASR 15 km monthly means of analysis products

ASR 15 km monthly means of forecast products

Publications including dataset evaluation or comparison with other data in Canada

Bromwich, D.H., A.B. Wilson, L. Bai, G.W.K. Moore, and P. Bauer, 2016: A comparison of the regional Arctic System Reanalysis and the global ERA-Interim Reanalysis for the Arctic. Q. J. R. Meteorol. Soc., 142, 644-658. https://doi.org/10.1002/qj.2527

Bromwich, D.H., K.M. Hines, and L.-S. Bai, 2009: Development and testing of Polar WRF: 2. Arctic Ocean. J. Geophys. Res., 114, D08122. https://doi.org/10.1029/2008JD010300

Smirnova, J., and P. Golubkin, 2017: Comparing polar lows in atmospheric reanalyses: Arctic System Reanalysis versus ERA-Interim. Mon. Wea. Rev., 145, 2375-2383, https://doi.org/10.1175/MWR-D-16-0333.1

Avila-Diaz, A., D.H. Bromwich, A.B. Wilson, F. Justino, S.-H. Wang, 2021: Climate extremes across the North American Arctic in modern reanalyses. J. Climate, , 34, 2385–2410, https://doi.org/10.1175/JCLI-D-20-0093.1

Chanona, M., and S. Waterman, 2020: Temporal Variability of Internal Wave-Driven Mixing in Two Distinct Regions of the Arctic Ocean. J. Geophys. Res. Oceans, 125, https://doi.org/10.1029/2020JC016181

Edel, L., C. Claud, C. Genthon, C. Palerme, N. Wood, T. L'Ecuyer, and D. Bromwich, 2020: Arctic snowfall from CloudSat observations and reanalyses. J. Clim., 33, 2093-2109, https://doi.org/10.1175/JCLI-D-19-0105.1

Kaiser-Weiss, A.K., M. Borsche, D. Niermann, F. Kaspar, C. Lussana, F.A. Isotta, E. van den Besselaar, G. van der Schrier, and P. Undén, 2019: Added value of regional reanalyses for climatological applications. Environ. Res. Commun., 1, https://doi.org/10.1088/2515-7620/ab2ec3

Gutjahr, O., and G. Heinemann, 2018: A model-based comparison of extreme winds in the Arctic and around Greenland. Int. J. Clmatol., 38, 5272-5292, https://doi.org/10.1002/joc.5729

Rabatel, M., P. Rampal, A. Carrassi, L. Bertino, and C. K. Jones, 2018: Impact of rheology on probabilistic forecasts of sea ice trajectories: Application for search and rescue operations in the Arctic. Cryosphere, 12, 935-953, https://doi.org/10.5194/tc-12-935-2018

Kohnemann, S.H., G. Heinemann, D.H. Bromwich, and O. Gutjahr, 2017: Extreme warming in the Kara Sea and Barents Sea during the winter period 2000-16. J. Clim., 30, 8913-8927, https://doi.org/10.1175/JCLI-D-16-0693.1

Kolstad, E.W., 2017: Higher ocean wind speeds during marine cold air outbreaks. Quarterly J. Roy. Meteor. Soc., 143, 2084-2092, https://doi.org/10.1002/qj.3068

Rampal, P., S. Bouillon, E. Ólason, and M. Morlighem, 2016: neXtSIM: a new Lagrangian sea ice model. The Cryosphere, 10, 1055-1073, https://doi.org/10.5194/tc-10-1055-2016

Wang, F., W. Li, and S. Wang, 2016: Polar cyclone identification from 4D climate data in a knowledge-driven visualization system. Climate, 4, https://doi.org/10.3390/cli4030043

7.4.9 *<u>Dataset</u>: NCEP North American Regional Reanalysis (NARR) - wind*

Overview

This document focuses on wind data from NARR. NARR is a regional reanalysis covering the North America using a Northern Lambert Conformal Conic grid with an approximately 0.3 degrees (32 km) spatial resolution at the lowest latitude. Dataset was originally produced at NOAA's National Center for Atmospheric Prediction (NCEP) and detailed description is provided at https://psl.noaa.gov/data/gridded/data.narr.html#detail with online Analysis and Plotting Tools at https://psl.noaa.gov/cgi-bin/data/getpage.pl.

Provider's contact information

Physical Sciences Laboratory: Data Management

NOAA/ESRL/PSL

325 Broadway

Boulder, CO 80305-3328

psl.data@noaa.gov.

Licensing

This work is licensed under a Creative Commons Attribution 4.0 International Licence.

There are no restrictions for the use of data.

If the data are taken from PSD, the providers ask that the data is acknowledged by including text such as NCEP Reanalysis data provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, from their Web site at http://www.esrl.noaa.gov/psd/ in any documents or publications using these data.

If the data are taken from NCAR, the citation should include the following: National Centers for Environmental Prediction/National Weather Service/NOAA/U.S. Department of Commerce. 2005, updated monthly. NCEP North American Regional Reanalysis (NARR). Research Data Archive at the National Center for Atmospheric Research, Computational and Information Systems Laboratory. https://rda.ucar.edu/datasets/ds608.0/. Accessed dd mmm yyyy.

Variable name and units:

The variables are divided into three sections: Pressure level, Monolevel (surface and others) and Subsurface. We present here wind data are available in the list of Monolevel variables (they are the output of the analysis and first guess forecast):

u wind [m/s] at 10 m, 30m

v wind [m/s] at 10 m, 30 m

Table with data available in NetCDF format at NOAA

Variable	**Statistic**	**Level**	**Download File**
U-wind at 10 m	3-hourly value	10 m	uwnd.10m.yyyy.nc
U-wind at 10 m	Daily Mean	10 m	uwnd.10m.yyyy.nc
U-wind at 10 m	Long-term Daily Mean	10 m	uwnd.10m.mon.ltm.nc
U-wind at 10 m	Monthly Mean	10 m	uwnd.10m.mon.mean.nc
V-wind at 10 m	3-hourly value	10 m	vwnd.10m.yyyy.nc
V-wind at 10 m	Daily Mean	10 m	vwnd.10m.yyyy.nc
V-wind at 10 m	Long-term Daily Mean	10 m	vwnd.10m.day.ltm.nc
V-wind at 10 m	Monthly Mean	10 m	vwnd.10m.mon.mean.nc
V-wind at 10 m	Long-term Monthly Mean	10 m	vwnd.10m.mon.ltm.nc

Values labelled 3 hourly values are output at that exact time (no averaging).

U-wind and V-wind from NARR are written so that they are earth-relative (along West-East direction and South-North direction). This is different from the operational NCEP forecasts that use grid-relative winds (along the grid X and Y axes). For the Lambert conformal and polar stereographic grids, one needs a rotation to convert from grid-relative to earth relative. NARR U-wind and V-wind have been already rotated and are provided for users using earth relative directions. They used this code for doing that.

For a complete list of model output variables, see NCEP's variable list. Details for Monolevel variables are provided on https://psl.noaa.gov/data/gridded/data.narr.monolevel.html .

Spatial coverage and resolution:

The data is available for all of North America at an approximate 0.3 degrees (32 km) spatial resolution at the lowest latitude, on a Northern Lambert Conformal Conic grid. Corners of this grid are 1.000001N, 145.5 W; 0.897945N, 68.32005W; 46.3544N, 2.569891W; 46.63433N, 148.6418E. A page describing the coverage along with information on reading the projection is available.

Temporal coverage and resolution:

Data is available as 3h values, Daily and Monthly means for 1979/01/01 to May 31, 2021, period.

Information about observations

The data that are assimilated in order to initialize the model are temperatures, winds, and moisture from radiosondes as well as pressure data from surface observations. Also included in this dataset are dropsondes, pibals, aircraft temperatures and winds, satellite radiance (a measure of heat) from polar (orbiting Earth) satellites, and cloud-drift winds from geostationary (fixed at one location viewing Earth) satellites. The sources of observations are summarized in the table below.

Dataset	Details	Source
Precipitation	Continental United States: comes from a 1/8-degree gauge dataset analyzed using PRISM and a least-squares distance-weighting algorithm. Canada and Mexico: comes from 1-degree gauge datasets and is disaggregated using NCEP R2 hourly precipitation weighting factors. Over oceans (<42.5°N): comes from the Climate Prediction Center (CPC) CMAP (CPC Merged Analysis of Precipitation), a merged combination of	NCEP/CPC,Canada, Mexico

	satellite and gauge precipitation. It is using a 15-degree "blending belt" between 27.5 and 42.5 N, with no CMAP north of 42.5 N.	
TOVS-1B radiances	Temperature, precipitable water over ocean	NESDIS
NCEP Surface	Wind, moisture	GR
TDL Surface	Pressure, wind, moisture	NCAR
COADS (ships/buoys)	Pressure, wind, moisture	NCEP/EMC
Air Force Snow	Snow depth (The Air Force Weather Agency snow depth is estimated daily by merging satellite-derived snow cover data with daily snow depth reports from ground stations.)	COLA and NCEP/EMC
SST	1-degree Reynolds, with Great Lakes SSTs	NCEP/EMC, GLERL
Sea and lake ice	Contains data on Canadian lakes, Great Lakes	NCEP/EMC, GLERL, Ice Services Canada
Tropical cyclones	Locations used for blocking of CMAP Precipitation	Lawrence Livermore National Laboratory

The following figure presents sample distributions of surface assimilated data.

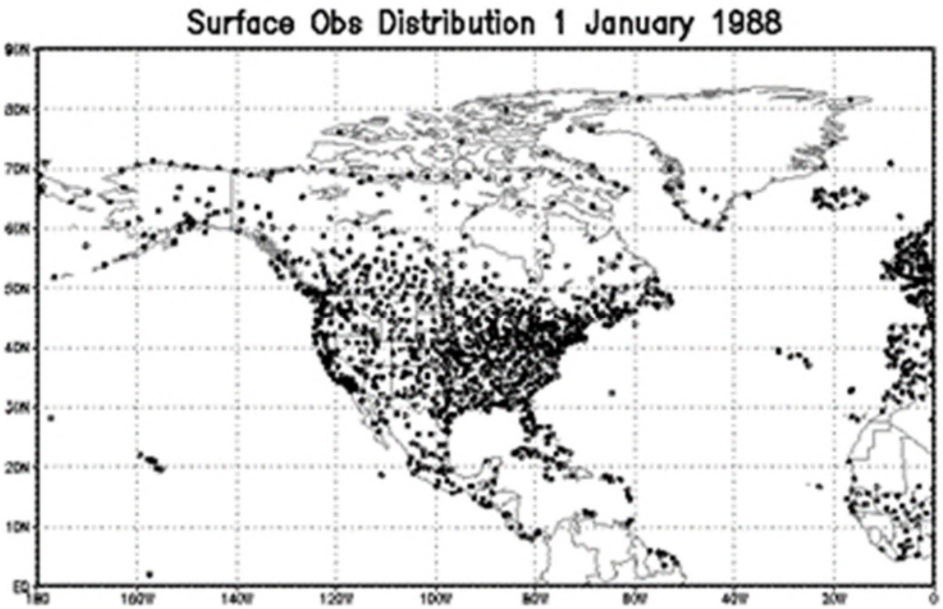

Figure 1. Sample distribution of surface observations

Methodology

The NARR project is an extension of the NCEP Global Reanalysis which is run over the North American Region. The NARR model uses a high-resolution NCEP Eta Model (32 km/45 layer) together with the Regional Data Assimilation System (RDAS) using 3DVAR method, and it is one of the few reanalysis that assimilates precipitation along with other variables, also over Canada this feature is much reduced comparable to the US. It is using the ETA / NOAH land surface model and it is assimilating snow depths from US Air Force daily snow depth analysis.

For more information, please refer to the publication in the references section below.

Information about the technical and scientific quality

The improvements in the model/assimilation have resulted in a dataset with substantial improvements in the accuracy of temperature, winds and precipitation compared to the NCEP-DOE Global Reanalysis 2 (the parent global reanalysis). Wind improvement is especially greatest in the upper troposphere in winter. The 10 m winds improved greatly in winter, a little bit in summer. Relative humidity also improved in both analysis and first guess forecast.

Precipitation over Canada: the number of gauge observations is insufficient to do better than the model is doing.

Tests on assimilation of 2 m land surface station air temperatures, in NARR proved to be harmful in the sense of making the first guess considerably worse, throughout the troposphere. Consequently, 2 m land surface station air temperatures are not assimilated by NARR.

Useful information can be found at NCEP's NARR FAQ page: http://www.emc.ncep.noaa.gov/mmb/rreanl/faq.html.

Data is updated on a monthly base.

Limitations and strengths for application in North Canada

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References to documents describing the methodology or/and the dataset

Mesinger, F., G. DiMego, E. Kalnay,K. Mitchell, P. C. Shafran, W. Ebisuzaki, D. Jović, J. Woollen, E. Rogers, E. H. Berbery, M. B. Ek, Y. Fan, R. Grumbine, W. Higgins, H. Li, Y. Lin, G. Manikin, D. Parrish, and W. Shi, 2006: North American Regional Reanalysis. Bulletin of the American Meteorological Society, 87(3), 343-360, doi:10.1175/BAMS-87-3-343.

Link to download the data and format of data:

NARR is available through NOAA ftp page, UCAR and from NCDC page.

NOAA: ftp://ftp.cdc.noaa.gov/Datasets/NARR/ (NetCDF standard format; the data are divided by variable and year and month into separate files; Missing data is flagged with a value of 9.96921e+36f.)

NCDC: https://www.ncdc.noaa.gov/data-access/model-data/model-datasets/north-american-regional-reanalysis-narr (GRIB format)

UCAR: https://rda.ucar.edu/datasets/ds608.0/ (GRIB format)

Publications including dataset evaluation or comparison with other data in northern Canada

7.4.10 <u>Dataset</u>: North American Precipitation and Land Surface Reanalysis - Regional Deterministic Reforecast System (RDRS) - wind

Overview

This document focuses on wind data from RDRSv2. RDRSv2 is a precipitation and surface reanalysis developed at the Canadian Centre for Meteorological and Environmental Prediction (CCMEP) of Environment and Climate Change Canada (ECCC). It provides various forecasted meteorological variables obtained with the Regional Deterministic Reforecast System (RDRS) two-way coupled with the Canadian Land Data Assimilation System (CaLDAS) and Precipitation Analysis (CaPA), and initialized and driven by ERA-Interim reanalysis. Results are provided at a spatial resolution of 10 km across North America. Data is currently available for the period of 1980-2017.

Provider's contact information

Data developed by the Canadian Centre for Meteorological and Environmental Prediction (CCMEP) of Environment and Climate Change Canada (ECCC)

Electronic Mail Address of the provider: The Canadian Surface Prediction Archive (caspar.data@uwaterloo.ca)

Licensing

The end-user licence for Environment and Climate Change Canada's data servers specifies the conditions of use of this data.

The Canadian Surface Prediction Archive Terms of Service

Variable name and units:

Several variables related to wind are available as **predicted values** at hourly time steps for two levels: 10 metres, and/or ~40 metres in elevation.

Variable	Variable long name	Unit	Level
RDRS_v2_P_UU_10m	U-component of the wind (along the grid X axis)	kts	10m
RDRS_v2_P_VV_10m	V-component of the wind (along the grid Y axis)	kts	10 m
RDRS_v2_P_UUC_10m	U-component of the wind (along West-East direction)	kts	10 m

RDRS_v2_P_VVC_10m	V-component of the wind (along South-North direction)	kts	10 m
RDRS_v2_P_UVC_10m	Wind Modulus (derived using UU and VV)	kts	10 m
RDRS_v2_P_WDC_10m	Meteorological wind direction (derived using UU and VV)	[degree]	10 m
RDRS_v2_P_UU_09944	U-component of the wind (along the grid X axis)	kts	~40 m
RDRS_v2_P_VV_09944	V-component of the wind (along the grid Y axis)	kts	~40 m
RDRS_v2_P_UUC_09944	U-component of the wind (along West-East direction)	kts	~40 m
RDRS_v2_P_VVC_09944	V-component of the wind (along South-North direction)	kts	~40 m
RDRS_v2_P_UVC_09944	Wind Modulus (derived using UU and VV)	kts	~40 m
RDRS_v2_P_WDC_09944	Meteorological wind direction (derived using UU and VV)	[degree]	~40 m

Note that RDRS_v2_P_UU, RDRS_v2_P_VV are raw model outputs (along the model grid axes). CaSPAr converted the u- and v-components into wind speed (UVC) and wind direction (WDC) as well as UUC and VVC along the unrotated grid (along West-East and South-North directions).

Information about other variables available for download can be found on CaSPAr data portal.

Spatial coverage and resolution:

The data is available for all of North America at an approximate 10 km x 10 km spatial resolution on a rotated pole grid.

Temporal coverage and resolution:

RDRSv2 is available for the period of 1980-2017 at **hourly time** steps.

Information about observations (number, homogeneity)

RDRSv2 is initialized and driven by ERA-Interim reanalysis and rely only on surface observations and no remote sensing observations, such as satellite or radar data. Observations were taken from ECCC's operational and climate data archives and include wind speed. The Integrated Surface Data (ISD, DS463.3) is used in the version v2.1 for the years prior to 2000. Table 3 from Gasset et al. (2021) summarizes the surface observation datasets used in the assimilation processes.

Table 3. Surface networks and variables used by CaLDAS and CaPA.

Network	Domain covered	Availability at CCMEP	Variables used by CaLDAS	Variables used by CaPA-6h	Variables used by CaPA-24h
METAR	North America	1992-present	T, T_d	P, T, $\|\|U\|\|$	P, T, $\|\|U\|\|$
SWOB	North America	2013-present	T, T_d, S_d	Not used	P, T, $\|\|U\|\|$
SYNOP	North America	1992-present	T, T_d, S_d	P, T, $\|\|U\|\|$	P, T, $\|\|U\|\|$
AdjDlyRS	Canada	1980-present	Not used	Not used	P
RMCQ	Province of Quebec	2011-present	Not used	Not used	P, T, $\|\|U\|\|$
SHEF	USA	1998-present	Not used	Not used	P, T, $\|\|U\|\|$

T: temperature, T_d: dew point temperature, S_d: snow depth, P: total precipitation, $||U||$: wind speed

Figure 1 from Lespinas et al. (2010) is presenting the spatial distribution of the meteorological stations assimilated by CaPA and geographical limits of the Canadian terrestrial ecozones.

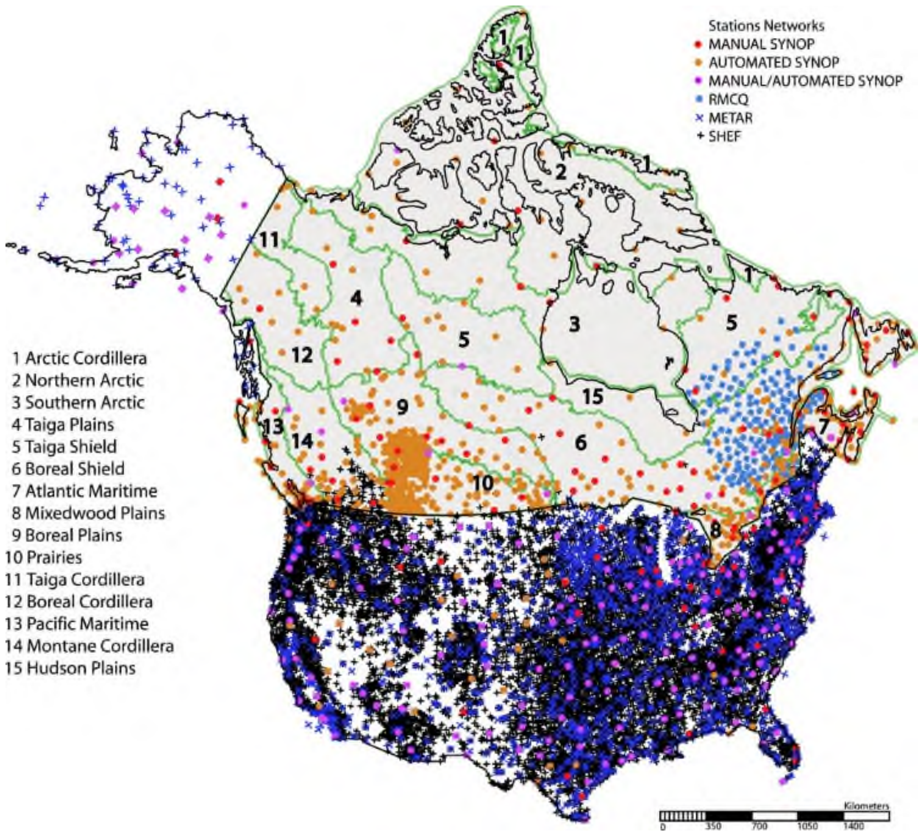


Figure 1. Spatial distribution of the meteorological stations assimilated by CaPA. Source: Journal of Hydrometeorology 16, 5; 10.1175/JHM-D-14-0191.1)

Supplementary information relevant for precipitation, soil moisture and snow: The 24 h a posteriori precipitation analysis, CaPA-24, is also using the Adjusted Daily Rain and Snow (AdjDlyRS) observations dataset (Wang *et al*., 2017). AdjDlyRS data features 3346 stations that are mainly manual stations from the Canadian synoptic network, and are known as the most reliable observations (they were adjusted for systematic errors, and in particular undercatch and evaporation caused by wind effects, gauge-specific wetting loss, as well as for trace precipitation amounts.).

There is no available information about RDRSv2.1 in this moment.

Methodology

ERA-Interim reanalysis is first used to initialize the atmospheric conditions of the Global Deterministic Reforecast System (GDRS) at a spatial resolution of 39 km. Additional surface conditions are input via the GEM-Surf model, which is also initialized by ERA-Interim. The GDRS output is then dynamically downscaled to 10 km using the RDRS. These finer resolution outputs are two-way coupled with the Canadian Land Data Assimilation System (CaLDAS) and Precipitation Analysis (CaPA) system (this means that outputs from RDRS is used to drive both the CaLDAS and CaPA system, and these results are then fed back into RDRS). This coupling results in significantly improved near-surface atmospheric and land-surface predictions.

Both GDRS and RDRS are based on the latest stable version of the Global Environment Multiscale (GEM v4.8-LTS) model and they are both using the same geophysical fields (i.e. orography, vegetation characteristics, soil thermal and hydraulic coefficients, glaciers fraction) as the corresponding forecast operational versions. The coupling with CaLDAs and CaPA allows for combining surface observations of temperature, humidity, snow depth and precipitation with the first guess provided by the RDRS. CaLDAS uses a one-dimensional Ensemble Kalman Filter (EnKF) to estimate soil moisture and soil temperature, and an optimal interpolation (OI) scheme to estimate snow depth. CaPA combines precipitation observations with a background field obtained from the short-term reforecast provided by the RDRS through an OI method. CaPA also serves to provide CaLDAS with 6-h precipitation analysis.

For more information, please refer to the publication in the references section below.

Information about the technical and scientific quality

Version 2 was evaluated and compared to the operational numerical weather prediction system (RDPS) over the period of 2010-2017. Gasset *et al*. (2021) mentions that the RDRS improves upon RDPS in most regions and for most variables, notably for Alaska and the Canadian Arctic, as well as Western USA.

In general, reanalyses often do not assimilate any observations of precipitation and of the land-surface state, but instead only provide short-term forecasts of these variables. RDRS do assimilate precipitation observations through the coupling with CaPA. Gasset *et al*. (2021) mentions that the coupling approach of the GDRS, RDRS, CaLDAS, and CaPA demonstrates significant improvements in the surface layer compared to the results obtained without coupling.

Strict quality control procedures are in place in CaPA to avoid the assimilation of biased observations, and in particular wind-induced undercatch of solid precipitation (based on a temperature analysis, different wind speed thresholds are used depending on the network, the type of gauge and whether the station is manned or automated).

In Gasset *et al*. (2021), short-term absolute temperature, dew point temperature, and wind speed forecasts from RDRSv2 were compared to observations from synoptic stations across North America. Results indicate that these data may be suitable in driving other environmental models. Likewise, a preliminary streamflow modelling study has also demonstrated that the RDRSv2 has some skill in driving hydrological models to predict runoff into Lake Erie, suggesting that the RDRSv2 may be useful for hydrological purposes.

Internal analyses at ECCC showed that RDRSv2 has good skill in estimating relative humidity in southeast Canada. However, no analysis was performed for northern Canada.

Data is available in netCDF format on CaSPAr data portal. Two scientific papers accompany the dataset, one detailing CaSPAr and the other detailing the RDRSv2 dataset. It is expected that the data will be updated regularly.

There is no available information about RDRSv2.1 in this moment.

Limitations and strengths for application in North Canada

RDRSv2 is initialized and driven by ERA-Interim, a reanalysis dataset that has been since superseded by ERA5. The pending data for the years 1980-1999 and 2018 will continue to use ERA-Interim, and tests are currently being conducted to determine the suitability and impacts of switching to another dataset. Furthermore, a bug that was identified during the development of the 2000-2017 reanalysis data: snow depth was expressed in metres in the code whereas it is supposed to be expressed in centimetres. It was verified that while biases and other errors for snow depth itself wasn't heavily impacted, snow density and snow water equivalent demonstrated significant differences. As such, these two fields are not distributed for 2000-2017 until later releases.

References to documents describing the methodology or/and the dataset

Gasset, N., V. Fortin, M. Dimitrijevic, M. Carrera, B. Bilodeau, R. Muncaster, É.,Gaborit, G. Roy, N. Pentcheva, M. Bulat, X. Wang, R. Pavlovic, F. Lespinas, and D. Khedhaouiria, 2021: A 10 km North American Precipitation and Land Surface Reanalysis Based on the GEM Atmospheric Model. Hydrology and Earth System Sciences, 25(9), 4917-4945, https://doi.org/10.5194/hess-25-4917-2021

Link to download the data and format of data:

The data can be accessed through the CaSPAr data catalogue as well as directly from their data portal:

Data catalogue: **https://github.com/julemai/CaSPAr/wiki/Available-products**

Data portal: https://caspar-data.ca/caspar **(NetCDF)**

Publications including dataset evaluation or comparison with other data

Mai, J., B.A. Tolson, H. Shen, É. Gaborit, V. Fortin, N. Gasset, H. Awoye, T. A. Stadnyk, L. M. Fry, E. A. Bradley, F. Seglenieks, A. G. T. Temgoua, D. G. Princz, S. Gharari, A. Haghnegahdar, M. E. Elshamy, S. Razavi, M. Gauch, J. Lin, X. Ni, Y. Yuan, M. McLeod, N. B. Basu, R. Kumar, O. Rakovec, L. Samaniego, S. Attinger, N. K. Shrestha, P. Daggupati, T. Roy, S. Wi, T. Hunter, J. R. Craig, and A. Pietroniro, 2021: Great Lakes Runoff Intercomparison Project Phase 3: Lake Erie (GRIP-E), Journal of Hydrologic Engineering, 26(9), 05021020-1-19. https://doi.org/10.1061/(ASCE)HE.1943-5584.0002097

Reference for CaPA:

Mahfouf, J.-F., B. Brasnett, and S. Gagnon, 2007: A Canadian precipitation analysis (CaPA) project: Description and preliminary results, Atmosphere-Ocean, 45(1), 1-17, DOI: 10.3137/ao.v450101.

Fortin, V., G. Roy, T. Stadnyk, K. Koenig, N. Gasset, and A. Mahidjiba, 2018: Ten Years of Science Based on the Canadian Precipitation Analysis: A CaPA System Overview and Literature Review, Atmosphere-Ocean, 56(3), 178-196, DOI: 10.1080/07055900.2018.1474728.

Lespinas, F., V. Fortin, G. Roy, P. Rasmussen, and T. Stadnyk, 2015: Performance Evaluation of the Canadian Precipitation Analysis (CaPA), Journal of Hydrometeorology, 16(5), 2045-2064. Retrieved May 26, 2021, from

https://journals.ametsoc.org/view/journals/hydr/16/5/jhm-d-14-0191_1.xml

7.4.11 *Dataset: NOAA-CIRES-DOE Twentieth Century Reanalysis (20CRv3) - wind*

Overview

This document provides an overview of the 10m wind data from Twentieth Century Reanalysis (20CRv3). The 20th Century Reanalysis Project is an effort led by NOAA's Physical Sciences Laboratory (PSL) and CIRES at the University of Colorado, supported by the Department of Energy (DOE), to produce reanalysis datasets spanning the entire 20th century and much of the 19th century. These reanalyses assimilate only surface observations of synoptic pressure into NOAA's Global Forecast System, and prescribed sea surface temperature and sea ice distribution in order to estimate atmospheric variables, from the surface to the top of the atmosphere throughout the 19th and 20th centuries. 20CRv3 is version 3 of the project. For version 3, the ensemble mean and standard deviation for each value were calculated over a set of 80 analyses and short-term forecasts.

Provider's contact information

20CRv3 is developed by the NOAA's Physical Sciences Laboratory (PSL) and CIRES at the University of Colorado, supported by the Department of Energy (DOE).

For help with the dataset please contact

Gilbert P. Compo

CIRES, University of Colorado at Boulder, and Physical Sciences Laboratory, National Oceanic and Atmospheric Administration

gilbert.p.compo at noaa.gov

Laura C. Slivinski

CIRES, University of Colorado at Boulder, and Physical Sciences Laboratory, National Oceanic and Atmospheric Administration

laura.slivinski at noaa.gov

Licensing and citation

20CRv3 data are provided by several collaborative organizations. User registration and agreement to terms and conditions of data service usage are required individually for each organization.

Data at NCAR RDA is licensed under a Creative Commons Attribution 4.0 International Licence.

The following citation should be used for data downloaded from NCAR RDA:

" **Slivinski**, L. C., et al. 2019. NOAA-CIRES-DOE Twentieth Century Reanalysis Version 3. Research Data Archive at the National Center for Atmospheric Research, Computational and Information Systems Laboratory. https://doi.org/10.5065/H93G-WS83. Accessed† dd mmm yyyy.

†Please fill in the "Accessed" date with the day, month, and year (e.g., - 5 Aug 2011) you last accessed the data from the RDA. "

The following citation should be used for data downloaded from Physical Sciences Laboratory (PSL) or from National Energy Research Scientific Computing Center (NERSC):

Papers using the NOAA-CIRES-DOE Twentieth Century Reanalysis Project version 3 dataset are requested to include the following text in their acknowledgments: "Support for the Twentieth Century Reanalysis Project version 3 dataset is provided by the U.S. Department of Energy, Office of Science Biological and Environmental Research (BER), by the National Oceanic and Atmospheric Administration Climate Program Office, and by the NOAA Physical Sciences Laboratory."

If you acquire 20th Century Reanalysis V3 data products from PSL, we are asked to acknowledge PSL by including also a text such as *20th Century Reanalysis V3 data provided by the NOAA/OAR/ESRL PSL, Boulder, Colorado, USA, from their Web site at /* in any documents or publications using these data and send a copy of the relevant publications to:

Physical Sciences Laboratory: Data Management

NOAA/ESRL/PSL

325 Broadway

Boulder, CO 80305-3328

psl.data@noaa.gov

Spatial coverage and resolution:

20CRv3 data, is a global dataset. 20CRv3 has a Gaussian T-254 grid (approximately 75 km at the equator).

Variable name and units:

The following table summarizes the 10m wind data.

Notation (name)	Units	Organisation (type)

VGRD10m at NERSC and VWND at PSL (V component of wind at 10 m above the surface)	m/s	PSL; NERSC; NCAR (Analysis Fields and First Guess Forecast Fields)
UGRD10m at NERSC and UWND at PSL (U component of wind at 10 m above the surface)	m/s	PSL; NERSC; NCAR (Analysis Fields and First Guess Forecast Fields)

Temporal coverage and resolution:

On PSL website, 20CRv3.SI is available for years 1836-1980 and 20CRv3.MO is available for years 1981-2015 (the only differences between these two versions are the prescribed sea surface temperatures and dates of availability):

- 3-hourly values for 1836/01/01 0Z to 2015/12/31 21Z.
- Daily average values for 1836/01/01 to 2015/12/31.
- Monthly values for 1836/01 to 2015/12 (Combined SI-MO).

At NCAR RDA, 20CRv3 is available from:

- 1835/12/31 18Z to 2016/01/01 0Z (Yearly Time Series 3-Hourly Analysis Fields (Gaussian T-254))
- 1806/12/31 18Z to 2015/12/31 12Z (Yearly Time Series 3-Hourly First Guess Forecast Fields (Gaussian T-254))
- 1806/12/31 21Z to 2015/12/31 15Z (Yearly Time Series 6-Hourly Analysis Fields (Gaussian T-254))

The data is updated on an irregular base.

Information about observations (number, homogeneity)

These reanalyses assimilate only surface observations of synoptic pressure. Boundary conditions of pentad sea surface temperature and monthly sea ice concentration and time-varying solar, volcanic, and carbon dioxide radiative forcings are prescribed.

The surface pressure observations: ISPD version 4.7, made available through international cooperation facilitated by the Atmospheric Circulation Reconstructions over the Earth (ACRE) initiative and working groups of the Global Climate Observing System and World Climate Research Program.

Sea Ice Concentration Boundary Condition: monthly HadISST2.3 sea ice (Slivinski *et al.*, 2019; Titchner & Rayner 2014; Walsh *et al.*, 2015)

Sea Surface Temperature Boundary Condition: prior to 1981(20CRv3.SI): 8 members of pentad interpolated to daily Simple Ocean Data Assimilation with Sparse Input (SODAsi) version 3 (SODAsi.3, Giese *et al.*, 2016) seasonally adjusted to the 1981-2010 HadISST2.2

climatology. Regions where sea ice was ever indicated in HadISST2.3 are filled with: HadISST2.2 daily (1963+); HadISST2.1 monthly interpolated to daily (1850-1962); or the 1861–1891 HadISST2.1 climatology (1849 and earlier). **1981 and later (20CRv3.MO)**: 8 members of pentad interpolated to daily HadISST2.2 sea surface temperatures.

Methodology

20CRv3 assimilates only surface observations of synoptic pressure into an 80-member the coupled Global Forecast System land-atmospheric model with prescribed sea surface temperatures and sea ice concentration. A coupled one-dimensional thermodynamic sea-ice model is also used. Boundary conditions of pentad sea surface temperature and monthly sea ice concentration and time-varying solar, volcanic, and carbon dioxide radiative forcings are prescribed.

Forecast model: 20CRv3 uses the atmospheric model from the NCEP Global Forecast System v14.0.1 coupled with the Noah land surface model and 2.5-layer thermodynamic sea ice model (Compo et al. (2011). The forecast system is run at a resolution of T254 (approximately 75 km at the equator) with 64 vertical levels up to .3 mb and it has 80 individual ensemble members.

Assimilation model: The data assimilation algorithm is the Ensemble Square Root Filter (Whitaker and Hamill 2002) with 4D Incremental Analysis Update (4D-IAU; Bloom et al., 1996, Lei & Whitaker 2016). The snow relaxes to a monthly climatology (Saha *et al*., 2010) over 60 days.

Streams: Every 5th year a stream is produced for a continuous 5 year period. Stream years are 1835, 1840, ... , 2005, 2010. Stream year 2010 will be extended beyond 2015.

Information about the technical and scientific quality

There are three previous versions of the reanalysis: V1, V2, and V2c. Several adjustments were made to the model prior to implementation in the 20CRv3 system. Updates to the parameterizations are described in Saha *et al*. (2010) and include revised solar radiation transfer, boundary layer vertical diffusion, cumulus convection, and gravity wave drag parameterizations. In addition, the cloud liquid water is a prognostic quantity with a simple cloud microphysics parameterization. Another important improvement is in the resolution and ensemble size. Previous 20CR versions were using a 56-member ensemble with a coarser spatial resolution (T62 28 levels), while the 20CRv3 is using 80 ensemble members with a finer spatial resolution (T254 64 levels). 20CRv3 also assimilates a larger set of observations, and includes an improved data assimilation system relative to its predecessor 20CRv2c.

Observations are first grossly tested for quality control: if the observation is outside the range 850 and 1090 hPa, or if the absolute difference between the observation and the first guess value is greater than 3.2 times the square root of the sum of the forecast ensemble variance and the observation error variance, the observation is rejected. (Slivinski *et al*., 2018). They are then subject to adaptive quality control and adaptive localization control.

Limitations and strengths for application in North Canada

Key Strengths: Length of record and estimates of uncertainty

Key Limitations: As with all reanalyses, users should take care in interpreting long-term trends - inconsistencies between 20CR and other data have been reported, especially on a regional scale.

References to documents describing the methodology or/and the dataset

Compo, G.P., J.S. Whitaker, P.D. Sardeshmukh, N. Matsui, R.J. Allan, X. Yin, B.E. Gleason, R.S. Vose, G. Rutledge, P. Bessemoulin, S. Brönnimann, M. Brunet, R.I. Crouthamel, A.N. Grant, P.Y. Groisman, P.D. Jones, M. Kruk, A.C. Kruger, G.J. Marshall, M. Maugeri, H.Y. Mok, Ø. Nordli, T.F. Ross, R.M. Trigo, X.L. Wang, S.D. Woodruff, and S.J. Worley, 2011: The Twentieth Century Reanalysis Project. Quarterly Journal of the Royal Meteorological Society, 137(654), 1-28, DOI: 10.1002/qj.776.

Slivinski, L.C., G. P. Compo, J. S. Whitaker, P. D. Sardeshmukh, B. S. Giese, C. McColl, R. Allan, X. Yin, R. Vose, H. Titchner, J. Kennedy, L. J. Spencer, L. Ashcroft, S. Brönnimann, M. Brunet, D. Camuffo, R. Cornes, T. A. Cram, R. Crouthamel, F. Domínguez-Castro, J. E. Freeman, J. Gergis, E. Hawkins, P. D. Jones, S. Jourdain, A. Kaplan, H. Kubota, F. Le Blancq, T.-C. Lee, A. Lorrey, J. Luterbacher, M. Maugeri, C. J. Mock, G.W. K. Moore, R. Przybylak, C. Pudmenzky, C. Reason, V. C. Slonosky, C. A. Smith, B. Tinz, B. Trewin, M. A. Valente, X. L. Wang, C. Wilkinson, K. Wood, and P. Wyszyński, 2019: Towards a more reliable historical reanalysis: Improvements for version 3 of the Twentieth Century Reanalysis system. Quarterly J. Roy. Meteorol. Soc., in press. DOI: 10.1002/qj.3598.

Link to download the data and format of data:

20CRv3 data are available at several organizations.

At NOAA/PSL, the ensemble mean and the ensemble uncertainty files are available in netCDF4 format: https://psl.noaa.gov/data/gridded/data.20thC_ReanV3.monolevel.html

At National Center for Atmospheric Research (NCAR), the ensemble mean and the ensemble uncertainty files are available in netCDF4 format: https://rda.ucar.edu/datasets/ds131.3/

At NERSC Science Gateway, data for every member of 20CRv3 are available in netCDF4 format: https://portal.nersc.gov/project/20C_Reanalysis/

Publications including dataset evaluation or comparison with other data in Canada

7.4.12 *Dataset: ECMWF 5th Generation Land Reanalysis (ERA5-Land) - wind*

Overview

This document provides an overview of the 10m wind of ERA5-Land, in the context of the larger ERA5-Land dataset. ERA5-Land is a replay of the land component of the ERA5 atmospheric global reanalysis using a finer spatial resolution and including a series of improvements making it more accurate for all types of land applications. ERA5-Land is produced by ECMWF framed within the Copernicus Climate Change Service (C3S) of the European Commission. The data covers a period from January 1950 to the present. It provides hourly data for many near-surface atmospheric and land-surface parameters.

Provider's contact information

ERA5-Land is produced by the Copernicus Climate Change Service (C3S) at ECMWF.

Copernicus User support (copernicus-support@ecmwf.int (external to C3S)).

Licensing

Licence: Copernicus (Licence agreement information can be found here or here).

Dataset citable as: **Muñoz Sabater**, J., 2019: ERA5-Land hourly data from 1981 to present. Copernicus Climate Change Service (C3S) Climate Data Store (CDS). (Accessed on < DD-MMM-YYYY >), 10.24381/cds.e2161bac

Variable name and units:

The 10m wind products of ERA5-Land over Northern Canada is the main focus of this document. This parameter has units of metres per second (m s^{-1}) and it is available as **hourly** and **monthly** subsets.

Name	Units	Description
10 m u-component of wind	m s^{-1}	Eastward component of the 10m wind. It is the horizontal speed of air moving towards the east, at a height of ten metres above the surface of the Earth, in metres per second. Care should be taken when comparing this variable with observations, because wind observations vary on small space and time scales and are affected by the local terrain, vegetation and buildings that are represented only on average in the ECMWF Integrated Forecasting System.

		This variable can be combined with the V component of 10m wind to give the speed and direction of the horizontal 10m wind.
10 m v-component of wind	m s^{-1}	Northward component of the 10m wind. It is the horizontal speed of air moving towards the north, at a height of ten metres above the surface of the Earth, in metres per second. Care should be taken when comparing this variable with observations, because wind observations vary on small space and time scales and are affected by the local terrain, vegetation and buildings that are represented only on average in the ECMWF Integrated Forecasting System. This variable can be combined with the U component of 10m wind to give the speed and direction of the horizontal 10m wind.

Those products can be found by selecting their name from the wind category on the pages below:

- hourly data from 1950 to present,
- monthly averaged data from 1981 to present,

Spatial coverage and resolution:

ERA5-Land is a global land-surface dataset. The atmospheric data is available on a regular latitude-longitude grid at 0.1° x 0.1° resolution (converted from native reduced-Gaussian grid resolution of approximately 9 km x 9 km), and on 4 surface layers. Oceans have been masked out and the data is available only over landmasses and inland lakes.

Temporal coverage and resolution:

ERA5-Land data is available from 1950 to present at hourly time step and from 1981 to present at monthly time step (the 1950 – 1980 back extension for the monthly data is scheduled to be available in 2022).

ERA5-Land data updates are made synchronously with ERA5 updates, approximately 2-3 months behind real time.

Information about observations (number, homogeneity)

ERA5-Land is not directly influenced by observations, but rather, indirectly influenced through the ERA5 atmospheric forcings. ERA5's data assimilation uses observations for all geophysical quantities from about 0.75 million observations per day in 1979 and about 24 million in 2018. The 2D-OI uses surface observations at 'screen level'. The online technical documentation provides tables with the satellite and in-situ observations used as input into ERA5. Further details can also be found in the ERA5 document previously prepared by the CCCS.

Methodology

ERA5-Land is produced under a single simulation of the land component of the ERA5 climate reanalysis, without coupling to the atmospheric module of the ECMWF's Integrated Forecasting System (IFS) and without data assimilation. The low atmospheric forcing is provided by the ERA5 reanalysis, with additional lapse-rate correction. The core of ERA5-Land is the Tiled ECMWF Scheme for Surface Exchanges over Land incorporating land surface hydrology (H-TESSEL). Because it runs without data assimilation, it makes it computationally affordable for relatively quick updates. For example, if significant improvements of the land surface model are implemented, the whole or part of the dataset can be reprocessed in a relatively short period. Updates are possible in case improved auxiliary datasets are used as input for the production.

Production of ERA5-Land is not produced as a single continuous segment, but instead as three segments: Stream-1 (2001 onwards), Stream-2 (1981-2000), and Stream-3 (1950-1980). This is because it allows parallel production of data enabling sooner public access to the data, and because the atmospheric forcings used by ERA5-Land is derived from ERA5, thus needing corresponding completed ERA5 segment. Each stream is initialized with various meteorological fields from ERA5 (temperature, precipitation, humidity, radiation, etc.). While ERA5-Land does not assimilate observations directly, they are introduced via the ERA5 atmospheric forcings. These forcings are adjusted using ERA5 derived lapse rates before being integrated with the ECMWF Carbon Hydrology-Tiled ECMWF Scheme for Surface Exchanges over Land (CHTESSEL) land surface model. This is done in 24-hour cycles, generating hourly outputs and the evolution of the land surface state and water and energy fluxes. For further details of the assimilation system used to obtain the ERA5 atmospheric forcings, please see the ERA5 document previously prepared by the CCCS.

Uncertainty estimate: Currently, ERA5-Land variable uncertainty estimates are those corresponding to ERA5. ERA5 uncertainty estimate is sampled by a 10-member lower-resolution Ensemble Data Assimilation (EDA) which provides background-error estimates for the deterministic HRES 4D-Var Data Assimilation system. The analysis method is the same for each EDA member and follows that of the HRES. Each member (except the control) is run with different random perturbations added to the observations. Likewise, the model physical tendencies are perturbed in the short forecasts that link subsequent analysis windows. Ensemble mean and spread have been pre-computed for convenience. Such uncertainty estimates are closely related to the information content of the available observing system

which has evolved considerably over time. They also indicate flow-dependent sensitive areas. To facilitate many climate applications, monthly-mean averages have been pre-calculated too, though monthly means are not available for the ensemble mean and spread.

The original plan was to apply the same methodology ERA5-Land was to provide an estimate of the uncertainty fields as was done for ERA5. However, the uncertainty was estimated to be extremely low, and would have assigned unrealistically high confidence to the ERA5-Land variables. As such, it is recommended to use the corresponding ERA5 uncertainty estimates for the time being until further studies are done.

Information about the technical and scientific quality

ERA5-Land represents one of the products of the latest global atmospheric reanalysis produced by Copernicus Climate Change Service at ECMWF. It is archived at a shorter (hourly) time step, has a fine spatial resolution, uses a more advanced assimilation system and includes more sources of data than previous versions (e.g., ERA-Interim-Land). It is accompanied by extensive technical documentation and two principal scientific documentation papers. A list of 'known issues' is maintained at the online documentation (https://confluence.ecmwf.int/display/CKB/ERA5-Land%3A+data+documentation).

Information on land surface model: The land surface model of the ERA5-Land was operational in 2018 with the IFS model cycle 45r1. While most of the changes from the IFS Cy41R2 used in ERA5 are primarily technical, there were a few improvements to various fields: 1) the parameterization of the soil thermal conductivity was updated to take the ice component of frozen soil into consideration, 2) conservation of the soil-water balance was fixed and improved, and 3) rain over snow is now accounted for and is not accumulated in snow pack. Furthermore, a bug exists in IFS Cy41R2, that affects potential evapotranspiration (PET) flux calculations over forests and deserts, has been corrected in ERA5-Land, and unlike ERA5, ERA5-Land PET is an available dataset. However, PET is now determined by assuming a vegetation type of crops and no soil moisture stress. These assumptions may not be always realistic, and therefore PET should be used cautiously. More information on the CHTESSEL land surface model used in ERA5-Land can be found in Muñoz-Sabater *et al*. (2021, preprint).

Limitations and strengths for application in North Canada

ERA5-Land is a newer land surface reanalysis and there are few available scientific evaluations of the dataset dedicated specifically to northern Canada. However, it should be noted that in northern Canada, there are currently no sub-daily records over a long historical period for many weather stations. Reanalyses data with hourly output cover this gap and, with suitable investigation and calibration (downscaling), could be valuable particularly for sub-daily extremes analyses.

As for all gridded data, observed values of 10 m wind at local scales can differ from the values provided by the gridded dataset, which represent a statistical summary of the area surrounding a grid point. As previously described in the variables section, care should be taken when comparing this variable with observations, because wind observations vary on small space and time scales and are affected by the local terrain, vegetation and buildings.

References to documents describing the methodology or/and the dataset

Muñoz Sabater, J., 2019: ERA5-Land hourly data from 1981 to present. Copernicus Climate Change Service (C3S) Climate Data Store (CDS). (Accessed on < 25-Jun-2021 >), https://doi.org/10.24381/cds.e2161bac

Muñoz-Sabater, J., E. Dutra, A. Agustí-Panareda, C. Albergel, G. Arduini, G., Balsamo, S. Boussetta, M. Choulga, S. Harrigan, H. Hersbach, B. Martens, D. G. Miralles, M. Piles, N. J. Rodríguez-Fernández, E. Zsoter, C. Buontempo, and J.-N. Thépaut, 2021: ERA5-Land: A state-of-the-art global reanalysis dataset for land applications. *Earth System Science Data*, *13*(9), 4349-4383. https://doi.org/10.5194/essd-2021-82

Hersbach, H., B .Bell, P. Berrisford, S. Hirahara, A. Horányi, J. Muñoz-Sabater, J. Nicolas, C. Peubey, R. Radu, D. Schepers, A. Simmons, C. Soci, S. Abdalla, X. Abellan, G. Balsamo, P. Bechtold, G. Biavati, J. Bidlot, M. Bonavita, G. Chiara, P. Dahlgren, D. Dee, M. Diamantakis, R. Dragani, J. Flemming, R. Forbes, M. Fuentes, A. Geer, L. Haimberger, S. Healy, R.J. Hogan, E. Hólm, M. Janisková, S. Keeley, P. Laloyaux, P. Lopez, C. Lupu, G. Radnoti, P. Rosnay, I. Rozum, F. Vamborg, S. Villaume, and J.-N. Thépaut, 2020: The ERA5 global reanalysis. Quarterly Journal of the Royal Meteorological Society, 146(730), 1999–2049. https://doi.org/10.1002/qj.3803.

Link to download the data and format of data:

Data Access: Copernicus | ECMWF (requires login)

ERA5-Land is available in GRIB and NetCDF formats

Link to download hourly and monthly data on Copernicus:

- hourly data from 1950 to present,
- monthly averaged data from 1981 to present

Publications including dataset evaluation or comparison with other data in Canada

7.5 Snow

7.5.1 <u>Dataset</u>: Bennett Townsite Automatic Weather Station, BC (Chilkoot Trail National Historic Site)

Overview

Single station operated near the Bennett Townsite, in area of cleared pine forest between Lindeman Lake and Bennett Lake, primarily to generate fire weather indices

Provider contact information

Operated by Parks Canada: overview information posted by Yukon Government at http://rwis.gov.yk.ca/stations/PCB/

Licensing: Not clear from posted information

Variable name and units

Snow Depth, Rainfall 1h, Air Temperature, Relative Humidity, Wind Direction, Wind Gust, Wind Speed

Spatial coverage and resolution

Point coverage local to 59.834°N 135.0°W, elevation 701.7 m

Temporal coverage and resolution

Established August 2015
Hourly values (averages / samples / totals, depending on metric) recorded

Information about related datasets

Part of Parks Canada Weather Network, but may also provide input to Yukon Wildland Fire Management / Community Services Weather Network

Limitations and strengths for application

Single isolated station, short period of record (to date). Not clear that data are available: no quality-control details provided.

References

None available

Link to download data (and format)

“Data web address” listed as http://rwis.gov.yk.ca/stations/PCB/ – but no means of accessing data available at this URL. On request from Parks Canada / Yukon Government.

7.5.2 *<u>Dataset</u>: Yukon Avalanche Association Weather Network*

Overview

Four stations listed as operated by YAA, with data for three others from Yukon Government departments: established primarily to provide near-real-time information relating to avalanche risk. Unfortunately only three stations record any snow-related metrics.

- YAA Mt Anderson, Wheaton Valley (YAAAND)
- YAA Fraser (YAAFRA)
- YAA Haines Pass (YAAHP)
- YAA Summit Creek (YAASUM)
- YG Hwy Fraser Highway Camp (HWYFRA)
- YG Hwy Mount Racine (HWYRAC)
- YG Wildland Fire Mgmt Mount Sima (SIMA)

Provider contact information

Yukon Avalanche Association http://www.yukonavalanche.ca
Yukon Government Highways michael.smith@gov.yk.ca / 867-456-3975
Same contact for Wildland Fire Management – Community Services Weather Network

Licensing

Archiving strategy not clear from available information: no response as yet to enquiries. Data provided by YG available on request, but with no guarantees as to response-time

Variable name and units

YAAAND: Air Temperature, Relative Humidity, Wind Speed, Wind Gust, Wind Direction
YAAFRA: Air Temperature, Snow Temperature, Relative Humidity, **Snow Depth**, Sea Level YAAHP: **Snow Depth**, **Snow-Water Equivalent**, Air Temperature, Relative Humidity, Wind Speed, Wind Gust, Wind Direction, Rain, Reflected (ie outgoing / upwelling) Shortwave Radiation
YAASUM: Air Temperature, Relative Humidity, Wind Speed, Wind Gust, Wind Direction
Pressure
HWYFRA: Air Temperature, Clouds, Liquid Precipitation 24hr, Max Temperature 24hr, Min Temperature 24hr, Sky Condition, **Snow**

Depth, Visibility, Wind Direction, Wind Speed
HWYRAC: Air Temperature, Relative Humidity, Wind Speed, Wind Direction
SIMA: Air Temperature, Relative Humidity, Wind Speed, Wind Gust, Wind Direction

Spatial coverage and resolution

YAAAND:	60.2096°N	135.1525°W	
YAAFRA:	59.7155°N	135.0503°W	
YAAHP:	59.6218°N	136.4429°W	952 m
YAASUM:	59.7020°N	135.0900°W	
HWYFRA:	59.7151°N	135.0470°W	855 m
HWYRAC:	59.9875°N	134.6962°W	1709 m
SIMA:	60.60445°N	135.06195°W	1165 m

Temporal coverage and resolution

YAAAND:	2012-	inactive (?)	
YAAHP:	2018-present	active	
YAAFRA:	2011-present	active	
YAASUM:	2016-present	active	
HWYFRA:	1970-present	inactive (?)	hourly
HWYRAC:	1970-present	active	hourly
SIMA:	2014-2017, 2018-present	inactive (?)	hourly

Note – SIMA flagged on YG site as inactive, but YAA site shows plots to current time (15 Sep 2021)

Information about related datasets

HWYFRA, HWYRAC contribute to YG Highways Weather Network and Wildland Fire Management – Community Services Weather Network, SIMA to latter only

Limitations and strengths for application

Not clear that data are available: no quality-control details provided

References

None available

Link to download data (and format)

Not clear if YAA data are archived or publicly available: seven-day plots on YAA web site, but not all are functioning (those for HWYRAC, YAAHP and SIMA appear to operational as of Sep 2021: YAAAND and YAASUM seem to have major errors: no data shown for others). Data from YG-operated stations is publicly available on request, but with no guarantees as to response-times.

YAAAND
http://www.yukonavalanche.ca/wx/weather.php?station=YAAAND
YAAFRA
http://www.yukonavalanche.ca/wx/weather.php?station=YAAFRA
YAAHP
http://www.yukonavalanche.ca/wx/weatherHP.php?station=YAAHP
YAASUM
http://www.yukonavalanche.ca/wx/weather.php?station=YAASUM
HWYFRA
http://www.yukonavalanche.ca/wx/weather.php?station=HWYFRA
http://rwis.gov.yk.ca/stations/FRAH/
HWYRAC
http://www.yukonavalanche.ca/wx/weather.php?station=HWYRAC
http://rwis.gov.yk.ca/stations/RAC/
SIMA
http://www.yukonavalanche.ca/wx/weather.php?station=SIMA
http://rwis.gov.yk.ca/Stations/SIM/

7.5.3 *__Dataset__: Arctic Institute of North America, Kluane Lake Research Station*

Overview

The Kluane Lake Research Station (KLRS), part of the Arctic Institute of North America (AINA, University of Calgary) has operated an automatic weather station since 2012. A Campbell Scientific SR50 sonic sensor has been installed throughout this time: the archive now offers (almost) continuous records from June 2017. It is intended that this station will remain operational indefinitely.

Provider contact information

KLRS – https://klrs.ca
AINA – https://arctic.ucalgary.ca

Licensing

Publicly available with no constraints – currently on request or

Variable name and units

Temperature, air, 2 m height: 30 min avg (°C)	(Temp_Air2m_Avg_30min)
Temperature, radiometer thermistor: 30min avg (K)	(Temp_RTD_Avg_30min)
Temperature, datalogger enclosure: 30min avg (°C)	(Temp_Enclosure_Avg_30min)
Temperature, air, 2 m height: 30 min min (°C)	(Temp_Air2m_Min_30min)
Temperature, air, 2 m height: 30 min max (°C)	(Temp_Air2m_Max_30min)
Relative Humidity: 30 min avg (%)	(RH_Air2m_Avg_30min)
Wind speed: 30 min avg (m/s)	(WindSpd_Avg_30min)
Wind speed: 30 min max (m/s)	(WindSpd_Max_30min)
Wind direction: 30 min avg (Deg)	(WindDirn_Avg_30min)
Wind direction: 30 min SD (Deg)	(WindDirn_SD_30min)
SW radiation, downwelling: 30 min avg, corrected (W/m^2)	(SW_in_Avg_30min)
SW radiation, downwelling: 30 min SD, corrected (W/m^2)	(SW_in_SD_30min)
SW radiation, upwelling: 30 min avg, corrected (W/m^2)	(SW_out_Avg_30min)
LW radiation, downwelling: 30 min avg, corrected (W/m^2)	(LW_in_Avg_30min)
LW radiation, downwelling: 30 min SD, corrected (W/m^2)	(LW_in_SD_30min)
LW radiation, upwelling: 30 min avg, corrected (W/m^2)	(LW_out_Avg_30min)

LW radiation, downwelling: 30 min avg, uncorrected (W/m²)	(LW_in_raw_30min)
LW radiation, upwelling: 30 min avg, uncorrected (W/m²)	(LW_out_raw_30min)
Rainfall: 30 min total (mm)	(Rainfall_Tot_30min)
Snow surface range from sensor: 30 min sample (m)	(Snow_Range_30min)
Snow depth: 30 min min (m)	(SnowDepth_Min_30min)
Snow depth: 30 min avg (m)	(SnowDepth_Avg_30min)
Atmos. Pressure: 30 min avg (mb)	(Pressure_Avg_30min)
Temperature, air, 2 m height: 5 min avg (°C)	(Temp_Air2m_Avg_5min)
Relative Humidity: 5 min avg (%)	(RH_Air2m_Avg_5min)
Wind speed: 5 min avg (m/s)	(WindSpd_Avg_5min)
Wind speed: 5 min max (m/s)	(WindSpd_Max_5min)
Wind direction: 5 min avg (Deg)	(WindDir_Avg_5min)
Wind direction: 5 min SD (Deg)	(WindDir_SD_5min)
SW radiation, downwelling: 5 min avg (W/m²)	(SW_in_Avg_5min)
SW radiation, upwelling: 5min avg (W/m²)	(SW_out_Avg_5min)
Nett radiation: 5 min avg (W/m²)	(NR_Wm2_Avg_5min)

Spatial coverage and resolution

Single point, at SW end of Kluane Lake: 61.02759°N, 138.41045°W, 793 m

Temporal coverage and resolution

30-minute observations:

Pressure_Avg_30min:	Aug 2012 – May 2013; Aug 2013 – Sep 2014; Jun 2017 – present
Rainfall_Tot_30min:	Aug 2013 – Sep 2014; Jun 2017 – present
RH_Air2m_Avg_30min:	Jun 2017 – present
Snow_Range_30min:	Aug 2012 – May 2013; Aug 2013 – Sep 2014; Jun 2017 – present
SnowDepth_Avg_30min:	Jun 2017 – present
SnowDepth_Min_30min:	Jun 2017 – present
LW_in_Avg_30min:	Jun 2017 – present
LW_in_raw_30min:	Jun 2017 – present

LW_in_SD_30min:	Jun 2017 – present
LW_out_Avg_30min:	Jun 2017 – present
LW_out_raw_30min:	Jun 2017 – present
SW_in_Avg_30min:	Jun 2017 – present
SW_in_SD_30min:	Jun 2017 – present
SW_out_Avg_30min:	Jun 2017 – present
Temp_Air2m_Avg_30min:	Jun 2017 – present
Temp_Air2m_Max_30min:	Jun 2017 – present
Temp_Air2m_Min_30min:	Jun 2017 – present
Temp_Enclosure_Avg_30min:	Jun 2017 – present
Temp_RTD_Avg_30min:	Jun 2017 – present
WindDirn_Avg_30min:	Jun 2017 – present
WindDirn_SD_30min:	Jun 2017 – present
WindSpd_Avg_30min:	Jun 2017 – present
WindSpd_Max_30min:	Jun 2017 – present

5-minute observations:

NR_Wm2_Avg_5min:	Aug 2012 – Sep 2014
RH_Air2m_Avg_5min:	Aug 2012 – Sep 2014
SW_in_Avg_5min:	Aug 2013 – Sep 2014
SW_out_Avg_5min:	Aug 2013 – Sep 2014
Temp_Air2m_Avg_5min:	Aug 2012 – Sep 2014
WindDir_Avg_5min:	Aug 2012 – Sep 2014
WindDir_SD_5min:	Aug 2012 – Sep 2014
WindSpd_Avg_5min:	Aug 2012 – Sep 2014
WindSpd_Max_5min:	Aug 2012 – Sep 2014

Information about related datasets

Observations are currently contributed to Global Cryosphere Watch and INTERACT. Efforts are under way to provide near-real-time updates from the station to a data repository managed as part of the Arctic Sensor Web, as part of the Arctic Connect initiative.

Limitations and strengths for application

Single site, operating continuously only from Jun 2017: currently no quality control applied to observed data

References

None available

Link to download data (and format)

By request, currently: on demand from database via web request in near future (2022)

7.5.4 *<u>Dataset</u>: Scotty Creek Research Site, NWT*

Overview

Developed as a research basin by Wilfred Laurier University since 1999. In the lower Liard River drainage: Scotty Creek flows into the Liard R. ~50 km south of Fort Simpson (where the Liard joins the Mackenzie).

Basin comprises broad permafrost wetlands: open fen, muskeg with islands of sparse woodland. Two permanent meteorological stations, and near Fort Simpson MSC weather station. Landscape comprises both discontinuous permafrost and peatland complexes, typical of 'continental high boreal' wetland region. Most of the basin comprises ~3 - 4 m of peat over thick clays and silts. Typical of S limits of permafrost, where peat insulates and preserves patches of permafrost in isolated raised plateaus.

Regional climate is dry continental with short, dry summers and long, cold winters: mean annual air temperature ~-3.2 °C, total annual precipitation ~369 mm (46% of which falls as snow).

Research focuses mainly on vegetation and permafrost dynamics, and effects on hydrological cycling.

Provider contact information

Dr. Bill Quinton
Professor, Geography and Environmental Studies; Director, Cold Regions Research Centre
Wilfred Laurier University, Waterloo, ON

wquinton@wlu.ca

519-884-0710 ext. 3281

Licensing

Information not provided – likely to be unrestricted (in general)

Variable name and units

Snow Surveys: depth, density, SWE

Meteorological: air temperature, relative humidity, IR ground surface temperature, wind speed, wind direction, net radiation, incoming and outgoing shortwave and longwave radiation, snow depth, ground heat flux, snow temperature, soil temperature (0-100 cm), precipitation

Volumetric soil moisture, shallow groundwater (active layer) measurements in different land cover types: frost table surveys (some peat plateaus)

Hydrometric: Water level, discharge, water temperature

High-resolution LiDAR

Spatial coverage and resolution

Basin drainage area 152 km^2: site focused around 61.30000°N, 121.30000°W

Three permanent weather stations: Bog Tower, Plateau Tower, Dense Tower (locations not provided)

Temporal coverage and resolution

Annual (usually) snow survey, frost table survey (some peat plateaus), soil moisture survey
Earliest snow surveys from 1995

Volumetric soil moisture: GB3 2000-2001, GB PL 2002-2012 30 min

Meteorological:
First stations established in 2001
Bog Tower, Plateau Tower 2004-17 30 min
Dense Tower 2007-17 30 min

Hydrometric (WSC) from 1993 15 min stage

Information about related datasets

n/a

Limitations and strengths for application

Local spatial focus, geared primarily towards hydrological research (landscape – snow – vegetation – permafrost – runoff dynamics)

References

Haynes, K.M., R.F. Connon, and W.L. Quinton, 2018: Hydrometeorological measurements in peatland-dominated, discontinuous permafrost at Scotty Creek, Northwest Territories, Canada [Dataset]. Scholars Portal Dataverse. https://doi.org/10.5683/SP/OQDRJG

Quinton, W.L., R.F. Connon, E.G.,Devoie, M. Hayashi, and T. Veness, 2018: Micrometeorological and freeze-thaw data at Scotty Creek, NT 2001-2017 [Canada] [Dataset]. Scholars Portal Dataverse. https://doi.org/10.5683/SP/EMDB8K

Site metadata from Global Water Futures network
https://gwfnet.net/Metadata/Record/T-2020-05-15-o1lc5QwDehk28bmpnV1cY5Q

Older metadata
http://giws.usask.ca/meta/Metadata_ScottyCreek.html

Overview from Changing Cold Regions Network
https://ccrnetwork.ca/science-programme/wecc-observatories/scotty-creek.php

Research basin website
http://www.scottycreek.com/

Link to download data (and format)

Two datasets published in Dataverse (see above). Data may be available from Global Water Futures data portal (requires login), or on request from the originator. WSC / MSC data also available from respective archives.

7.5.5 <u>Dataset</u>: Trail Valley Creek Research Site, NWT

Overview

This site has been developed by Dr. Phil Marsh (Professor and Canada Research Chair in Cold Regions Water Sciences, Wilfred Laurier University) since 1992, ~55 km NNE of Inuvik, E of Mackenzie River Delta. Basin area ~58 km^2, with flow generally NW. Undulating terrain, some incised valleys: ~50 to 180m ASL: mean slope ~3°. In continuous permafrost zone: max thickness ~350 - 375 m observed active layer depths ~0.3 - 0.8 m. Soils are organic cryosols with upper peat layer ~0.2 - 0.5 m thick, underlain by mineral (silty clay) soil.

At N edge of boreal forest, in the tundra ecotone: primarily sparse / shrub tundra, tundra ponds. Dominant upland open tundra cover comprises grasses, lichens, mosses: hill slopes, valley bottoms are shrub tundra, ~0.5 - 3m high alder, birch, willow, with sparse pockets of black spruce forest.

Regional climate characterized by short summers and long cold winters, with snow cover for eight months annually. Most annual precipitation (66% at Inuvik) is snow, which melts over a relatively short time during spring.

Provider contact information

Dr. Phil Marsh
Professor and Canada Research Chair in Cold Regions Water Sciences
Wilfred Laurier University, Waterloo, ON

philip.marsh@outlook.com

226-868-1941

Licensing

Information not provided – likely to be unrestricted (in general)

Variable name and units

Snow surveys: snow depth (acoustic sensor SR50), soil temperature, soil water content (TDR), soil heat flux, barometric pressure

Meteorological: three permanent weather stations: precipitation, air temperature, relative humidity, wind speed, wind direction, incoming + outgoing SW, incoming + outgoing LW

Hydrometric: two gauges, +WSC gauge 10ND002: hourly water level and streamflow

Spatial coverage and resolution

Focused on 68.742915°N, 133.499625°W: ~55 km NNE of Inuvik, just east of Mackenzie River Delta. Basin area ~58 km².

Three permanent weather stations:
TMM (level open tundra) 68.74633°N, 133.50183°W (UTM 8W 560605 7626818) ~85m ASL
TUP (level open tundra) 68.69367°N, 133.69733°W (UTM 8W 552817 7620762) ~160m ASL
TTS (higher alder, willow shrubs) 68.67050°N, 133.70050°W (UTM 8W 552746 7618179) ~145m ASL

Temporal coverage and resolution

Snow surveys:	1991-2013	annual
Meteorological:	1991-2013	30 min
Hydrometric:	1977-2013	hourly

Information about related datasets

n/a

Limitations and strengths for application

Local spatial focus geared primarily towards hydrological research (landscape – snow – vegetation – runoff dynamics)

References

Site metadata from Global Water Futures network
https://gwfnet.net/Metadata/Record/T-2020-05-15-X1lTNlDtLSUapI5Y1o0kqxg

Older metadata
http://giws.usask.ca/meta/Metadata_TrailValleyCreek.html

Overview from Changing Cold Regions Network
https://ccrnetwork.ca/science-programme/wecc-observatories/trail-valley.php

Link to download data (and format

Data may be available from Global Water Futures data portal (requires login), or on request from the originator. WSC / MSC data also available from respective archives.

7.5.6 <u>Dataset</u>: Havikpak Creek Research Site, NWT

Overview

The Haikpak Creek Basin, located a few km N of Inuvik Airport, covers ~17 km² of northern boreal forest within the continuous permafrost zone. The climate comprises short summers and long, cold winters, with snow lying for ~eight months annually. Mean annual air temperature is ~-10°C, and mean annual precipitation is ~266 mm (66% as snow).

This site has been developed by as a research basin since the early 1990s, with a meteorological station installed in 1992 (Environment Canada - National Water Research Insitute) and a gauge in 1994 (Water Survey of Canada). A single 15 m meteorological tower is installed in a forested location: there is also a Meteorological Service of Canada upper air station, and another MSC station at Inuvik Airport. Research focuses on hydrology-related dynamics involving snow, vegetation, energy balance, active layer depth, thermokarst, soil water storage, and runoff.

Provider contact information

Dr. Phil Marsh
Professor and Canada Research Chair in Cold Regions Water Sciences
Wilfred Laurier University, Waterloo, ON

philip.marsh@outlook.com

226-868-1941

Licensing

Information not provided – likely to be unrestricted (in general)

Variable name and units

Meteorological: precipitation, air temperature, relative humidity, wind speed, wind direction, incoming + outgoing SW and LW radiation.

Hydrometric: water level, discharge at WSC station 10LC017

Snow surveys: snow depth (SR50 sensor), soil temperature, soil water content (TDR), soil heat flux, barometric pressure.

Spatial coverage and resolution

Focused on 68.33333°N, 133.50000°W: located a few km N of Inuvik Airport. Basin area ~17 km².

Temporal coverage and resolution

Snow surveys: 1991-2013 annual, mid to late April (some years missed)
Snow nipher (manual) data available for 1991-2001
Meteorological: 1991-2013 30 min
Hydrometric: 1996-2013 hourly

Information about related datasets

n/a

Limitations and strengths for application

Local spatial focus, geared primarily towards hydrological research (snow – vegetation – thermokarst –runoff dynamics)

References

Site metadata from Global Water Futures network
https://gwfnet.net/Metadata/Record/T-2020-05-15-d110wOsPs1U65GKhQhc1PsA

Older metadata
http://giws.usask.ca/meta/Metadata_HavikpakCreek.html

Overview from Changing Cold Regions Network
https://ccrnetwork.ca/science-programme/wecc-observatories/havikpak-creek.php

Link to download data (and format)

Data may be available from Global Water Futures data portal (requires login), or on request from the originator. WSC / MSC data also available from respective archives.

7.5.7 *Dataset: Wolf Creek Research Basin, YT*

Overview

The Wolf Creek research basin, located ~20 km SSW of Whitehorse, Yukon, covers a variety of terrain and land cover in the Boreal Cordillera ecozone. The drainage covers ~200 km^2, mainly from SW to NE, with elevations spanning 880 m to 2250 m. Surface cover ranges from dense Boreal Forest at lower elevations (~22%), through sparse forest, open meadow and shrub tundra (subalpine taiga: ~58%) at higher elevations, with exposed alpine areas (alpine tundra: ~20%) around summits. The basin hosts permafrost and several firn patches on leeward slopes at higher elevations.

The regional climate is classified as subarctic continental, characterized by wide seasonal variation in temperature, low relative humidity and relatively low precipitation. Mean annual temperature is ~-3°C, with mean monthly temperatures of 5°C – 15°C in summer, and -10°C – -20°C in winter. Summer (winter) extremes of 25°C (-40°C) are not uncommon. Mean annual precipitation is 300 – 400 mm, with approximately 40% falling as snow.

The basin's terrain, land cover and climate are thus representative of much of the interior subarctic cordillera landscape. It has hosted a wide range of environmental research since the 1992, when it was initiated as a long-term multidisciplinary research project, supported by (as it was then) Indian and Northern Affairs Canada's Arctic Environmental Strategy, in partnership with Environment Canada's National Hydrology Research Institute. Data generated by instruments installed in the basin have informed a series of major hydrometeorological research projects, led particularly by the University of Saskatchewan's Centre for Hydrology, McMaster University, and the Water Resources Branch of Yukon Environment. Other studies have covered climate and climate change, vegetation, forestry, fisheries and wildlife.

Provider contact information

Dr. Sean Carey
Professor; Director, Watershed Hydrology Group
McMaster University, Hamilton, ON

careysk@mcmaster.ca

905-525-9140 ext. 20134

Tyler DeJong – data manager (?)
McMaster University, Hamilton, ON

tyler.dejong@mcmaster.ca

Licensing

Information not provided – likely to be unrestricted (in general)

Variable name and units

Snow Surveys: depth, density, SWE
Snow Pillow: SWE
Blowing Snow: snow particle detector
Hanging Tree: Tree weight, interpreted interception and evaporation
Snowmelt Photographs

Meteorological (varies with the station): Air temperature, relative humidity, IR canopy temperature, IR ground surface temperature, wind speed (upper and lower) and direction, net radiation, incoming + outgoing SW + LW radiation, **snow depth**, **snow temperature**, ground heat flux, barometric pressure, soil temperature (10 cm), precipitation (**nipher**, tipping bucket, Geonor, standpipe, Pluvio)

Soil Moisture and Temperature: Volumetric soil moisture and ground temperature profiles

Hydrometric: Water level, discharge, water temperature

Isotope data: Stream, rain isotopes

Groundwater: Water table depth, temperature

Soil Surveys: Soil horizons, coarse content, structure, texture, etc.

Water Chemistry, Aquatic Organisms: Inorganics, metals, nutrients, organics, physical, invertebrates

Ground Temperature: deep thermistors

Eddy Correlation (Granger Basin only): Latent and sensible heat flux

GIS data: DEM from high-resolution LiDAR survey

Spatial coverage and resolution

Main basin:
Three main meteorological stations:

Forest	60.596000°N, 134.952833°W
Alpine	60.567267°N, 135.184652°W
Buckbrush	60.521630°N, 135.197151°W

Granger Sub-Basin:

Granger Basin	60.5465420°N, 135.184652°W

GB 2, Stream Site (nearby well-gauge)
GB 3, South-Facing Slope
GB 4, North-Facing Slope
GB 5, Upper Granger
GB Plateau

Three hydrometric stations:

Wolf Creek @ Hwy	60.6000°N, 134.9500°W
Coal Lake Outlet	60.5101620°N, 135.162273°W
Upper Wolf Creek	60.4908930°N, 135.291596°W

Snow Surveys: three traditional snow survey sites at Forest, Alpine, and ShrubTundra, each a 25 point transect with 5 density measurements.
Snow Pillow: Buckbrush station only
Blowing Snow: Snow particle detector at all 3 weather stations.
Hanging Tree: Forest station only.
Snowmelt Photographs: Buckbrush station only, and from GB N- + S-facing slopes

Soil moisture, temperature: at the three main weather stations, + GB3, GB PL: profiles at 5,15,30,80 cm depth

Groundwater: one deep groundwater well located in the lower portion of the basin.

Soil Surveys: 67 plots throughout basin. Bulk density and soil carbon data also available from separate surveys.

Water Chemistry, Aquatic Organisms: sampled at Wolf Creek @ Hwy by Environment Canada Freshwater Quality Monitoring and Surveillance, as part of Pacific Yukon Water Quality Monitoring Program and Canadian Aquatic Biomonitoring Network

Ground Temperature
Deep Thermisters
2006-2013
Local
University of Ottawa permafrost studies operated by Antoni Lewkowicz.

Eddy Correlation: GB 2, GB 3, GB 4, and GB Plateau stations.

Temporal coverage and resolution

Snow surveys:

Main basin:	2004-2014 (+?)	Monthly
Granger Basin	1997-2008	Variable
Snow Pillow	1996-2013	3 hr (real-time telemetry)
Blowing Snow	1993-2010	30 min
Hanging Tree	1997-2003	
Snowmelt Photographs	2012-2013	twice daily

Meteorological:

Forest, Alpine, Buckbrush	1993-2018	30 min
GB2:	1998-2009	
GB3:	1998-2004	
GB4:	1998-2004	
GB5:	1999-2008	
GB PL:	2002-2013	

Soil moisture, temperature:

ain basin stns:	1993-2018	30 min
GB3:	2000-2004	30 min
GB PL:	2002-2012	30 min

Hydrometric:

Main gauges:	1993-2013	15 min stage

(continuously from early May to early Oct: discharge also measured ~monthly, year-round)

Nr GB2	1998-2013	15 min stage
Isotope data:	2013- (+ variable samples prior) mostly biweekly	
Groundwater:	2001-2013	1hr
Soil Surveys:	1998	Non-recurring
Water chem., aquatic org.:	1993-1996, 2004-Present	Infrequent
Ground Temperature:	2006-2013	
Eddy Correlation	1999-2003	30 min

Information about related datasets

n/a

Limitations and strengths for application

Local spatial focus, geared primarily towards hydrological research (landscape – snow – vegetation – runoff dynamics): some datasets project-driven rather than strategic: potentially multiple data sources (universities, research networks, Yukon Government)

References

Published data paper:
Rasouli K., Pomeroy J.W., Janowicz J.R., Williams T.J. and Carey S. (2019) A long-term hydrometeorological dataset (1993-2014) of a northern mountain basin: Wolf Creek Research Basin, Yukon Territory, Canada. Earth Syst. Sci. Data, 11, 89-100, https://doi.org/10.5194/essd-11-89-2019

Published dataset:
Rasouli K., Pomeroy J., Janowicz J.R., Williams T. and Carey S. (2018) Hydrometeorological data collected at Wolf Creek Research Basin, Yukon Territory, Canada over 1993-2014 [Dataset]. Federated Research Data Repository. https://doi.org/10.20383/101.0113

Site metadata from Global Water Futures network
https://gwfnet.net/Metadata/Record/T-2021-02-27-M1M2i2h80VKUijFOFoBEM3wFw

Older metadata
http://giws.usask.ca/meta/Metadata_WolfCreek.html

Overview from Changing Cold Regions Network
https://ccrnetwork.ca/science-programme/wecc-observatories/wolf-creek.php

Detailed descriptions of instrumentation
http://giws.usask.ca/meta/Wolf%20Creek%20sensors.xlsx

Link to download data (and format)

Data may be available from Global Water Futures data portal (requires login), or on request from the originator. Some data available from Yukon Government (see Water Data Catalogue). WSC / MSC data also available from respective archives.

7.5.8 <u>Dataset</u>: Baker Creek Research Site, NWT

Overview

Research in the Baker Creek watershed (mainly by University of Saskatchewan and Carleton University) began in 2004, primarily in support of the Mackenzie GEWEX Study (MAGS II). At its outlet, located ~7 km north of Yellowknife, NWT, the basin drains ~155 km^2 of the Great Slave Lake watershed. The drainage comprises a series of large lakes, connected by short streams with highly variable flow regimes.

The basin is mainly exposed bedrock (40%), water bodies (23%), with coniferous forest hill slopes and deciduous forest (21%), peatlands and wetlands (16%). The basin overlies discontinuous permafrost. Overburden varies from less than 1 m to over 10 m: peat thickness ranges from a thin layer to ~1.2 m. The region's climate is subarctic, with short, cool summers and long, cold winters. Mean annual precipitation is 289 mm, with ~41% as snowfall.

The basin hosts a range of instruments to observe hydrometric, meteorological and groundwater conditions, and snow surveys are conducted annually.

Provider contact information

Dr. Chris Spence
Research Scientist
National Hydrology Research Centre, Environment & Climate Change Canada
Saskatoon, SK

chris.spence@canada.ca

306 975 6907

Licensing

Information not provided – likely to be unrestricted (in general)

Variable name and units

Snow surveys: snow depth, density and water equivalent

Groundwater: soil moisture + temperature

Soil moisture: volumetric soil moisture at surface, 25 cm and 40 cm depth

Meteorological: Air temperature, relative humidity, wind speed, wind direction, four-component net radiation, turbulent fluxes, rainfall.

Hydrometric: water level and discharge

Water chemistry (ion suite, physicals, nutrients and dissolved metals), isotope data (d18O and d2H)

Soil temperature: temperatures at surface 25 cm and 40 cm depth

LiDAR-derived 1m DEM
10 m land cover

Spatial coverage and resolution

Basin drainage area 155 km²: site focused around 62.58333°N, 114.43333°W

Snow surveys:
Eight 25 point snow courses over five land cover types conducted each spring in the first week of April.

Meteorological:
Four stations on exposed bedrock, two over lakes, one in a wetland. Additional tipping buckets at some gauging sites. MSC Yellowknife A station is 5 km from the basin.

Hydrometric:

07SB013 Baker Creek at Outlet of Lower Martin Lake (WSC)	62.5133°N, 114.4097°W
Baker Creek at outlet of Landing Lake	62.5499°N, 114.4005°W
Baker Creek at Vital Narrows	62.5792°N, 114.4159°W
Baker Creek above Vital Lake	62.5946°N, 114.4436°W
Moss Creek at the outlet of Lake 690	62.6190°N, 114.4545°W
Baker Creek at outlet of Duckfish Lake	62.6476°N, 114.4477°W

Water chemistry (ion suite, physicals, nutrients and dissolved metals), isotope data (d18O and d2H) measured at five hydrometric gauges, six wells. Wells are in organic and brunisol soils or either clayey or sandy texture.

Soil moisture, temperature:
Volumetric soil moisture at surface, 25 cm and 40 cm depth
Six sites associated with wells, four in organic soil columns, two in brunisol soil columns.
Temperature also at one deep (>10 m) thermistor string and one in exposed bedrock to 50 cm depth

Groundwater:
Ten wells at mean maximum active layer depth: six associated with soil moisture and temperature, four in organic soil columns, two in brunisol soil columns.

Temporal coverage and resolution
(note: data may now be available to more recent dates)

Snow surveys	2004-2013	Annually (early April)
Meteorological:	2005-2013 (+ later?), 30 min	
Hydrometric:		
07SB013 Baker Creek at Outlet of Lower Martin Lake (WSC)	1983-2019 (No level pre-2002)	30 min
Baker Creek at outlet of Landing Lake	2003-2016 (seasonal)	30 min
Baker Creek at Vital Narrows	2005-2016 (seasonal)	30 min
Baker Creek above Vital Lake	2008-2016 (seasonal)	30 min
Moss Creek at the outlet of Lake 690	2008-2016 (seasonal)	30 min
Baker Creek at outlet of Duckfish Lake	2009-2016 (seasonal)	30 min
Spence & Hedstrom, 2018		
Water chemistry	2010-2013	monthly
Isotope data	1995-2013	monthly
Soil moisture	2005-2013	30 min
Soil temperature	2005-2013	30 min
Groundwater	2007-2013	Semi-annually

Information about related datasets

n/a

Limitations and strengths for application

Local spatial focus, geared primarily towards hydrological research (landscape – snow – vegetation – runoff dynamics)

References

Spence C. and Hedstrom N. (2018) Hydrometeorological data from Baker Creek Research Watershed, Northwest Territories, Canada. Earth Syst. Sci. Data, 10, 1753-1767 https://doi.org/10.5194/essd-10-1753-2018

Spence C. and Hedstrom N. (2018) Baker Creek Research Catchment Hydrometeorological and Hydrological Data [Dataset]. Federated Research Data Repository. https://doi.org/10.20383/101.026

Site metadata from Global Water Futures network
https://gwfnet.net/MetadataEditor/Index/T-2021-02-27-v1pkgcEko90q7enkMmhv1Jog

Older metadata
http://giws.usask.ca/meta/Metadata_BakerCreek.html

Overview from Changing Cold Regions Network
https://ccrnetwork.ca/science-programme/wecc-observatories/baker-creek.php

Details associated with use for MESH community hydrology / land surface model
https://wiki.usask.ca/display/MESH/Baker+Creek

Link to download data (and format)

See ref to published dataset above. Data may be available from Global Water Futures data portal (requires login), or on request from the originator. WSC / MSC data also available from respective archives.

7.5.9 *__Dataset__: ANUSPLIN Canadian dataset - snow depth*

Overview

This document provides an overview of the snow depth gridded dataset created by the Canadian Forest Service, Natural Resources Canada. The dataset provides gridded snow depth from 1955 to 2017 at the daily, pentad, monthly and 30-year average time scales over Canada. It was generated using ANUSPLIN with a 60 arc-second (approximately 2 km) and with a 300 arc-second (approximately 10 km) Digital Elevation Model (DEM; Lawrence et al., 2008) and station observations from Environment and Climate Change Canada (ECCC) and the National Oceanic and Atmospheric Administration (NOAA).

Provider's contact information

This spatial dataset was developed by researchers from the Integrated Ecology and Economics Division at Canadian Forest Service at Natural Resources Canada (Dr. Dan McKenney, Dr. Heather MacDonald, John Pedlar, Kevin Lawrence, Pia Papadopol, Kaitlin de Boer from the CFS and Dr. Michael Hutchinson from Fenner School of Environment and Society, Australian National University). If you have questions about this dataset, please contact Dr. Dan McKenney (dan.mckenney@canada.ca)

Licensing

Freely available. Contact Dr. Dan McKenney, Canadian Forest Service, Natural Resources Canada, dan.mckenney@canada.ca

The following data citations should be used if you use these data in publications:

MacDonald, H., and D. McKenney, 2021: Canadian Snow Depth Spatial Models, 1950-2017. OSF. July 7. doi:10.17605/OSF.IO/UZAC9.

MacDonald, H., and D. McKenney, 2021: Comparison of Snow Depth Spatial Models Generated for Year 2000 Using Global Historical Climate Network Daily (GHCN-D) and Environment and Climate Change Canada (ECCC) in Situ Station Records." OSF. July 6. osf.io/abhng. DOI 10.17605/OSF.IO/ABHNG

Variable name and units:

Daily - Snow depth in centimetres (cm);

Pentad – Average 5-day snow depth in cm (cm);

Monthly – Maximum snow depth in centimetres (cm);

30-year Average – monthly average snow depth over 30 years in centimetres (cm)

Spatial coverage and resolution:

Two products are available over Canada:

1) at 60 arc-second (approximately 2 km),

2) at 300 arc second spatial resolution (approximately 10 km)

Temporal coverage and resolution:

Daily – 1955-2017

Pentad – 1955-2017

Monthly – 1955-2017

30-year Average – 1961/1990, 1971/2000

The data will continue to be updated regularly.

Information about observations (number, homogeneity)

The spatial gridded data of 30-year averages were constructed using 1224 stations for the 1961-1990 period and 1723 stations for the 1971-2000 period. For monthly, pentad and daily data, the number of ECCC observations ranged from 220 in 1955 to more than 2000 observations in the 1990s, declining to fewer than 2000 stations post-1996 (Figure 1). The data are not homogenized for time series analysis and are not evenly distributed in space (many stations are located in southern Canada and fewer in northern Canada). Brown et al. (2021) provide an analysis of in situ data over Canada. In-house analyses at CFS indicated that there are differences between the spatial gridded models developed in ANUSPLIN using just ECCC stations versus those using just GHCD stations (the surface means for the data developed using GHCD data are higher than those created using ECCC data). Based on Brown et al. (2021) analysis of ECCC in-situ measurements and the in-house comparison, it was decided to construct the present dataset using ECCC stations for 1955-2002 period and NOAA's GHCD station observations for the 2000-2017 period.

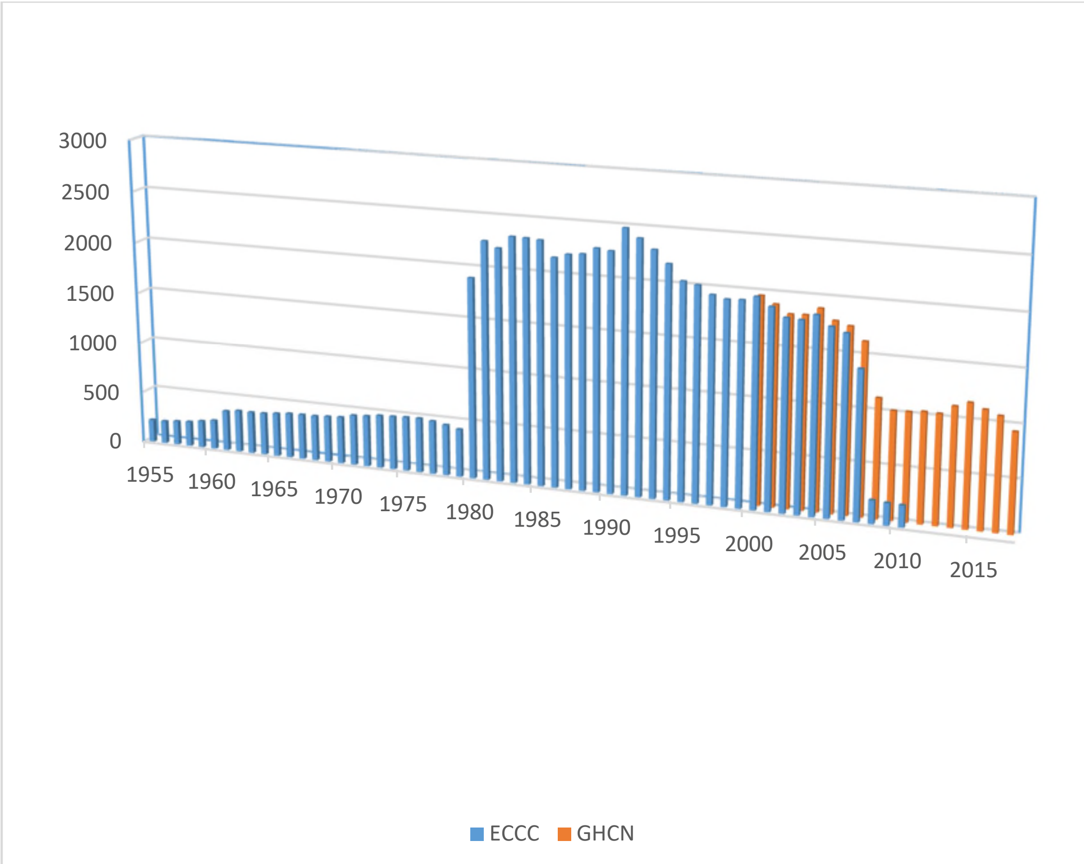


Figure 1. Number of station observations with snow depth measurements from ECCC and GHCN.

Methodology

Snow depth station observations were used to create thin-plate spline models in ANUSPLIN (Hutchinson & Xu, 2013). Snow depth observations from ECCC were available from 1955-2002 period. Those were completed with snow depth observations from the National

Oceanic and Atmospheric Administration (NOAA)'s GHCD[7] from 2000-2017 period. Station records were not joined, and instead each record was linked to the exact observation location (see description in MacDonald *et al*., 2021). Details on methodology are presented in the T1 technical documentation (provided by CFS/NRcan) at the end of this document.

Information about the technical and scientific quality

The data were quality controlled and use up-to-date spatial modelling methods as detailed in MacDonald *et al*., 2021. See also Brown *et al.* (2021) for a description of the application and assessment of snow depth estimates generated from these models.

Limitations and strengths for application in North Canada

These spatial models are based on in-situ stations. As noted by Brown *et al*. (2021), the station network exhibits "greater reliance on automated sensors over northern regions of Canada (e.g., over 80% of the Canadian surface SD-observing network north of 55°N was equipped with sonic sensors)." With respect to data quality of models based on in-situ observing stations, Brown *et al.* (2021) conclude that "the spatial and temporal coverage is insufficient to provide a complete picture of snow cover trends across Canada, but it does provide information for the most populated regions and at the community level across northern Canada."

References to documents describing the methodology or/and the dataset

Brown, R. D., C. Smith, C. Derksen, and L. Mudryk, 2021: Canadian in situ snow cover trends for 1955-2017 including an assessment of the impact of automation. Atmosphere-Ocean, 59(2), 77-92. https://doi.org/10.1080/07055900.2021.1911781

Lawrence, K. M., M. F. Hutchinson, and D. W. McKenney, 2008: Multi-scale digital elevation models for Canada. Natural Resources Canada, Great Lakes Forestry Centre Frontline Tech. Note 109, 4 pp., https://d1ied5g1xfgpx8.cloudfront.net/pdfs/31499.pdf.

Hutchinson, M. F., and T. Xu, 2013: ANUSPLIN version 4.4 user guide. Australian National University, Fenner School of Environment and Society Doc., 55 pp., https://fennerschool.anu.edu.au/files/anusplin44.pdf.

MacDonald, H., D.W. McKenney, P. Papadopol, K. Lawrence, J. Pedlar, and M. F. Hutchinson, 2020: North American historical monthly spatial climate dataset, 1901–2016. Scientific Data, 7(1), 411-411. https://doi.org/10.1038/s41597-020-00737-2

[7] https://www1.ncdc.noaa.gov/pub/data/ghcn/daily/by_year/

*MacDonald, H., D. W. McKenney, X. L. Wang, J. Pedlar, P. Papadopol, K. Lawrence, Y. Feng, and M. F. Hutchinson, 2021: Spatial models of adjusted precipitation for Canada at varying time scales. Journal of Applied Meteorology and Climatology, 60(3), 291-304. https://doi.org/10.1175/JAMC-D-20-0041.1

*Describes spatial models at the pentad time scale for adjusted precipitation, *ANUSPLIN-AdjPdly*

Technical documentation:

See T1 below detailing comparison of ECCC and GHCD spatial models for 2000.

Link to download the data and format of data:

All data is available in asci format at Canadian Forest Service, NRCan (contact Dr. Dan McKenney, dan.mckenney@canada.ca if you are interested in the asci datasets)

Monthly dataset with 300 arc-second spatial resolution in netCDF format is available at Canadian Center for Climate Services, ECCC (contact the Climate Services Support Desk, https://climate-change.canada.ca/support-desk/Inquiry, if you are interested in this netCDF subset of data)

Publications including dataset evaluation or comparison with other data in northern Canada

This dataset is a new product and was not used yet in scientific publications over northern Canada.

T1. Technical documentation Comparison of Snow Depth Spatial Datasets developed from station observations from Environment and Climate Change Canada (ECCC) and from Global Historical Climate Data (GHCD) for the year 2000

We extended a series of snow depth spatial models developed using station observation data from 1955 to 2002 from Environment and Climate Change Canada using Global Historical Climate Data (GHCD) from 2000 to 2017. This technical documentation is comparing ANUSPLIN-generated statistics **for the year 2000** that were obtained for spatial gridded models of snow depth developed using (1) ECCC and (2) GHCD stations. The analysis includes:

- Root GCV (RTGCV), or the square root of the generalized cross validation (GCV). The GCV is calculated for each value of the smoothing parameter ρ by implicitly removing each data point and calculating the residual from the omitted data point of a surface fitted to all other data points (Wahba 1990).
- Ratio of signal to the number of knots (NK) (the S:NK ratio). The signal is a measure of the complexity of the fitted surface that ranges between a small positive integer and the number of stations used to create the model (Wahba 1990). S:NK ratios greater than 0.8 or less than 0.2 represent problematic spatial surfaces (i.e. >0.8 or <0.2; Hutchinson & Xu, 2013).

Number of Stations in the Comparison

The ECCC dataset comprised 1984 observing stations overall compared to 1963 Canadian stations in the GHCD (see tables 2 and 3).

Results of the Comparison

The Root GCV (spatially averaged standard error, see Hutchinson & Xu, 2003) is somewhat lower for the spatial models using ECCC compared to GHCD, but comparable overall. The surface mean tends to be higher for spatial models built from GHCD data compared to those from ECCC data (Figure 2).

The S:NK ratio was problematic for ECCC snow depth surfaces for April, May and September 2000. For the GHCD, the April 2000 surface was problematic (red text).

Conclusion

There are differences between the spatial models developed in ANUSPLIN using ECCC versus GHCD data. Specifically, the surface means for the spatial models developed using GHCD data had higher surface means compared to those created using ECCC data. The spatial models presented here have not been homogenized for time series analysis. However, Brown et al. (2021) provide analysis of in situ snow cover trends over Canada. Future efforts will include accessing GHCD snow depth data for the entire time period.

Table 1: Statistics for Spatial Model (year=2000) using GHCD snow depth

Month	Number of Points	Error*	Signal*	Ratio*	Rt GCV (cm)	Surface Mean (cm)
1	1084	661.8	422.2	64.36	11.73	25.55
2	1147	696.2	450.8	65.33	11.47	17.28
3	1229	688.7	540.3	75.57	5.51	8.79
4	1457	748.7	708.3	83.53	1.45	2.70
5	1529	908	621	68.62	0.24	0.35
9	1590	950.6	639.4	68.83	0.03	.09
10	1408	833.6	574.4	71.44	0.44	0.77

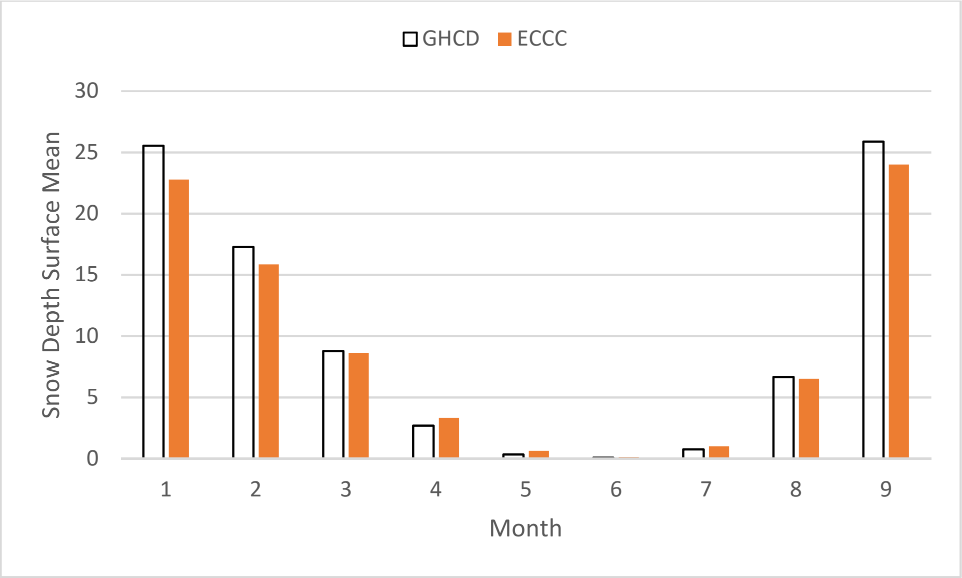
11	1137	700.1	436.9	65.8	3.67	6.66
12	1076	722.1	353.9	55.38	10.48	25.88

Table 2: Statistics for Spatial Model (year=2000) using ECCC snow depth

Mth	Number of Points	Error*	Signal*	Ratio*	Rt GCV (cm)	Surface Mean (cm)
1	1402	885.5	516.5	62.53	11.35	22.76
2	1406	902.3	503.7	61.05	10.91	15.84
3	1435	822.2	612.8	73.21	6.11	8.62
4	1530	708.2	821.8	92.03	1.28	3.32
5	1577	654.3	922.7	98.9	0.10	0.63
9	1634	677.8	956.2	99.92	0.002	0.12
10	1527	953	574	65.08	0.70	0.98
11	1440	1010.1	429.9	51.86	4.63	6.50
12	1382	980.5	401.5	49.63	11.37	24.00

* Signal to the number of knots (S:NK) ratio. S:NK Ratios >80 or <20 represent problematic surfaces (Hutchinson & Xu, 2013).

Figure 1: Comparison of Snow Depth Spatial Model Surface Means by Data Source



References

Brown, R. D., C. Smith, C. Derksen, and L. Mudryk, 2021: Canadian in situ snow cover trends for 1955-2017 including an assessment of the impact of automation. Atmosphere-Ocean, 59(2), 77-92. https://doi.org/10.1080/07055900.2021.1911781

Hutchinson, M. F., and T. Xu, 2013: ANUSPLIN version 4.4 user guide. Australian National University, Fenner School of Environment and Society Doc., 55 pp., https://fennerschool.anu.edu.au/files/anusplin44.pdf.

Wahba, G., 1990: Spline Models for Observational Data. CBMS-NSF Regional Conference Series in Applied Mathematics, Vol. 59, SIAM, 161 pp., https://doi.org/10.1137/1.9781611970128.

7.5.10 *Dataset*: Canadian Historical Daily Snow Depth Dataset (updated)

Overview

This dataset includes historical observations of the daily depth of snow on the ground (daily climate element 013) made at Environment and Climate Change Canada (ECCC) sites by manual ruler or by a sonic sensor equipped autostations. The history of the ECCC daily snow depth observing program is provided in Brown *et al.* (2021) along with a detailed intercomparison of ruler and sonic sensor observations that showed manual observations typically report more snow than a nearby sonic sensor. The database includes a measurement method flag to differentiate between the two methods. This update extends the Canadian historical daily snow depth database (originally provided on the "Canadian Snow CD" in 2000) up to the end of the 2016/17 snow season (July 31). The same procedures were applied to fill missing values and QC data - see MSC (2000) and Brown and Braaten (1998).

Daily snow depth data for the period after July 31, 2017, can be downloaded using the daily climate data extraction tool at the Canadian Centre for Climate Services (https://climate-change.canada.ca/climate-data/#/daily-climate-data), but these data will not be having the same quality control applied.

Some of the snow depth data provided in this dataset may also exist in the CanSWE dataset (an update to the Canadian Historical Snow Survey Dataset, CHSSD). However the focus of that dataset is on SWE, not snow depth, and may include additional sources. The Canadian Historical Daily Snow Depth dataset is based solely on the ECCC in situ snow depth network because these data are in the public domain.

Provider's contact information

Colleen Mortimer, colleen.mortimer@ec.gc.ca

Licensing

Licence: Open Government License - Canada.

Dataset citable as: **Brown**, Ross, Canadian Historical Daily Snow Depth Data, Environment and Climate Change Canada, (last access: DD MM YYYY),http://doi.org/10.18164/e75562d9-625c-4dd8-9481-682d50adf2d7, Sep 2021.

Variable name and units:

- Snow depth [cm]
- Station information: latitude, longitude, elevation, measurement type (ruler or automated).

Spatial coverage and resolution:

Canada, point data.

Temporal coverage and resolution:

1883 - 2017, variable frequency.

Information about observations (number, homogeneity)

Total number of measurements of either type has declined since the early 1980s. Since the mid-1990s the fraction stations using ruler measurements has declined and the fraction of automated measurements has increased (see Fig 1 from Brown et al. 2021).

Information about the technical and scientific quality

- This quality-controlled dataset isolates and corrects over 2000 anomalous SD values present in the archive of raw data.
- QC procedures were identical to the circa 2000 dataset. See Brown and Braaten (1998).
- The automated sensor technology deployed across Canada (SR50 and SR50A sensors) is reliable and robust, with an accuracy of ± 2 cm compared with a co-located ruler observation; however there is a significant bias between the two measurement types. Thus a weather station transition from manual ruler observations to automated sensor will create a discontinuity in the historical time series. Generally station IDs are changed demarking the switch in measurement type, but exceptions were found in some cases.

Limitations and strengths for application in North Canada

- Coverage of Northern Canada is less dense than other locations.
- The majority of northern locations now take automated measurements (see Fig. 2 of Brown et al. 2021) so there may be breaks or discontinuities in their time series that occurred during the transitions from manual to ruler measurements.
- Some Arctic sites exhibit behaviour that differs noticeably from historical manual observations (e.g., strong day-to-day variability and/or extended periods with a very shallow SD of 1–2 cm). These may well reflect local effects from blowing snow and wind scour, which are impossible to verify, and will introduce discontinuities into the historical SD record.
- Dataset not restricted to Northern Canada (requires that one select pertinent data from amongst all included)
- No current plans to update. Data after 2017 must be retrieved through the Canadian Centre for Climate Services (https://climate-change.canada.ca/climate-data/#/daily-climate-data) data extractor. However these are not quality controlled.

References to documents describing the methodology or/and the dataset

Brown, R. D., and R. O. Braaten, 1998: Spatial and temporal variability of Canadian monthly snow depths, 1946–1995. *Atmos.-Ocean*, 36, 37–54, https://doi.org/10.1080/07055900.1998.9649605.

Brown, R. D., C. Smith, C. Derksen, and L. Mudryk, 2021: Canadian In Situ Snow Cover Trends for 1955–2017 Including an Assessment of the Impact of Automation, Atmosphere-Ocean, 59:2, 77-92, http://doi.org/10.1080/07055900.2021.1911781.

Link to download the data and format of data:

https://data-donnees.ec.gc.ca/data/climate/scientificknowledge/canadian-historical-daily-snow-depth-database/?lang=en

7.5.11 <u>Dataset</u>: Canadian Historical Snow Water Equivalent dataset (CanSWE)

Overview

The Canadian historical Snow Water Equivalent dataset (CanSWE) includes manual and automated pan-Canadian observations of Snow Water Equivalent (SWE) collected by national, provincial and territorial agencies as well as hydropower companies and their partners. Snow depth and derived bulk snow density are also included when available. This dataset supersedes the most recent update of the Canadian Historical Snow Survey (CHSSD) dataset published by Brown et al. (2019). The creation of CanSWE used the 2019 CHSSD update as a starting point and involved three main steps: (i) correction and cleaning of the 2019 CHSSD update (correction of metadata, removal of duplicates), (ii) update of this cleaned dataset until July 2020 and addition of snow data from new stations and agencies, and (iii) consistent quality control of the final dataset. CanSWE is described in detail in Vionnet et al. (2021, submitted).

Provider's contact information

Vincent Vionnet (Environment and Climate Change Canada)

Colleen Mortimer (Environment and Climate Change Canada)

Licensing

Licence: Open Government License - Canada.

Licence: Hydro-Québec's data are available under the terms of a Creative Commons Attribution – non Commercial – Share A Like 4.0 International Licence.

Dataset citable as: **Vionnet**, Vincent, Mortimer, Colleen, Brady, Mike, Arnal, Louise, & Brown, Ross. (2021). Canadian historical Snow Water Equivalent dataset (CanSWE, 1928-2020) (Version v1) [Data set]. Zenodo. http://doi.org/10.5281/zenodo.4734372.

Variable name and units:

- Snow water equivalent, snw [kg m^{-2}]; snow depth, snd [m], derived snowpack bulk density, den [kg m^{-3}].
- Station information: latitude, longitude, elevation, data provider, measurement type/method.
- Agency and CanSWE data quality flags specified independently.

Spatial coverage and resolution:

Canada, point data.

Temporal coverage and resolution:

1928 -2020, variable frequency.

Information about observations (number, homogeneity)

The final dataset includes over one million SWE measurements from 2607 different locations across Canada over the snow seasons 1928 – 2020 where a snow season is defined as starting August 01 and ending July 31.

Information about the technical and scientific quality

This dataset represents a single collection spanning a broad time period with improved quality control and consistency. [Obtaining data separately through many of the agencies must be done by direct request (email) so obtaining up-to-date information even for small regions is a challenge. Also, when merging regional data with the national database we often identify metadata issues that need correcting and correspond directly with the contributing agency. These corrections may or may not make their way into the provincial/territorial system.]

Limitations and strengths for application in North Canada

- For the period available this dataset likely represent the majority of data available, nonetheless coverage of Northern Canada is less dense than other locations. An important exception is that data from the Quebec Ministry of Env. And Climate Change is not currently permitted to be shared/included in the combined product.
- Dataset not restricted to Northern Canada (requires that one select pertinent data from amongst all included)
- Tentative plans to update annually. However this is resource-dependent.

References to documents describing the methodology or/and the dataset

Vionnet, V., C. Mortimer, M. Brady, L. Arnal, and R. Brown, 2021: Canadian historical Snow Water Equivalent dataset (CanSWE, 1928-2020), submitted to Earth System Science Data, May 2021, https://doi.org/10.5194/essd-2021-160.

Link to download the data and format of data:

https://zenodo.org/record/4734372 (netCDF).

7.5.12 *<u>Dataset</u>: GlobSnow Snow Water Equivalent Products*

Overview

The GlobSnow project aims to create temporally and spatially extensive snow products with well-known accuracy characteristics. The snow products are based on current state of the art algorithms that can be employed for global scale snow monitoring. Two snow parameters: snow extent (SE) and snow water equivalent (SWE) are produced within GlobSnow. All versions of GlobSnow snow water equivalent products represent *snow depth* solutions optimized to fit three sources of data: observed microwave brightness temperatures, observed synoptic weather station snow depths, and modelled microwave emission characteristics related to snow grain size. For all GlobSnow products snow depth solutions are converted to snow water equivalent using a static density parameter. While GlobSnow updates have continued, parallel development of a Snow CCI SWE product has also occurred, hence there are similarities between the two suites of products.

Provider's contact information

General Information about the GlobSnow Project: http://www.globsnow.info/swe/

Key contact is Dr. Kari Luojus (firstname.lastname@fmi.fi)

Licensing

Licence: Public/None

Dataset citable as: **Takala,** M., K. Luojus, J. Pulliainen, C. Derksen, J. Lemmetyinen, J.-P Kärnä, J. Koskinen, B. Bojkov, 2011: Estimating northern hemisphere snow water equivalent for climate research through assimilation of spaceborne radiometer data and ground-based measurements, Remote Sensing of Environment, Vol. 115, Issue 12, 15 December 2011, doi: 10.1016/j.rse.2011.08.014.

Variable name and units:

Snow water equivalent, snw [mm] (1 mm = 1 kg m^{-2})

Spatial coverage and resolution:

- Northern Hemisphere
- Products provided in Equal-Area Scalable Earth Grid (EASE-Grid) (Lambert equal-area azimuthal - projection).

- The nominal resolution of single pixel is 25 km x 25 km; geometry of the pixels varies
- The data field has the size of 721 x 721 (rows x columns).
- Product is limited between latitudes 35^{o}N and 85^{o}N for physical reasons.

Temporal coverage and resolution:

1979-01-06 – 2018-05-31 (v3.0).

Three frequencies of output available:

- Daily Snow Water Equivalent (Daily L3A SWE), snow water equivalent (mm) for each grid cell for all evaluated land areas of the Northern Hemisphere
- Weekly Aggregated Snow Water Equivalent (Weekly L3B SWE), calculated for each day based on a 7-day sliding time window aggregation of the daily SWE product.
- Monthly Aggregated Snow Water Equivalent (Monthly L3B SWE) a single product for each calendar month providing the average and maximum SWE, calculated from the weekly aggregated SWE product.
- There also exists a bias-corrected monthly product available for Feb-May only. The bias corrected product uses in situ snow transects to correct SWE amounts in the monthly product at the continental scale (Pulliainen et al. 2020). Sub-continental scale biases may still exist. Corrections are considered most appropriate for March. Availability of in situ data may influence other months.

For the period from 1979 to May 1987, the products are available every second day.

From October 1987 till May 2018, the products are available daily.

Products are only generated for the Northern Hemisphere winter seasons, usually from beginning of October till the middle of May.

Information about related datasets

- GlobSnow version 3.0: most current algorithm version
- GlobSnow version 1.0, 1.3, 2.0, 2.1: previous versions of the product (no longer updated, available over shorter periods
- GlobSnow NRT: near-real-time version constrained by low-latency selection of synoptic snow depth data

- Copernicus NRT: GlobSnow SWE NRT product combined with IMS-mask and regridded to 0.05° lat/lon.

Limitations and strengths for application in North Canada

In situ snow depth observations are used to constrain the satellite snow depth retrievals. This information is sparser in Northern Canada such that the resulting retrievals are based on data interpolated/extrapolated from further away. The effect of this process on product uncertainty is not completely understood.

Because of known limitations in alpine terrain, a complex-terrain mask is applied based on the sub-grid variability in elevation determined from a high-resolution digital elevation model. All land ice and large lakes are also masked.

Products have been shown to be less accurate in deep snow (SWE >200 mm)

References to documents describing the methodology or/and the dataset

Version 3.0:

Improvements to the GlobSnow algorithm implemented for v3.0 include the utilization of an advanced emission model with an improved forest transmissivity module and treatment of sub-grid lake ice. Because of the importance of the weather station snow-depth observations on the SWE retrieval, there is improved screening for consistency through the time series.

Bias-corrected version:

Pulliainen, J., K. Luojus, C. Derksen, *et al.* Patterns and trends of Northern Hemisphere snow mass from 1980 to 2018. *Nature* **581,** 294–298 (2020). https://doi.org/10.1038/s41586-020-2258-0

Original GlobSnow algorithm:

General description at: https://www.globsnow.info/index.php?page=Snow_Water_Equivalent

Pulliainen, J., J. Grandell, and M. T. Hallikainen, 1999: HUT Snow Emission Model and its Applicability to Snow Water Equivalent Retrieval. IEEE Transactions on Geoscience and Remote Sensing. 37: 1378-1390.

Pulliainen, J., 2006: Mapping of snow water equivalent and snow depth in boreal and sub-arctic zones by assimilating space-borne microwave radiometer data and ground-based observations. Remote Sensing of Environment. 101: 257-269. DOI: 10.1016/j.rse.2006.01.002.

Takala, O. M., J. Pulliainen, S. Metsämäki, and J. Koskinen, 2009: Detection of snowmelt using spaceborne microwave radiometer data in Eurasia From 1979 to 2007. IEEE Transactions on Geoscience and Remote Sensing, 47, 2996-3007.

Takala, M., K. Luojus, J. Pulliainen, C. Derksen, J. Lemmetyinen, J.-P. Kärnä, J. Koskinen, B. Bojkov, B., 2011: Estimating northern hemisphere snow water equivalent for climate research through assimilation of spaceborne radiometer data and ground-based measurements, Remote Sensing of Environment, Vol. 115, Issue 12, 15 December 2011, doi: 10.1016/j.rse.2011.08.014.

Link to download the data and format of data:

GlobSnow Product Versions: http://www.globsnow.info/swe/ (net CDF; some versions available in HDF)

Copernicus NRT version: https://land.copernicus.eu/global/products/swe

7.5.13 *<u>Dataset</u>: European Space Agency (ESA) Snow Climate Change Initiative (Snow CCI)*

Overview

Snow CCI data is one component of an European Space Agency (ESA) initiative to generate historical records of essential climate variables that meet the requirements of the Global Climate Observing System (GCOS). The Snow CCI project has developed both snow cover fraction products and snow water equivalent (SWE) products. SWE products are derived from multiple sensors/instruments housed on a variety of satellites (SMMR, SSM/I, and SSMIS from a sequence of DMSP F-series satellites starting in 1978 until present day); various efforts are used to ensure long-term consistency in the records. The Snow CCI SWE product algorithm advanced upon the GlobSnow SWE algorithm and hence shares similarities with GlobSnow product versions. All versions of these snow water equivalent products represent *snow depth* solutions optimized to fit three sources of data: observed microwave brightness temperatures, observed synoptic weather station snow depths, and modelled microwave emission characteristics related to snow grain size. Snow depth solutions are converted to snow water equivalent using either a static density parameter (Snow CCI v1.0) or a spatially and temporally varying parameter interpolated from in situ snow density data (Snow CCI v2.0, forthcoming). For more information please see the Snow CCI product user guide.

Provider's contact information

ESA Snow CCI Project Page: https://climate.esa.int/en/projects/snow/

ESA Snow CCI Development Team Contact: http://snow-cci.enveo.at/contact.html

Licensing

Licence: described here.

Dataset citable as: **Luojus**, K., M. Moisander, J. Pulliainen, M. Takala, J. Lemmetyinen, C. Derksen, C. Mortimer, G. Schwaizer, T. Nagler, 2020: ESA Snow Climate Change Initiative (Snow CCI): Snow Water Equivalent (SWE) level 3C daily global climate research data package (CRDP) (1979 – 2018), version 1.0. Centre for Environmental Data Analysis, 20 April 2020. doi:10.5285/fa20aaa2060e40cabf5fedce7a9716d0.

Variable name and units:

Snow water equivalent, snw [mm] (1 mm = 1 kg m^{-2})

Spatial coverage and resolution:

- Northern Hemisphere
- Products provided on regular lon-lat grid: 0.25º x 0.25º (v1.0) and 0.10º x 0.10º (v2.0)
- Product is limited between latitudes 35ºN and 85ºN for physical reasons.

Temporal coverage and resolution:

1979-01-06 -- 2020-05-31. (v2.0)

1979-01-06 -- 2018-05-31. (v1.0)

For the period from 1979 to May 1987, the products are available every second day.

From October 1987 until May 2018, the products are available daily.

Products are only generated for the Northern Hemisphere winter seasons, usually from beginning of October until the middle of May.

Information about related datasets

Internal Snow CCI versions (1.1, 1.2, 1.3, 1.4, 1.5): development versions not officially released but publically available for research purposes.

GlobSnow versions 1.0, 1.3, 2.0, 2.1, 3.0, nrt: see GlobSnow document

Limitations and strengths for application in North Canada

In situ snow depth observations (and for v2.0 in situ snow density observations) are used to constrain the satellite snow depth retrievals. This information is sparser in Northern Canada such that the resulting retrievals are based on data interpolated/extrapolated from further away. The effect of this process on product uncertainty is not completely understood.

Because of known limitations in alpine terrain, a complex-terrain mask is applied based on the sub-grid variability in elevation determined from a high-resolution digital elevation model. Permanent land ice (glaciers, ice sheets) and large lakes are also masked.

Products have been shown to be less accurate in deep snow (SWE >200 mm)

References to documents describing the methodology or/and the dataset

Snow CCI:

Improvements to the GlobSnow algorithm implemented for Snow CCI version 1.0 include the utilization of an advanced emission model with an improved forest transmissivity module and treatment of sub-grid lake ice. Because of the importance of the weather station snow-depth observations on the SWE retrieval, there is improved screening for consistency through the time series. Snow CCI v2.0 will include a spatially and temporally varying snow density (Venäläinen et al., 2021) to convert snow depth to SWE and will use an updated satellite data time series.

Venäläinen, P., K. Luojus, J. Lemmetyinen, J. Pulliainen, M. Moisander, and M. Takala, 2021: Impact of dynamic snow density on GlobSnow snow water equivalent retrieval accuracy, *The Cryosphere, 15(6),* https://doi.org/10.5194/tc-15-2969-2021

Original GlobSnow algorithm:

General description at: https://www.globsnow.info/index.php?page=Snow_Water_Equivalent

Pulliainen, J., J. Grandell, and M. T. Hallikainen, 1999: HUT Snow Emission Model and its Applicability to Snow Water Equivalent Retrieval. IEEE Transactions on Geoscience and Remote Sensing. 37: 1378-1390.

Pulliainen, J., 2006: Mapping of snow water equivalent and snow depth in boreal and sub-arctic zones by assimilating space-borne microwave radiometer data and ground-based observations. Remote Sensing of Environment. 101: 257-269. DOI: 10.1016/j.rse.2006.01.002.

Takala, O. M., J. Pulliainen, S. Metsämäki, and J. Koskinen, 2009: Detection of snowmelt using spaceborne microwave radiometer data in Eurasia From 1979 to 2007. IEEE Transactions on Geoscience and Remote Sensing, 47, 2996-3007.

Takala, M., K. Luojus, J. Pulliainen, C. Derksen, J. Lemmetyinen, J.-P. Kärnä, J. Koskinen, B. Bojkov, 2011: Estimating northern hemisphere snow water equivalent for climate research through assimilation of spaceborne radiometer data and ground-based measurements, Remote Sensing of Environment, Vol. 115, Issue 12, 15 December 2011, doi: 10.1016/j.rse.2011.08.014.

Link to download the data and format of data:

https://climate.esa.int/en/odp/#/project/snow (multiple snow variables available)

http://dx.doi.org/10.5285/fa20aaa2060e40cabf5fedce7a9716d0 (SWE v1.0, netcdf)

http://dx.doi.org/10.5285/4647cc9ad3c044439d6c643208d3c494 (SWE v2.0)

7.5.14 <u>Dataset</u>: *ECMWF 5th Generation Land Reanalysis (ERA5-Land) - snow*

Overview

This document provides an overview of the snow products of ERA5-Land, in the context of the larger ERA5-Land dataset. ERA5-Land is a replay of the land component of the ERA5 atmospheric global reanalysis using a finer spatial resolution and including a series of improvements making it more accurate for all types of land applications. ERA5-Land is produced by ECMWF framed within the Copernicus Climate Change Service (C3S) of the European Commission. The data covers a period from January 1950 to the present. It provides hourly data for many near-surface atmospheric and land-surface parameters.

Provider's contact information

ERA5-Land is produced by the Copernicus Climate Change Service (C3S) at ECMWF.

Copernicus User support (copernicus-support@ecmwf.int (external to C3S)).

Licensing

Licence: Copernicus (Licence agreement information can be found here or here).

Dataset citable as: **Muñoz Sabater**, J., 2019: ERA5-Land hourly data from 1981 to present. Copernicus Climate Change Service (C3S) Climate Data Store (CDS). (Accessed on < DD-MMM-YYYY >), 10.24381/cds.e2161bac

Variable name and units:

Several snow-related variables are available as **hourly** and **monthly** subsets. The table below provide more details for each of them and the names used in ERA5.

Name	Units	Description
Snow albedo	dimensionless	It is defined as the fraction of solar (shortwave) radiation reflected by the snow, across the solar spectrum, for both direct and diffuse radiation. It is a measure of the reflectivity of the snow-covered

		grid cells. Values vary between 0 and 1. Typically, snow and ice have high reflectivity with albedo values of 0.8 and above.
Snow cover	%	It represents the fraction (0-1) of the cell / grid box occupied by snow (similar to the cloud cover fields of ERA5).
Snow density	kg m-3	Mass of snow per cubic metre in the snow layer. The ECMWF Integrated Forecast System (IFS) model represents snow as a single additional layer over the uppermost soil level. The snow may cover all or part of the grid box.
Snow depth	metres	This parameter is provided as an **instantaneous variable**. It is the grib-box average of the snow thickness on the ground (excluding snow on canopy).
Snow depth water equivalent	metres of water equivalent	Depth of snow from the snow-covered area of a grid box. Its units are metres of water equivalent, so it is the depth the water would have if the snow melted and was spread evenly over the whole grid box. The ECMWF Integrated Forecast System represents snow as a single additional layer over the uppermost soil level. The snow may cover all or part of the grid box.
Snow evaporation	m of water equivalent	This parameter is an **accumulated variable**. Evaporation from snow averaged over the grid box (to find flux over snow, divide by snow fraction). This variable is accumulated from the beginning of the forecast time to the end of the forecast step.
Snowfall	m of water equivalent	This parameter is **the accumulated** snow that falls to the Earth's surface. It is the sum of large-scale snowfall and convective snowfall. If snow has melted during the period over which this variable was accumulated, then it will be higher than the snow depth. This variable is the total amount of water accumulated from the beginning of the forecast time to the end of the forecast step. The units given measure the depth the water would have if the snow melted and was spread evenly over the grid box. Care should be taken when comparing model variables with observations, because observations are

		often local to a particular point in space and time, rather than representing averages over a model grid box and model time step.
Snow Melt	m of water equivalent	This parameter is **the accumulated** amount of water that has melted from snow in the snow-covered area of a grid box. The ECMWF Integrated Forecasting System (IFS) represents snow as a single additional layer over the uppermost soil level. The snow may cover all or part of the grid box. This parameter is the depth of water there would be if the melted snow (from the snow-covered area of a grid box) were spread evenly over the whole grid box. For example, if half the grid box were covered in snow with a water equivalent depth of 0.02 m, this parameter would have a value of 0.01 m. For the reanalysis, the accumulation period is over the 1 hour ending at the validity date and time. For the ensemble members, ensemble mean and ensemble spread, the accumulation period is over the 3 hours ending at the validity date and time.

Those products can be found by selecting their name from the snow category on the pages below:

- hourly data from 1950 to present,
- monthly averaged data from 1981 to present,

Note: The convention for accumulations used in ERA5-Land differs with that for ERA5. In ERA5-Land. In ERA5-Land, they are accumulated from the beginning of the forecast to the end of the forecast step.

ECMWF provides a conversion table for accumulated variables (total precipitation/fluxes) for ERA5-Land and ERA5. The table shows how accumulated variables from a number of C3S and ECMWF datasets should be processed to derive values for an hour, a day, a month and a year. In the documentation, 'total precipitation' and 'solar radiation' are used for illustration, but the same processing should be applied to all precipitation and radiative flux variables.

Spatial coverage and resolution:

ERA5-Land is a global land-surface dataset. The atmospheric data is available on a regular latitude-longitude grid at 0.1° x 0.1° resolution (converted from native reduced-Gaussian grid resolution of approximately 9 km x 9 km), and on 4 surface layers. Oceans have been masked out with data available over landmasses and inland lakes.

Temporal coverage and resolution:

ERA5-Land data is available from 1950 to present at hourly time step. Monthly data is also available from 1981 to present (the 1950 – 1980 back extension is scheduled to be available in 2022).

ERA5-Land data updates are made synchronously with ERA5 updates, approximately 2-3 months behind real time.

Information about observations (number, homogeneity)

ERA5-Land is not directly influenced by observations, but rather, indirectly influenced through the ERA5 atmospheric forcings. ERA5's data assimilation uses observations for all geophysical quantities from about 0.75 million observations per day in 1979 and about 24 million in 2018. The 2D-OI uses surface observations at 'screen level'. The online technical documentation provides tables with the satellite and in-situ observations used as input into ERA5. Further details can also be found in the ERA5 document previously prepared by the CCCS.

Methodology

ERA5-Land is produced under a single simulation of the land component of the ERA5 climate reanalysis, without coupling to the atmospheric module of the ECMWF's Integrated Forecasting System (IFS) and without data assimilation. The low atmospheric forcing is provided by the ERA5 reanalysis, with additional lapse-rate correction. The core of ERA5-Land is the Tiled ECMWF Scheme for Surface Exchanges over Land incorporating land surface hydrology (H-TESSEL). Because it runs without data assimilation, it makes it computationally affordable for relatively quick updates. For example, if significant improvements of the land surface model are implemented, the whole or part of the dataset can be reprocessed in a relatively short period. Updates are possible in case improved auxiliary datasets are used as input for the production.

Production of ERA5-Land is not produced as a single continuous segment, but instead as three segments: Stream-1 (2001 onwards), Stream-2 (1981-2000), and Stream-3 (1950-1980). This is because it allows parallel production of data enabling sooner public access to the data, and because the atmospheric forcings used by ERA5-Land is derived from ERA5, thus needing corresponding completed ERA5 segment. Each stream is initialized with various meteorological fields from ERA5 (temperature, precipitation, humidity, radiation, etc.). While ERA5-Land does not assimilate observations directly, they are introduced via the ERA5 atmospheric forcings. These forcings are adjusted using ERA5 derived lapse rates before being integrated with the ECMWF Carbon Hydrology-Tiled ECMWF Scheme for Surface Exchanges over Land (CHTESSEL) land surface model. This is done in 24-hour cycles, generating hourly outputs and the evolution of the land surface state and water and energy fluxes. For further details of the assimilation system used to obtain the ERA5 atmospheric forcings, please see the ERA5 document previously prepared by the CCCS.

Uncertainty estimate: Currently, ERA5-Land variable uncertainty estimates are those corresponding to ERA5. ERA5 uncertainty estimate is sampled by a 10-member lower-resolution Ensemble Data Assimilation (EDA) which provides background-error estimates for the deterministic HRES 4D-Var Data Assimilation system. The analysis method is the same for each EDA member and follows that of the HRES. Each member (except the control) is run with different random perturbations added to the observations. Likewise, the model physical tendencies are perturbed in the short forecasts that link subsequent analysis windows. Ensemble mean and spread have been pre-computed for convenience. Such uncertainty estimates are closely related to the information content of the available observing system which has evolved considerably over time. They also indicate flow-dependent sensitive areas. To facilitate many climate applications, monthly-mean averages have been pre-calculated too, though monthly means are not available for the ensemble mean and spread.

The original plan was to apply the same methodology ERA5-Land was to provide an estimate of the uncertainty fields as was done for ERA5. However, the uncertainty was estimated to be extremely low, and would have assigned unrealistically high confidence to the ERA5-Land variables. As such, it is recommended to use the corresponding ERA5 uncertainty estimates for the time being until further studies are done.

Information about the technical and scientific quality

ERA5-Land represents one of the products of the latest global atmospheric reanalysis produced by Copernicus Climate Change Service at ECMWF. It is archived at a shorter (hourly) time step, has a fine spatial resolution, uses a more advanced assimilation system and includes more sources of data than previous versions (e.g., ERA-Interim-Land). It is accompanied by extensive technical documentation and two principal scientific documentation papers. A list of 'known issues' is maintained at the online documentation (https://confluence.ecmwf.int/display/CKB/ERA5-Land%3A+data+documentation).

Information on land surface model: The land surface model of the ERA5-Land was operational in 2018 with the IFS model cycle 45r1. While most of the changes from the IFS Cy41R2 used in ERA5 are primarily technical, there were a few improvements to various fields: 1) the parameterization of the soil thermal conductivity was updated to take the ice component of frozen soil into consideration, 2) conservation of the soil-water balance was fixed and improved, and 3) rain over snow is now accounted for and is not accumulated in snow pack. Furthermore, a bug exists in IFS Cy41R2, that affects potential evapotranspiration (PET) flux calculations over forests and deserts, has been corrected in ERA5-Land, and unlike ERA5, ERA5-Land PET is an available dataset. However, PET is now determined by assuming a vegetation type of crops and no soil moisture stress. These assumptions may not be always realistic, and therefore PET should be used cautiously. More information on the CHTESSEL land surface model used in ERA5-Land can be found in Muñoz-Sabater et al. (2021, preprint) and the ERA5 document previously prepared by the CCCS

Limitations and strengths for application in North Canada

ERA5-Land is a newer land surface reanalysis and there are few available scientific evaluations of the dataset dedicated specifically to northern Canada. However, it should be noted that in northern Canada, there are currently no sub-daily records over a long historical period for many weather stations. Reanalyses data with hourly output cover this gap and, with suitable investigation and calibration (downscaling), could be valuable particularly for hydrological models.

As for all gridded data, observed values of the various snow parameters at local scales can differ from the values provided by the gridded dataset, which represent a statistical summary of the area surrounding a grid point.

Most importantly, in mountainous regions above about 1,500 m, ERA5 snow depth is unrealistically large. In contrast, ERA5-Land snow mass and snow depth are improved for mid-latitude mountains, although ERA5 snow depth estimates match better on mountain heights > 3300 m. Per continent, ERA5-Land snow fields demonstrate the most skill in the United States over complex mountain terrains, implying that that near-surface temperature may be more accurate. **Overall, however, ERA5-Land skill for the snow varies depending on the geographic region.**

References to documents describing the methodology or/and the dataset

Muñoz Sabater, J., 2019: ERA5-Land hourly data from 1981 to present. Copernicus Climate Change Service (C3S) Climate Data Store (CDS). (Accessed on < 25-Jun-2021 >), https://doi.org/10.24381/cds.e2161bac

Muñoz-Sabater, J., E. Dutra, A. Agustí-Panareda, C. Albergel, G. Arduini, G., Balsamo, S. Boussetta, M. Choulga, S. Harrigan, H. Hersbach, B. Martens, D. G. Miralles, M. Piles, N. J. Rodríguez-Fernández, E. Zsoter, C. Buontempo, and J.-N. Thépaut, 2021: ERA5-Land: A state-of-the-art global reanalysis dataset for land applications. Earth System Science Data, 13(9), 4349-4383. https://doi.org/10.5194/essd-2021-82

Hersbach, H., B .Bell, P. Berrisford, S. Hirahara, A. Horányi, J. Muñoz-Sabater, J. Nicolas, C. Peubey, R. Radu, D. Schepers, A. Simmons, C. Soci, S. Abdalla, X. Abellan, G. Balsamo, P. Bechtold, G. Biavati, J. Bidlot, M. Bonavita, G. Chiara, P. Dahlgren, D. Dee, M. Diamantakis, R. Dragani, J. Flemming, R. Forbes, M. Fuentes, A. Geer, L. Haimberger, S. Healy, R.J. Hogan, E. Hólm, M. Janisková, S. Keeley, P. Laloyaux, P. Lopez, C. Lupu, G. Radnoti, P. Rosnay, I. Rozum, F. Vamborg, S. Villaume, and J.-N. Thépaut, 2020: The ERA5 global reanalysis. Quarterly Journal of the Royal Meteorological Society, 146(730), 1999–2049. https://doi.org/10.1002/qj.3803.

Link to download the data and format of data:

Data Access: Copernicus | ECMWF (requires login)

ERA5-Land is available in GRIB and NetCDF formats

Link to download hourly and monthly data on Copernicus:

- hourly data from 1950 to present,
- monthly averaged data from 1981 to present

Publications including dataset evaluation or comparison with other data in Canada

7.5.15 *Dataset: NCEP North American Regional Reanalysis (NARR) - snow*

Overview

This document focuses on snow-related data from NARR. NARR is a regional reanalysis covering the North America using a Northern Lambert Conformal Conic grid with an approximately 0.3 degrees (32 km) spatial resolution at the lowest latitude. Dataset was originally produced at NOAA's National Center for Atmospheric Prediction (NCEP), and detailed description is provided at https://psl.noaa.gov/data/gridded/data.narr.html#detail with online Analysis and Plotting Tools at https://psl.noaa.gov/cgi-bin/data/getpage.pl.

Provider's contact information

Physical Sciences Laboratory: Data Management

NOAA/ESRL/PSL

325 Broadway

Boulder, CO 80305-3328

psl.data@noaa.gov.

Licensing

This work is licensed under a Creative Commons Attribution 4.0 International Licence.

There are no restrictions for the use of data.

If the data are taken from PSD, the providers ask that the data is acknowledged by including text such as NCEP Reanalysis data provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, from their Web site at http://www.esrl.noaa.gov/psd/ in any documents or publications using these data.

If the data are taken from NCAR, the citation should include the following: National Centers for Environmental Prediction/National Weather Service/NOAA/U.S. Department of Commerce. 2005, updated monthly. NCEP North American Regional Reanalysis (NARR). Research Data Archive at the National Center for Atmospheric Research, Computational and Information Systems Laboratory. https://rda.ucar.edu/datasets/ds608.0/. Accessed dd mmm yyyy.

Variable name and units:

The variables are divided into three sections: Pressure level, Monolevel (surface and others) and Subsurface. Several snow related variables are available in the list of Monolevel variables and they are the output of the analysis and first guess forecast:

Accumulated snow [kg/m^2] – this is the instantaneous state of the water equivalent snowpack

Snow cover [%]

Snow depth [m]

Table with snow variables available in NetCDF format at NOAA

Variable	**Statistic**	**Level**	**Download File**
Snow Depth	3-hourly value	Surface	snod.yyyy.nc
Snow Depth	Daily Mean	Surface	snod.yyyy.nc
Snow Depth	Monthly Mean	Surface	snod.mon.mean.nc
Snow Depth	Long-term Monthly Mean	Surface	snod.mon.ltm.nc
Snow Cover	3-hourly value	Surface	snowc.yyyy.nc
Snow Cover	Daily Mean	Surface	snowc.yyyy.nc
Snow Cover	Monthly Mean	Surface	snowc.mon.mean.nc
Snow Cover	Long-term Monthly Mean	Surface	snowc.mon.ltm.nc
Accumulated Snow	3-hourly values from forecast	Surface	weasd.yyyy.nc

Accumulated Snow	Daily Mean	Surface	weasd.yyyy.nc
Accumulated Snow	Monthly Mean	Surface	weasd.mon.mean.nc
Accumulated Snow	Long-term Monthly Mean	Surface	weasd.mon.ltm.nc

Values labelled 3 hourly values are output at that exact time (no averaging).

WEASD is ***the instantaneous state of the water equivalent snowpack*** *on the ground (in units of millimetres, or equivalently Kg/m**2)*

For a complete list of model output variables, see NCEP's variable list. Details for Monolevel variables are provided on https://psl.noaa.gov/data/gridded/data.narr.monolevel.html .

Spatial coverage and resolution:

The data is available for all of North America at an approximate 0.3 degrees (32 km) spatial resolution at the lowest latitude, on a Northern Lambert Conformal Conic grid. Corners of this grid are 1.000001N, 145.5 W; 0.897945N, 68.32005W; 46.3544N, 2.569891W; 46.63433N, 148.6418E. A page describing the coverage along with information on reading the projection is available.

Temporal coverage and resolution:

Data is available as 3h values, Daily and Monthly means for 1979/01/01 to May 31, 2021, period.

Information about observations

The data that are assimilated in order to initialize the model are temperatures, winds, and moisture from radiosondes as well as pressure data from surface observations. Also included in this dataset are dropsondes, pibals, aircraft temperatures and winds, satellite radiance (a measure of heat) from polar (orbiting Earth) satellites, and cloud-drift winds from geostationary (fixed at one location viewing Earth) satellites. The sources of observations are summarized in the table below.

Dataset	Details	Source

Precipitation	Continental United States: comes from a 1/8-degree gauge dataset analyzed using PRISM and a least-squares distance-weighting algorithm. Canada and Mexico: comes from 1-degree gauge datasets and is disaggregated using NCEP R2 hourly precipitation weighting factors. Over oceans (<42.5°N): comes from the Climate Prediction Center (CPC) CMAP (CPC Merged Analysis of Precipitation), a merged combination of satellite and gauge precipitation. It is using a 15-degree "blending belt" between 27.5 and 42.5 N, with no CMAP north of 42.5 N.	NCEP/CPC,Canada, Mexico
TOVS-1B radiances	Temperature, precipitable water over ocean	NESDIS
NCEP Surface	Wind, moisture	GR
TDL Surface	Pressure, wind, moisture	NCAR
COADS (ships/buoys)	Pressure, wind, moisture	NCEP/EMC
Air Force Snow	**Snow depth (The Air Force Weather Agency snow depth is estimated daily by merging satellite-derived snow cover data with daily snow depth reports from ground stations.)**	**COLA and NCEP/EMC**
SST	1-degree Reynolds, with Great Lakes SSTs	NCEP/EMC, GLERL

Sea and lake ice	Contains data on Canadian lakes, Great Lakes	NCEP/EMC, GLERL, Ice Services Canada
Tropical cyclones	Locations used for blocking of CMAP Precipitation	Lawrence Livermore National Laboratory

The following figure presents sample distributions of surface assimilated data.

a) b)

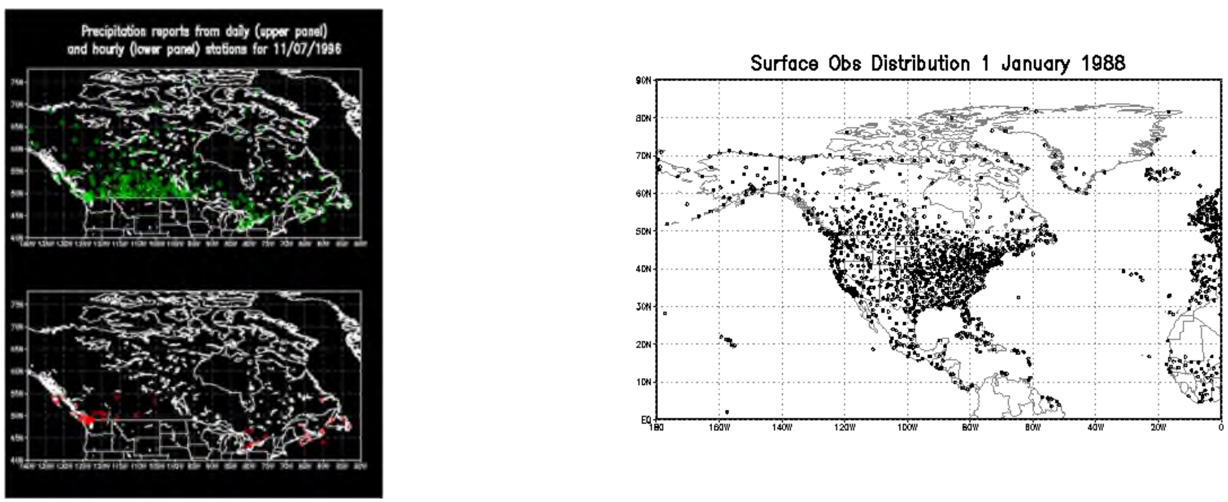


Figure 1. a) Sample distribution of Canadian precipitation assimilated data; b) Sample distribution of surface observations

Methodology

The NARR project is an extension of the NCEP/NCAR Global Reanalysis 2. It is initialized and driven by NCEP/NCAR Global Reanalysis 2 and run over the North American Region using a high-resolution NCEP Eta Model (32 km/45 layer) together with the Regional Data Assimilation

System (RDAS) using 3DVAR method, and it is one of the few reanalysis that assimilates precipitation along with other variables, also over Canada this feature is much reduced comparable to the US. It is using the ETA / NOAH land surface model and it is assimilating snow depths from US Air Force daily snow depth analysis.

For more information, please refer to the publication in the references section below.

Information about the technical and scientific quality

The improvements in the model/assimilation have resulted in a dataset with substantial improvements in the accuracy of temperature, winds and precipitation compared to the NCEP-DOE Global Reanalysis 2 (the parent global reanalysis). Wind improvement is especially greatest in the upper troposphere in winter. The 10 m winds improved greatly in winter, a little bit in summer. Relative humidity also improved in both analysis and first guess forecast.

Precipitation over Canada: the number of gauge observations is insufficient to do better than the model is doing.

Tests on assimilation of 2 m land surface station air temperatures, in NARR proved to be harmful in the sense of making the first guess considerably worse, throughout the troposphere. Consequently, 2 m land surface station air temperatures are not assimilated by NARR.

Useful information can be found at NCEP's NARR FAQ page: http://www.emc.ncep.noaa.gov/mmb/rreanl/faq.html.

Data is updated on a monthly base.

Limitations and strengths for application in North Canada

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References to documents describing the methodology or/and the dataset

Mesinger, F., G. DiMego, E. Kalnay,K. Mitchell, P. C. Shafran, W. Ebisuzaki, D. Jović, J. Woollen, E. Rogers, E. H. Berbery, M. B. Ek, Y. Fan, R. Grumbine, W. Higgins, H. Li, Y. Lin, G. Manikin, D. Parrish, and W. Shi, 2006: North American Regional Reanalysis. Bulletin of the American Meteorological Society, 87(3), 343-360, doi:10.1175/BAMS-87-3-343.

Link to download the data and format of data:

NARR is available through NOAA ftp page, UCAR and from NCDC page.

NOAA: ftp://ftp.cdc.noaa.gov/Datasets/NARR/ (NetCDF standard format; the data are divided by variable and year and month into separate files; Missing data is flagged with a value of 9.96921e+36f.)

NCDC: https://www.ncdc.noaa.gov/data-access/model-data/model-datasets/north-american-regional-reanalysis-narr (GRIB format)

UCAR: https://rda.ucar.edu/datasets/ds608.0/ (GRIB format)

Publications including dataset evaluation or comparison with other data in northern Canada

7.5.16 *Dataset: North American Precipitation and Land Surface Reanalysis - Regional Deterministic Reforecast System (RDRS) - snow*

Overview

RDRS is a precipitation and surface reanalysis developed at the Canadian Centre for Meteorological and Environmental Prediction (CCMEP) of Environment and Climate Change Canada (ECCC). It provides various forecasted meteorological variables obtained with the Regional Deterministic Reforecast System (RDRS) two-way coupled with the Canadian Land Data Assimilation System (CaLDAS) and Precipitation Analysis (CaPA), and initialized and driven by ERA-Interim reanalysis. Results are provided at a spatial resolution of 10 km across North America. Data for RDRSv2.1 version was produced for the period of 1980-2018 and it is currently under evaluation. RDRSv2 is an early version that covers a shorter period: 2000-2017.

Provider's contact information

Data developed by the Canadian Centre for Meteorological and Environmental Prediction (CCMEP) of Environment and Climate Change Canada (ECCC)

Electronic Mail Address of the provider: The Canadian Surface Prediction Archive (caspar.data@uwaterloo.ca)

Licensing

The end-user licence for Environment and Climate Change Canada's data servers specifies the conditions of use of this data.

The Canadian Surface Prediction Archive Terms of Service

Variable name and units:

Snow depth and snow water equivalent are presently available just at ECCC as original FST files. The plan is to release the data to public on CaSPAr data portal were presently data from the previous version, RDRSv2, is available for many variables but not for snow depth and snow water equivalent, because of a coding error. The new version RDRv2.1 has corrected the error.

Information about other variables available for download can be found on CaSPAr data portal.

Spatial coverage and resolution:

The data is available for all of North America at an approximate 10 km x 10 km spatial resolution on a rotated pole grid.

Temporal coverage and resolution:

RDRSv2.1 is available for the period of 1980-2018 at **hourly time** steps.

Information about observations (number, homogeneity)

RDRS is initialized and driven by ERA-Interim reanalysis and rely only on surface observations and no remote sensing observations, such as satellite or radar data. Observations were taken from ECCC's operational and climate data archives and include snow depth and total precipitation. The Integrated Surface Data (ISD, DS463.3) is used in the version v2.1 for the years prior to 2000. Table 3 from Gasset *et al.* (2021) summarizes the surface observation datasets used in the assimilation processes for the early version of the product that covered just 2000-2017 period. The period 1980-2000 was produced just recently and there is no available information about observations for this period, yet.

Table 3. Surface networks and variables used by CaLDAS and CaPA.

Network	Domain covered	Availability at CCMEP	Variables used by CaLDAS	Variables used by CaPA-6h	Variables used by CaPA-24h
METAR	North America	1992-present	T, T_d	$P, T, \|\|U\|\|$	$P, T, \|\|U\|\|$
SWOB	North America	2013-present	T, T_d, S_d	Not used	$P, T, \|\|U\|\|$
SYNOP	North America	1992-present	T, T_d, S_d	$P, T, \|\|U\|\|$	$P, T, \|\|U\|\|$
AdjDlyRS	Canada	1980-present	Not used	Not used	P
RMCQ	Province of Quebec	2011-present	Not used	Not used	$P, T, \|\|U\|\|$
SHEF	USA	1998-present	Not used	Not used	$P, T, \|\|U\|\|$

T: temperature, T_d: dew point temperature, S_d: snow depth, P: total precipitation, $||U||$: wind speed

Figure 1 from Lespinas *et al.* (2010) is presenting the spatial distribution of the meteorological stations assimilated by CaPA and geographical limits of the Canadian terrestrial ecozones.

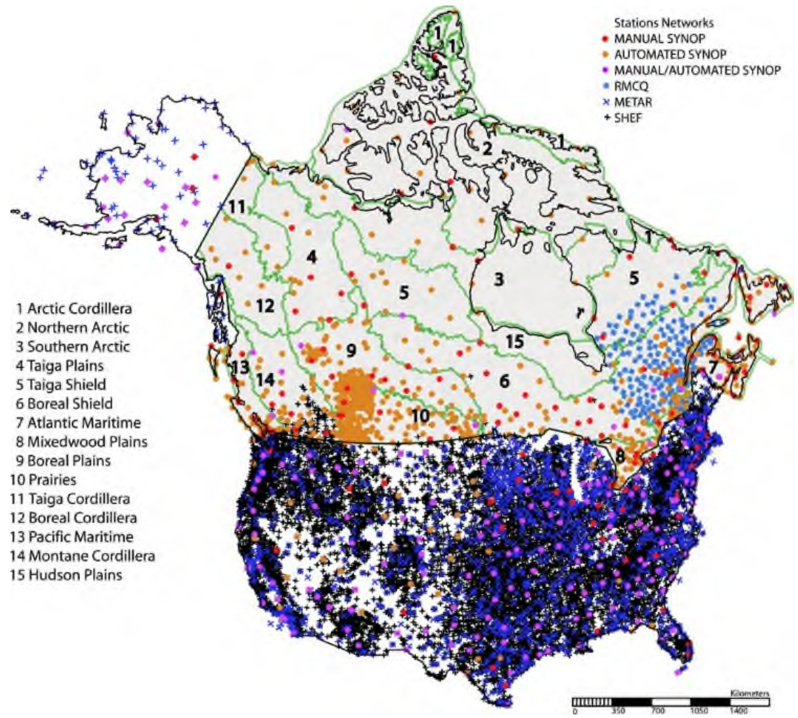

Figure 1. Spatial distribution of the meteorological stations assimilated by CaPA. Source: Journal of Hydrometeorology 16, 5; 10.1175/JHM-D-14-0191.1)

Supplementary information relevant for precipitation, soil moisture and snow: The 24 h a posteriori precipitation analysis, CaPA-24, is also using the Adjusted Daily Rain and Snow (AdjDlyRS) observations dataset (Wang *et al*., 2017). AdjDlyRS data features 3346 stations that are mainly manual stations from the Canadian synoptic network, and are known as the most reliable observations (they were adjusted for systematic errors, and in particular undercatch and evaporation caused by wind effects, gauge-specific wetting loss, as well as for trace precipitation amounts.).

Methodology

ERA-Interim reanalysis is first used to initialize the atmospheric conditions of the Global Deterministic Reforecast System (GDRS) at a spatial resolution of 39 km. Additional surface conditions are input via the GEM-Surf model, which is also initialized by ERA-Interim. The GDRS output is then dynamically downscaled to 10 km using the RDRS. These finer resolution outputs are two-way coupled with the

Canadian Land Data Assimilation System (CaLDAS) and Precipitation Analysis (CaPA) system (this means that outputs from RDRS is used to drive both the CaLDAS and CaPA system, and these results are then fed back into RDRS). This coupling results in significantly improved near-surface atmospheric and land-surface predictions.

Both GDRS and RDRS are based on the latest stable version of the Global Environment Multiscale (GEM v4.8-LTS) model and they are both using the same geophysical fields (i.e. orography, vegetation characteristics, soil thermal and hydraulic coefficients, glaciers fraction) as the corresponding forecast operational versions. The coupling with CaLDAs and CaPA allows for combining surface observations of temperature, humidity, snow depth and precipitation with the first guess provided by the RDRS. CaLDAS uses a one-dimensional Ensemble Kalman Filter (EnKF) to estimate soil moisture and soil temperature, and an optimal interpolation (OI) scheme to estimate snow depth. CaPA combines precipitation observations with a background field obtained from the short-term reforecast provided by the RDRS through an OI method. CaPA also serves to provide CaLDAS with 6-h precipitation analysis.

In the snow analysis, all state variables of the ISBA snow model are cycled, with the exception of snow depth, which is obtained from an external analysis. This external analysis uses an optimal interpolation approach to blend a first guess of snow depth provided by the ISBA model. An ensemble of analyses is produced, one for each CaLDAS members: random perturbations are added to the precipitation and temperature fields that are provided to the external snow model in order to obtain the background field for the analysis system, however, no perturbations are added to the snow depth observations themselves.

For more information, please refer to the publication in the references section below.

Information about the technical and scientific quality

Version 2 of the dataset was evaluated and compared to the operational numerical weather prediction system (RDPS) over the period of 2010-2017. Gasset *et al.* (2021) mentions that the RDRS improves upon RDPS in most regions and for most variables, notably for Alaska and the Canadian Arctic, as well as Western USA.

In general, reanalyses often do not assimilate any observations of precipitation and of the land-surface state, but instead only provide short-term forecasts of these variables. RDRS do assimilate precipitation observations through the coupling with CaPA. Gasset *et al*. (2021) mentions that the coupling approach of the GDRS, RDRS, CaLDAS, and CaPA demonstrates significant improvements in the surface layer compared to the results obtained without coupling.

Strict quality control procedures are in place in CaPA to avoid the assimilation of biased observations, and in particular wind-induced undercatch of solid precipitation (based on a temperature analysis, different wind speed thresholds are used depending on the network, the type of gauge and whether the station is manned or automated).

In Gasset *et al*. (2021), short-term absolute temperature, dew point temperature, and wind speed forecasts from RDRSv2 were compared to observations from synoptic stations across North America. Results indicate that these data may be suitable in driving other environmental models. Likewise, a preliminary streamflow modelling study has also demonstrated that the RDRSv2 has some skill in driving hydrological models to predict runoff into Lake Erie, suggesting that the RDRSv2 may be useful for hydrological purposes.

Data for the RDRSv2 is available in netCDF format on CaSPAr data portal. Two scientific papers accompany the dataset, one detailing CaSPAr and the other detailing the RDRSv2 dataset. It is expected that the data will be updated regularly.

The evaluation of the new version (RDRSv2.1) is presently under development.

Limitations and strengths for application in North Canada

RDRSv2 and RDRSv2.1 were initialized and driven by ERA-Interim, a reanalysis dataset that has been since superseded by ERA5. Tests are currently being conducted to determine the suitability and impacts of switching to another dataset. A bug that was identified during the development of the RDRSv2: snow depth was expressed in metres in the code whereas it is supposed to be expressed in centimetres. It was verified that while biases and other errors for snow depth itself wasn't heavily impacted, snow density and snow water equivalent demonstrated significant differences. As such, these two fields are not distributed for RDRSv2 version. The error was corrected in RDRSv2.1 version.

References to documents describing the methodology or/and the dataset

Gasset, N., V. Fortin, M. Dimitrijevic, M. Carrera, B. Bilodeau, R. Muncaster, É.,Gaborit, G. Roy, N. Pentcheva, M. Bulat, X. Wang, R. Pavlovic, F. Lespinas, and D. Khedhaouiria, 2021: A 10 km North American Precipitation and Land Surface Reanalysis Based on the GEM Atmospheric Model. Hydrology and Earth System Sciences, 25(9), 4917-4945, https://doi.org/10.5194/hess-25-4917-2021

Link to download the data and format of data:

Snow depth and snow water equivalent from RDRSv2.1 are presently available just at ECCC as original FST files. They will be soon released to public through the CaSPAr data catalogue as well as directly from their data portal:

Data catalogue: https://github.com/julemai/CaSPAr/wiki/Available-products

Data portal: https://caspar-data.ca/caspar **(NetCDF)**

Publications including dataset evaluation or comparison with other data

Mai, J., B.A. Tolson, H. Shen, É. Gaborit, V. Fortin, N. Gasset, H. Awoye, T. A. Stadnyk, L. M. Fry, E. A. Bradley, F. Seglenieks, A. G. T. Temgoua, D. G. Princz, S. Gharari, A. Haghnegahdar, M. E. Elshamy, S. Razavi, M. Gauch, J. Lin, X. Ni, Y. Yuan, M. McLeod, N. B. Basu, R. Kumar, O. Rakovec, L. Samaniego, S. Attinger, N. K. Shrestha, P. Daggupati, T. Roy, S. Wi, T. Hunter, J. R. Craig, and A. Pietroniro, 2021: Great Lakes Runoff Intercomparison Project Phase 3: Lake Erie (GRIP-E), Journal of Hydrologic Engineering, 26(9), 05021020-1-19. https://doi.org/10.1061/(ASCE)HE.1943-5584.0002097

Reference for CaPA:

Mahfouf, J.-F., B. Brasnett, and S. Gagnon, 2007: A Canadian precipitation analysis (CaPA) project: Description and preliminary results, Atmosphere-Ocean, 45(1), 1-17, DOI: 10.3137/ao.v450101.

Fortin, V., G. Roy, T. Stadnyk, K. Koenig, N. Gasset, and A. Mahidjiba, 2018: Ten Years of Science Based on the Canadian Precipitation Analysis: A CaPA System Overview and Literature Review, Atmosphere-Ocean, 56(3), 178-196, DOI: 10.1080/07055900.2018.1474728.

Lespinas, F., V. Fortin, G. Roy, P. Rasmussen, and T. Stadnyk, 2015: Performance Evaluation of the Canadian Precipitation Analysis (CaPA), Journal of Hydrometeorology, 16(5), 2045-2064. Retrieved May 26, 2021, from

https://journals.ametsoc.org/view/journals/hydr/16/5/jhm-d-14-0191_1.xml

7.5.17 *__Dataset__: ECMWF 5th Generation Atmospheric Reanalysis (ERA5) - snow*

Overview

This document provides an overview of the snow products of ERA5, in the context of the larger ERA5 dataset. As background, ERA5 is the 5th generation of the global atmospheric reanalysis (the latest – it replaces the ERA-Interim reanalysis) produced by the Copernicus Climate Change Service at ECMWF, covering the period from January 1950 to present. It provides hourly data on many atmospheric, land-surface and sea-state parameters together with estimates of uncertainty.

Provider's contact information

ERA5 is produced by the Copernicus Climate Change Service (C3S) at ECMWF.

Copernicus User support (copernicus-support@ecmwf.int (external to C3S)).

Licensing

Licence: Copernicus (Licence agreement information can be found here or here).

Dataset citable as: Copernicus Climate Change Service (C3S) (2017): ERA5: Fifth generation of ECMWF atmospheric reanalyses of the global climate . Copernicus Climate Change Service Climate Data Store (CDS), date of access. https://cds.climate.copernicus.eu/cdsapp#!/home

Variable name and units:

Several snow-related variables are available as **hourly** and **monthly** subsets. The table below provide more details for each of them and the names used in ERA5.

Name	Units	Description
Snow depth	meters of water equivalent	This parameter is provided by **analysis** and by the **forecast** as an **instantaneous variable**. It is the amount of snow from the snow-covered area of a grid box. The snow may cover all or part of the grid box. Its units are metres of water equivalent, so it is the depth the water would have if the snow melted and was spread evenly over the whole grid box. Therefore, it

		is in fact the snow water equivalent. Users can use Snow density to convert the meter of equivalent water to meters.
Snow density	kg m-3	This parameter is an **instantaneous** measure provided by **analysis** and by the **forecas**t and it is the mass of snow per cubic metre in the snow layer. The snow may cover all or part of the grid box. This parameter is defined over the whole globe, even where there is no snow. Regions without snow can be masked out by only considering grid points where the snow depth (m of water equivalent) is greater than 0.0.
Snow albedo	Dimensionless	This parameter is an **instantaneous** measure provided by **analysis** and by the **forecas**t and it is a measure of the reflectivity of the snow-covered part of the grid box. It is the fraction of solar (shortwave) radiation reflected by snow across the solar spectrum. The snow may cover all or part of the grid box. This parameter changes with snow age and also depends on vegetation height. It has a range of values between 0 and 1. For low vegetation, it ranges between 0.52 for old snow and 0.88 for fresh snow. For high vegetation with snow underneath, it depends on vegetation type and has values between 0.27 and 0.38. This parameter is defined over the whole globe, even where there is no snow. Regions without snow can be masked out by only considering grid points where the snow depth (m of water equivalent) is greater than 0.0.
Snow evaporation	m of water equivalent	This parameter is provided **by the forecast** only and it is the **accumulated**. This parameter is the depth of water there would be if the evaporated snow (from the snow-covered area of a grid box) were liquid and were spread evenly over the whole grid box. This parameter is accumulated over a particular time period. For the reanalysis, the accumulation period is over the 1 hour ending at the validity date and time. The IFS convention is that downward fluxes are positive. Therefore, negative values indicate evaporation and positive values indicate deposition.
Snowfall	m of water equivalent	This parameter is provided by **the forecast** only and it is **the accumulated** snow that falls to the Earth's surface. It is the sum of large-scale snowfall and convective snowfall. Large-scale

		snowfall is generated by the cloud scheme in the ECMWF Integrated Forecasting System (IFS). The cloud scheme represents the formation and dissipation of clouds and large-scale precipitation due to changes in atmospheric quantities (such as pressure, temperature and moisture) predicted directly at spatial scales of the grid box or larger. Convective snowfall is generated by the convection scheme in the IFS, which represents convection at spatial scales smaller than the grid box. In model, precipitation is comprised of rain and snow. This parameter is accumulated over a particular time period. For the reanalysis, the accumulation period is over the 1 hour ending at the validity date and time. The units of this parameter are depth in metres of water equivalent. It is the depth the water would have if it were spread evenly over the grid box. Care should be taken when comparing model parameters with observations, because observations are often local to a particular point in space and time, rather than representing averages over a model grid box.

Those products can be found by selecting their name from the snow category on the pages below:

- hourly data on single levels from 1950 to 1978,
- hourly data on single levels from 1979 to present,
- monthly averaged data on single levels from 1950 to 1978,
- monthly averaged data on single levels from 1979 to present,

More broadly, ERA5 provides four main subsets available, with **hourly** and **monthly** sampling: **pressure levels (upper air fields)** and **single levels (atmospheric, ocean-wave and land surface quantities.**

Note: The convention for accumulations used in ERA5 and in ERA5-Land differs.

ECMWF provides a conversion table for accumulated variables (total precipitation/fluxes) for ERA5-Land and ERA5. The table shows how accumulated variables from a number of C3S and ECMWF datasets should be processed to derive values for an hour, a day, a month and a year. In the documentation, 'total precipitation' and 'solar radiation' are used for illustration, but the same processing should be applied to all precipitation and radiative flux variables.

Spatial coverage and resolution:

ERA5 data, is a global dataset. The atmospheric data is available on a regular latitude-longitude grid at 0.25° x 0.25° resolution (converted from native reduced-Gaussian grid resolution of approximately 31 km x 31 km), and on 37 pressure levels.

Temporal coverage and resolution:

ERA5 data, is available from 1950 to present (split into two entries: primary from 1979 onwards and a back extension from 1950-1978). The back extension is a preliminary version that has been released in 2020, and an updated version (that corrects some issues in the tropics) will appear around the end of 2021.

The data is available at hourly and monthly sampling (see above).

ERA5 data, is updated daily with a latency of about 5 days in an early product and with a final release 2 to 3 months later.

Information about observations (number, homogeneity)

Like any other climate variable from a reanalysis product, snow is potentially influenced by all observations assimilated into the product. ERA5's data assimilation uses observations for all geophysical quantities from about 0.75 million observations per day in 1979 and about 24 Million in 2018. The 2D-OI uses surface observations at 'screen level'. The online technical documentation provides tables with the satellite and in-situ observations used as input into ERA5.

The satellite measurements used in ERA5 are: temperature, humidity, ozone, column water vapour, cloud liquid water, precipitation, ocean surface wind speed, wind vector, soil moisture, wave height.

The in-situ data is provided by WMO WIS and consists in measurements for: surface pressure, temperature, humidity, wind, wind profiles and snow depth. Figure 4 from Hersbach et al. (2020) presents the conventional observations assimilated per day in ERA5 during the period 1979–2018.

ERA5 assimilates rain rates from ground-based radar–gauge composite observations from 2009, and snow cover (NH only) from NOAA/NESDIS IMS. **The snow analysis is updated based on a two-dimensional optimal interpolation of station observations of snow depth and the IMS 4-km resolution snow cover**. The IMS snow cover is not used above 1500 m.

Methodology

Like any other reanalysis, ERA5 data is strongly influenced by the data assimilation methodology. ERA5 is produced using 4D-Var data assimilation with the ECMWF's Integrated Forecast System (IFS) model (CY41R2). The forecast model has 137 hybrid sigma/pressure (model) levels in the vertical, with the top level at 0.01 hPa. The IFS is coupled to a land-surface model and an ocean wave model. The model uses as boundary conditions the sea surface temperature, the sea ice cover, the greenhouse gases, the aerosols, and the total solar irradiance. Climate variables are offered from the atmospheric model, the surface model and the wave model.

The ERA5 dataset contains one (31 km) high resolution realization (HRES) and a reduced resolution 10-member ensemble (EDA). The model time step is 12 minutes for the HRES and 20 minutes for the Ensemble Data Assimilation (EDA), though occasionally these numbers are adjusted to cope with instabilities. Climate variables result from analyses and short (18 hours) forecasts, initialized twice daily from analyses at 06 and 18 UTC. Most of climate variables from the analyses are also available from the forecasts. However, there are several climate variables from forecast, e.g., mean rates and accumulations, that are not available from the analyses. More information on the differences between analysis, forecast, instantaneous, accumulated and mean rate parameters are provided on https://confluence.ecmwf.int/pages/viewpage.action?pageId=85402030.

The ERA5 atmospheric analysis is based on a hybrid incremental 4-dimensional variational data assimilation (4D-Var) system including variational bias correction (VarBias). The method finds the best estimate of the state of the atmosphere/land/surface ocean within an assimilation time window, given a background forecast valid at the start of the window and observations falling within that window. The 4D-Var data assimilation uses 12 hour windows from 09 UTC to 21 UTC and 21 UTC to 09 UTC (the following day).

Uncertainty estimate: An uncertainty estimate is sampled by a 10-member lower-resolution Ensemble Data Assimilation (EDA) which provides background-error estimates for the deterministic HRES 4D-Var Data Assimilation system. The analysis method is the same for each EDA member and follows that of the HRES. Each member (except the control) is run with different random perturbations added to the observations. Likewise, the model physical tendencies are perturbed in the short forecasts that link subsequent analysis windows. Ensemble mean and spread have been pre-computed for convenience. Such uncertainty estimates are closely related to the information content of the available observing system which has evolved considerably over time. They also indicate flow-dependent sensitive areas. To facilitate many climate applications, monthly-mean averages have been pre-calculated too, though monthly means are not available for the ensemble mean and spread.

Information about the technical and scientific quality

ERA5 data represents the latest global atmospheric reanalysis produced by Copernicus Climate Change Service at ECMWF. It is archived at a shorter (hourly) time step, has a finer spatial resolution, uses a more advanced assimilation system and includes more sources of data than previous versions. It is accompanied by extensive technical documentation and two principal scientific documentation papers. A list of 'known issues' is maintained at the online documentation (https://confluence.ecmwf.int/display/CKB/ERA5%3A+data+documentation#ERA5:datadocumentation-Knownissues).

A prerelease quality control revealed some problems affecting the performance in the tropics (tropical cyclones are too intense) and that the deep soil moisture tends to be too dry for the 1950-1978 dataset. A new version of the data should gradually become available by late 2021. This issue will be of little direct relevance to data in Canada's north, but the user should be aware of the reason for this update.

Information on model improvement: The forecast model of the ERA5 is the IFS Cycle 41r2. In the ten-year period between ERA-Interim (Cy31r2) and ERA5 (Cy41r2), many significant improvements have been made to the representation of atmospheric physical processes (see Section 4 of Hersbach *et al*. (2020)). ERA5 snow-related processes will be influenced by several changes to ERA5's parameterization schemes. ERA5's HTESSEL land surface scheme (Balsamo et al., 2015) accounts for seasonally varying monthly vegetation maps specified from a MODIS-based satellite dataset. In addition, an enhanced snowpack parameterization allows a more realistic timing of runoff and terrestrial water storage variations and a better match of the albedo to satellite products. The chosen parameterization for lakes (FLake), allows consideration of both subgrid and resolved water bodies, which is potentially relevant for the lake-enriched Canadian sub-Arctic. This series of changes contributes to significant improvements in the soil moisture and land surface fluxes consistency, which allowed for the usage of satellite data in ERA5 to analyze soil moisture. This will influence the surface energy budget. Some important improvements in the wave model include: an updated model bathymetry with a more recent version of ETOPO2 and a revised unresolved bathymetry scheme. Some of these changes are associated with better accounting for wave propagation along coastlines and better modelling of the impact of previously unresolved features like islands and narrow embayments (e.g., Moore et al. in prep).

Limitations and strengths for application in North Canada

ERA5 is a new atmospheric reanalysis and there are not available scientific evaluations of the dataset dedicated specifically to North Canada. However, evaluations in other regions, have shown that i**n mountainous regions above about 1,500 m, the snow depth is unrealistically large in ERA5.**

References to documents describing the methodology or/and the dataset

Hersbach, H., B. Bell, P. Berrisford, G. Biavati, A. Horányi, J. Muñoz Sabater, J. Nicolas, C. Peubey, R. Radu, I. Rozum, D. Schepers, A. Simmons, C. Soci, D. Dee, J.-N. Thépaut, 2018: ERA5 hourly data on single levels from 1979 to present. Copernicus Climate Change Service (C3S) Climate Data Store (CDS). (Accessed on < 29-Apr-2019 >), https://doi.org/10.24381/cds.adbb2d47

Hersbach, H., B .Bell, P. Berrisford, S. Hirahara, A. Horányi, J. Muñoz-Sabater, J. Nicolas, C. Peubey, R. Radu, D. Schepers, A. Simmons, C. Soci, S. Abdalla, X. Abellan, G. Balsamo, P. Bechtold, G. Biavati, J. Bidlot, M. Bonavita, G. Chiara, P. Dahlgren, D. Dee, M. Diamantakis, R. Dragani, J. Flemming, R. Forbes, M. Fuentes, A. Geer, L. Haimberger, S. Healy, R.J. Hogan, E. Hólm, M. Janisková, S. Keeley, P. Laloyaux, P. Lopez, C. Lupu, G. Radnoti, P. Rosnay, I. Rozum, F. Vamborg, S. Villaume, and J.-N. Thépaut, 2020: The ERA5 global reanalysis. Quarterly Journal of the Royal Meteorological Society, 146(730), 1999–2049. https://doi.org/10.1002/qj.3803.

Online technical documentation: https://confluence.ecmwf.int/display/CKB/ERA5%3A+data+documentation

Link to download the data and format of data:

Data Access: Copernicus | NCAR | ECMWF

ERA5 is available in GRIB1 and NetCDF formats

Link to download hourly and monthly data on Copernicus:

- hourly data on single levels from 1950 to 1978,
- hourly data on single levels from 1979 to present,
- hourly data on pressure levels from 1950 to 1978,
- hourly data on pressure levels from 1979 to present,
- monthly averaged data on single levels from 1950 to 1978,
- monthly averaged data on single levels from 1979 to present,
- monthly averaged data on pressure levels from 1950 to 1978,
- monthly averaged data on pressure levels from 1979 to present.

Publications including dataset evaluation or comparison with other data in Canada

7.5.18 Dataset: The NCAR Arctic System Reanalysis (ASRv2) - snow

Overview

This document provides an overview of snow products of ASRv2. ASRv2 is a multi-agency, university-led regional reanalysis product that covers the Arctic. It is produced using high-resolution versions of the Polar Weather Forecast Model (PWRF) and the WRF-VAR and High Resolution Land Data Assimilation (HRLDAS) systems that have been optimized for the Arctic. The final version, which has 15 km horizontal resolution and spans 2000-2016 period, is available online through the NCAR's RDA.

Provider's contact information

ASRv2 is produced by Polar Meteorology Group, Byrd Polar & Climate Research Center, The Ohio State University **and is available at NCAR CISL RDA.**

RDA NCAR User support manager schuster@ucar.edu.

Licensing

Licence: This data are licensed under Creative Commons Attribution 4.0 International Licence (Licence agreement information can be found here)

Dataset citable as: National Center for Atmospheric Research/University Corporation for Atmospheric Research, and Polar Meterology Group/Byrd Polar and Climate Research Center/The Ohio State University. 2017. Arctic System Reanalysis version 2. Research Data Archive at the National Center for Atmospheric Research, Computational and Information Systems Laboratory. https://doi.org/10.5065/D6X9291B , https://rda.ucar.edu/datasets/ds631.1/

Bromwich, D., L. Bai, K. Hines, S. Wang, Z. Liu, H. Lin, Y. Kuo, and M. Barlage. 2012. Arctic System Reanalysis (ASR) Project. Research Data Archive at the National Center for Atmospheric Research, Computational and Information Systems Laboratory.

Variable name and units:

ASRv2 provides 2 products kind, analysis and forecast. The table below provide details for the snow-related products in ASRv2.

Name (parameter)	Units	dataset

SNOW (SNOW WATER EQUIVALENT)	kg m-2	ASRv2.0 2D surface analysis ASRv2.0 2D surface forecast
SNOWH (PHYSICAL SNOW DEPTH)	m	ASRv2.0 2D surface analysis
SNOWNC (ACCUMULATED 3 hour TOTAL GRID SCALE SNOW AND ICE))	mm	ASRv2.0 2D surface forecast
SNOALB (ANNUAL MAX SNOW ALBEDO IN FRACTION)	0~1	ASRv2.0 2D surface analysis ASRv2.0 2D surface forecast
SNOWC (FLAG INDICATING SNOW COVERAGE : 1 FOR SNOW COVER)	0~1	ASRv2.0 2D surface analysis ASRv2.0 2D surface forecast

Spatial coverage and resolution:

Geographical Coverage: 15kmx15km (at 60 N) oriented 175 W (720x720 North Polar Stereographic).

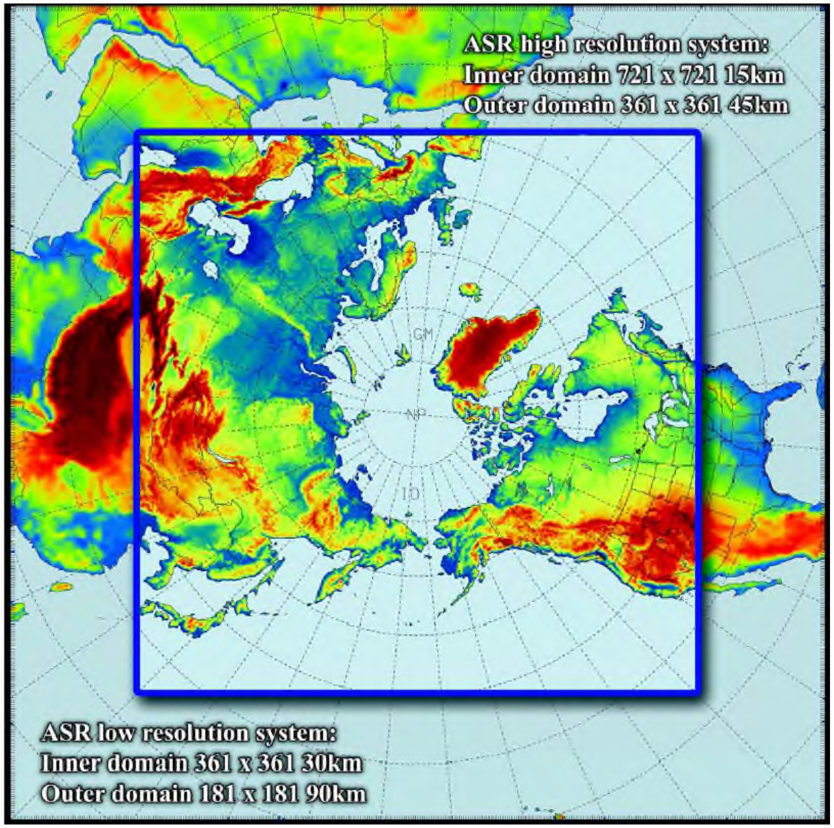

Figure 1. ASR domain (from http://polarmet.osu.edu/ASR/)

Temporal coverage and resolution:

ASRv2 snow products are available from 2000 to 2016 as **3-hourly** subsets and monthly means.

Methodology

ASRv2 provides a high resolution description of the atmosphere-sea ice-land surface system of the Arctic. It is using the polar version of the Weather Research and Forecasting (WRF) model version 3.6.0. It uses the 3DVAR technique and the High Resolution Land Data Assimilation (HRLDAS) data assimilation systems that have been optimized for the Arctic. ASR employs the Noah Land Surface Model (LSM) with several improvements, including fractional sea ice within each grid cell and specified sea ice characteristics (e.g., thickness, snow cover over sea ice, albedo).

A full description of ASRv2 is presented in the Bulletin of the American Meteorological Society (PDF).

Observations data in ASRv2

The observations data used in ASRv2 (Figure 2) includes synoptic surface observations (black dots), METARs (purple plus signs), ship observations (royal blue dots), buoys (navy-blue dots), radiosondes (purple asterisks), global positioning system refractivity observations (red dots), wind profiler (yellow dots), aviation in-flight weather reports (green dots), QuikSCAT sea surface winds (orange dots), and satellite atmospheric motion vectors (aqua dots).

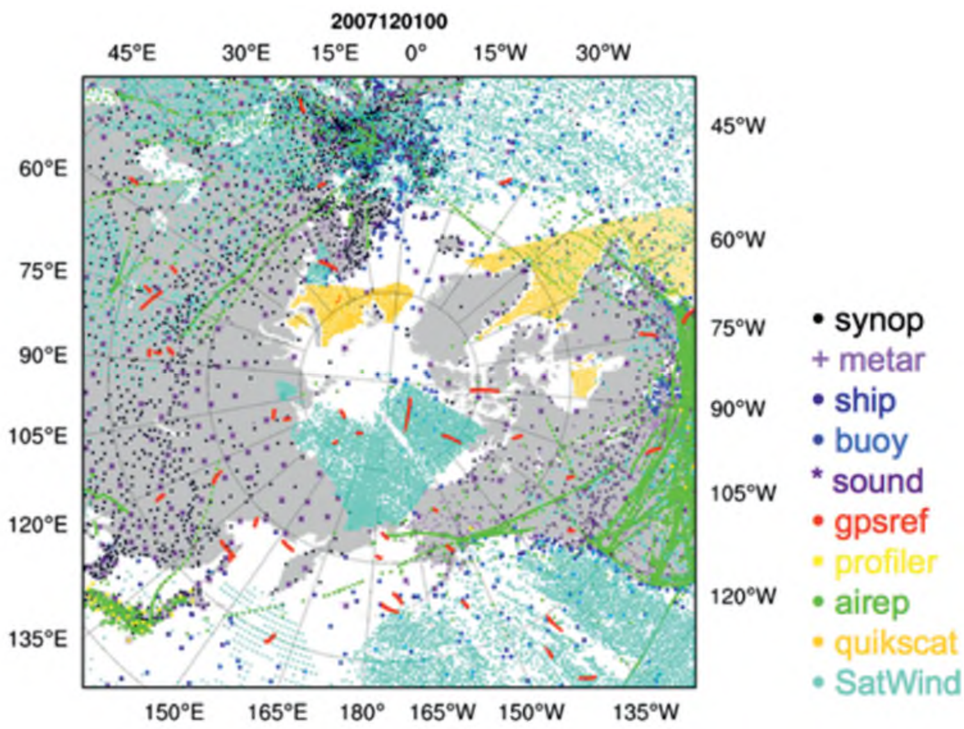

Figure 2. Sample distribution of observations

Sea ice fractions are prescribed from daily NSIDC SSMI/I microwave radiometer measurements for the Polar WRF model. These prescribed values include first-order seasonal variations for the Arctic Ocean that depend on latitude and time of year. A seasonal cycle is used for the sea ice albedo which varies annually based on melt/freeze dates from satellite observations. Snow cover and snow albedo are assimilated from the National Environmental Satellite, Data, and Information Service (NESDIS) observations and vary seasonally, again, to represent melting and freezing.

Information about the technical and scientific quality

New features in ASRv2 compared to ASRv1 are higher horizontal resolution, updated model physics including sub-grid scale cloud fraction interaction with radiation, and a dual outer loop routine for more accurate data assimilation.

The following document compares near-surface variables from ASRv1, ASRv2, and ERAI to observations from ~4500 surface stations provided by the National Centers for Environmental Information (https://www.ncdc.noaa.gov/) for the period December 2006-November 2007: **http://polarmet.osu.edu/ASR/asr_v2_table.pdf**

Presently there are plans to update ASRv2. The updated version will use the latest version of WRF and WRFDA, a more advanced data assimilation procedure, implement Morrison microphysics with a specified variable aerosol concentration, change to Noah-MP land surface model, incorporate a thermodynamic sea ice model, and increase the horizontal resolution to at least 10 km with ~ 100 vertical levels. This version will be known as ASRv3. Plans are to conduct a reanalysis of the MOSAiC drift period (fall 2019 - fall 2020) and it will be available through NCAR.

Limitations and strengths for application in North Canada

The following notes are general observations provided at https://climatedataguide.ucar.edu/climate-data/arctic-system-reanalysis-asr :

Key Strengths: Excellent reproduction of near-surface and tropospheric variables

Key Limitations: A dry bias is still present during the cooler months in ASRv2.

References to documents describing the methodology or/and the dataset

Bromwich, D., Y.-H. Kuo, M. Serreze, J. Walsh, L.S. Bai, M. Barlage, K. Hines, and A, Slater, 2010: Arctic System Reanalysis: Call for community involvement. EOS Trans. AGU, 91, 13-14. https://doi.org/10.1029/2010EO020001

Online technical description: **https://rda.ucar.edu/datasets/ds631.0/#!docs**

Link to download the data and format of data:

Data Access:NCAR/RDA

ASRv2 is available in NetCDF formats

Link to download 3 hourly and monthly data on RDA:

3 hourly data surface analysis from 2000 to 2016

3 hourly data surface forecast from 2000 to 2016

ASR 15 km monthly means of analysis products

ASR 15 km monthly means of forecast products

Publications including dataset evaluation or comparison with other data in Canada

Bromwich, D.H., A.B. Wilson, L. Bai, G.W.K. Moore, and P. Bauer, 2016: A comparison of the regional Arctic System Reanalysis and the global ERA-Interim Reanalysis for the Arctic. Q. J. R. Meteorol. Soc., 142, 644-658. https://doi.org/10.1002/qj.2527

Bromwich, D.H., K.M. Hines, and L.-S. Bai, 2009: Development and testing of Polar WRF: 2. Arctic Ocean. J. Geophys. Res., 114, D08122. https://doi.org/10.1029/2008JD010300

Smirnova, J., and P. Golubkin, 2017: Comparing polar lows in atmospheric reanalyses: Arctic System Reanalysis versus ERA-Interim. Mon. Wea. Rev., 145, 2375-2383, https://doi.org/10.1175/MWR-D-16-0333.1

Avila-Diaz, A., D.H. Bromwich, A.B. Wilson, F. Justino, S.-H. Wang, 2021: Climate extremes across the North American Arctic in modern reanalyses. J. Climate, , 34, 2385–2410, https://doi.org/10.1175/JCLI-D-20-0093.1

Chanona, M., and S. Waterman, 2020: Temporal Variability of Internal Wave-Driven Mixing in Two Distinct Regions of the Arctic Ocean. J. Geophys. Res. Oceans, 125, https://doi.org/10.1029/2020JC016181

Edel, L., C. Claud, C. Genthon, C. Palerme, N. Wood, T. L'Ecuyer, and D. Bromwich, 2020: Arctic snowfall from CloudSat observations and reanalyses. J. Clim., 33, 2093-2109, https://doi.org/10.1175/JCLI-D-19-0105.1

Kaiser-Weiss, A.K., M. Borsche, D. Niermann, F. Kaspar, C. Lussana, F.A. Isotta, E. van den Besselaar, G. van der Schrier, and P. Undén, 2019: Added value of regional reanalyses for climatological applications. Environ. Res. Commun., 1, https://doi.org/10.1088/2515-7620/ab2ec3

Gutjahr, O., and G. Heinemann, 2018: A model-based comparison of extreme winds in the Arctic and around Greenland. Int. J. Clmatol., 38, 5272-5292, https://doi.org/10.1002/joc.5729

Rabatel, M., P. Rampal, A. Carrassi, L. Bertino, and C. K. Jones, 2018: Impact of rheology on probabilistic forecasts of sea ice trajectories: Application for search and rescue operations in the Arctic. Cryosphere, 12, 935-953, https://doi.org/10.5194/tc-12-935-2018

Kohnemann, S.H., G. Heinemann, D.H. Bromwich, and O. Gutjahr, 2017: Extreme warming in the Kara Sea and Barents Sea during the winter period 2000-16. J. Clim., 30, 8913-8927, https://doi.org/10.1175/JCLI-D-16-0693.1

Kolstad, E.W., 2017: Higher ocean wind speeds during marine cold air outbreaks. Quarterly J. Roy. Meteor. Soc., 143, 2084-2092, https://doi.org/10.1002/qj.3068

Rampal, P., S. Bouillon, E. Ólason, and M. Morlighem, 2016: neXtSIM: a new Lagrangian sea ice model. The Cryosphere, 10, 1055-1073, https://doi.org/10.5194/tc-10-1055-2016

Wang, F., W. Li, and S. Wang, 2016: Polar cyclone identification from 4D climate data in a knowledge-driven visualization system. Climate, 4, https://doi.org/10.3390/cli4030043

7.5.19 <u>Dataset</u>: Modern-Era Retrospective analysis for Research and Applications, Version 2 (MERRA-2) - snow

Overview

This document provides an overview of the snow products from the Modern-Era Retrospective analysis for Research and Applications, Version 2 (MERRA-2). MERRA-2 represents a third generation atmospheric global reanalysis produced by the Global Modeling and Assimilation Office (GMAO) at NASA. It begins in 1980 and it replaces the original MERRA reanalysis (Rienecker et al., 2011) using an upgraded version of the Goddard Earth Observing System Model, Version 5 (GEOS-5) data assimilation system. Alongside the meteorological data assimilation using a modern satellite database, MERRA-2 includes an interactive analysis of aerosols that feed back into the circulation, uses NASA's observations of stratospheric ozone and temperature, and takes steps towards representing cryogenic processes by including a representation of ice sheets over Greenland and Antarctica.

Provider's contact information

MERRA-2 is developed by the Global Modeling and Assimilation Office (GMAO) and produced through NASA's Modeling, Analysis and Prediction (MAP) program.

Data Download questions should go to the GES DISC help email: gsfc-help-disc@lists.nasa.gov

Science questions regarding MERRA-2 data be emailed to: merra-questions@lists.nasa.gov

When contacting these emails, provide specific information and links to where you have attempted the data downloads. They also ask you to familiarize yourself with the existing documentation first (MERRA-2: http://gmao.gsfc.nasa.gov/reanalysis/MERRA-2/docs/)

Licensing and citation

MERRA-2 data is freely available from the Goddard Earth Sciences (GES) Data Information Services center (DISC). Note that each MERRA-2 data collection has a citable DOI, that should be used in peer-reviewed publications.

Citing MERRA-2 data has 2 steps for a full citation:

- First pick the correct variable here.
- When you click on the correct variable, it will take you to a second webpage with tabs that you can click that include: (1) documentation papers you need to cite, and (2) the correct variable citation information. You need both types of citation.

Variable name and units:

Snow depth and Total snow storage are available as time-averaged **hourly** and **monthly** products. Each time-averaged collection consists of a continuous sequence of data averaged over the indicated interval and time stamped with the central time of the interval. For hourly data, for example, these times are 00:30 GMT, 01:30 GMT, 02:30 GMT, etc. Monthly files represent averages for the calendar months, accounting for leap years.

Name	Description	Units
SNODP	Snow depth	m
SNOMAS	Snow mass (or snow water equivalent)	Kg m-2
FRSNO	fractional area of land snowcover	No units

Those variables are available in the Land Surface Diagnostics (LSD) collection. In the LND collection of variables, all the data are derived from the land model, and are not weighted according to the land fraction at that grid point. This data is provided to better compute land budgets for soil water and land energy. LND is land only, while all other collections are representative of the whole grid box.

In MERRA-2, Snow depth (SNODP) is recorded as the snow depth within the snow-covered portion only. Snow mass (SNOMAS), on the other hand, is recorded relative to the entire grid cell area, including the snow-covered and snow-free portions. The snow depth averaged across the entire grid cell (including the snow-covered and snow-free portions) can be computed by multiplying SNODP with FRSNO.

More broadly, **MERRA-2 File Specification** document has a comprehensive list of datasets available, as well as description of the horizontal and vertical grids.

Spatial coverage and resolution:

MERRA-2 data, is a global dataset. All variables are provided on the same horizontal regular latitude-longitude grid that has 576 points in the longitudinal direction and 361 points in the latitudinal direction, corresponding to a resolution of 0.625° × 0.5°.

Temporal coverage and resolution:

MERRA-2 data, is available from 1980 to present.

Snow data is available at hourly and monthly time step.

MERRA-2 data, is updated on a monthly base (each new month is available approximately between the 15th and 20th of the next month.).

Information about observations (number, homogeneity)

Like any other climate variable from a reanalysis product, snow is potentially influenced by all observations assimilated into the product. MERRA-2 assimilates conventional and satellite-based observations.

Conventional observations include surface, upper air, and aircraft measurements. **From land based surface meteorology stations, only surface pressure is assimilated in MERRA and MERRA-2**. Radiosonde stations may contribute to the lower level analysis (T, Qv, U, V). Likewise, commercial aircraft can provide lower level data on the ascent and descent (T, U, V). There are also wind profilers (U,V). Over ocean, ships and buoys may provide PS, T, Qv, U and V.

Spaceborne observations include satellite radiances and retrieved measurements of the temperature and moisture fields, and satellite observations of wind (derived retrievals of surface and upper-air wind). Spaceborne observations represent the majority of the global observing system, and the percentage of the global observing system that is measured from space increases from 62% in Jan 1980 to 88% in Dec 2014. Modern hyperspectral radiance and microwave observations, along with GPS-Radio Occultation and NASA ozone datasets are now assimilated in MERRA-2.

See the MERRA-2 Observations Tech Memo for more details.

Also, gauge precipitation is not assimilated by the assimilation system, MERRA-2 uses observation-based precipitation data as forcing for the land surface parameterization. However, the forcing precipitation is not purely gauge observations, as it tapers back to MERRA-2 model generated precipitation poleward of 42.5° latitude, and is completely MERRA-2 modelled precipitation poleward of 62.5°, therefore over the northern Canada.

Methodology

Like any other reanalysis, MERRA-2 data is strongly influenced by the data assimilation methodology. MERRA-2 is currently being produced with the GMAO/GEOS-5 Data Assimilation System Version 5.12.4, which incorporates the Global Statistical Interpolation (GSI) analysis scheme of Wu *et al.* (2002). The system utilizes a revised version of the GEOS global atmospheric model (Molod *et al*., 2014). MERRA-2 is intended to replace the MERRA reanalysis product (which was created with GEOS-5.2.0). Details of the MERRA-2 system, including the major changes from the MERRA system, are summarized in the companion GMAO Office Note No. 10. The major motivation for replacing MERRA with MERRA-2 is the fact that the MERRA data assimilation system was frozen in 2008 and is not capable of ingesting several important new data types as the newer microwave sounders and hyperspectral infrared radiance instruments. The GEOS-5 system actively assimilates roughly 2×10^6 observations for each analysis, including about 7.5×10^5 AIRS radiance data. The input stream is roughly twice this volume, but because of the large volume, the data are thinned commensurate with the analysis grid to reduce the computational burden. Data are also rejected from the analysis through quality control procedures.

There is a fundamental change between MERRA and MERRA-2 over land surfaces. Soil moisture in MERRA-2 is initialized using a separate observation-based precipitation product (variable PRECTOTCORR in “flx” collections). This approach improves the representation of land surface properties and runoff, and is similar to the soil moisture initialization scheme developed for MERRA-Land (Reichle *et al*., 2011; Reichle, 2012; Reichle and Liu, 2014). The forcing precipitation is primarily based on gauge observations at low and midlatitudes, and gradually tapers to the MERRA-2 modelled precipitation over a zonal range from 42.5° to 62.5° latitude. The forcing precipitation is entirely composed of the MERRA-2 modelled precipitation poleward of 62.5°.

MERRA-2 is produced as four production Streams, each of the first three covering approximately a third of the MERRA-2 period, with the fourth stream starting within a couple years of real time. Initial conditions for the four MERRA-2 streams were derived from MERRA with a subsequent single year spin-up period, which has not been released in MERRA-2.

Information about the technical and scientific quality

MERRA-2 replaces the original NASA MERRA reanalysis (Rienecker et al., 2011) using an upgraded version of the data assimilation system, and of the forecast model. It is accompanied by extensive technical documentation (see section below on reference to s describing the methodology or/and the dataset). It incorporates observations from the more recent satellite instruments, uses observation-corrected precipitation forcing for the land surface, includes stratospheric ozone products and assimilates interactive aerosols and observed time varying emissions.

A webpage is provided with FAQ answers here: https://gmao.gsfc.nasa.gov/reanalysis/MERRA-2/FAQ/#

Limitations and strengths for application in North Canada

Key general limitations:

- Discontinuities occur in the sea ice and SST boundary condition fields that affect certain time series analysis
- Discontinuities associated with major observing system variations do occur
- The forcing precipitation is entirely composed of the MERRA-2 modelled precipitation poleward of 62.5°. Care must be taken in mass balance studies as the difference between the observation-based and model-generated precipitation will affect the water budget when land and atmosphere budgets are combined. More generally, precipitation is thought to be too large over polar oceans, and is excessive over high topography in tropical latitudes

References to documents describing the methodology or/and the dataset

MERRA-2 Overview: The Modern-Era Retrospective Analysis for Research and Applications, Version 2 (MERRA-2), Ronald Gelaro, et al., 2017, J. Clim., doi: 10.1175/JCLI-D-16-0758.1

The American Meteorological Society has a special collection of articles relevant to MERRA-2. This collection, coordinated by Mike Bosilovich, is available at http://journals.ametsoc.org/collection/MERRA2.

There are several MAO Technical Memoranda that document and evaluate different aspects of the MERRA-2 system aspects of the MERRA-2 system:

#43, Bosilovich et al. – MERRA-2: Initial Evaluation of the Climate

#45, Randles et al. – The MERRA-2 Aerosol Assimilation

#46, McCarty et al. – MERRA-2 Input Observations: Summary and Assessment

Description of the observation corrected precipitation process used in MERRA-2:

Reichle, R., Q. Liu, R. Koster, C. Draper, S. Mahanama, and G. Partyka, 2017: Land Surface Precipitation in MERRA-2. *J. Clim.* doi:10.1175/JCLI-D-16-0570.1 Link.

Description of the GEOS-5 model changes between the MERRA and MERRA-2 systems:

Molod, A., L.T akacs, M. Suarez, and J. Bacmeister, 2015: Development of the GEOS-5 atmospheric general circulation model: evolution from MERRA to MERRA-2, *Geosci. Model Dev.*, 8, 1339-1356, doi:10.5194/gmd-8-1339-2015. Link.

Description of the mass constraint used in MERRA-2:

Takacs, L. L., M. Suarez, and R. Todling, 2015: Maintaining Atmospheric Mass and Water Balance Within Reanalysis. *NASA/TM–2014-104606*, Vol. 37 Document.

Link to download the data and format of data:

The MERRA-2 data are available online through the Goddard Earth Sciences (GES) Data and Information Services Center (DISC) (http://disc.sci.gsfc.nasa.gov/mdisc/). All MERRA-2 data are organized into file collections that contain fields with common characteristics. Snow related data are grouped in the following collections:

MERRA-2 tavg1_2d_lnd_Nx: 1-Hourly time averaged data containing Land Surface Diagnostics

MERRA-2 tavgM_2d_lnd_Nx: Monthly time average data containing Land Surface Diagnostics.

MERRA-2 data files are provided in netCDF-4 format. Due to the size of the MERRA-2 archive, most product collections are compressed with a GRIB like method that is invisible to the user. This method does degrade the precision of the data, but every effort has been made to ensure that differences between the product and the original, non-degraded data are not scientifically meaningful.

Publications including dataset evaluation or comparison with other data in Canada

7.5.20 *Dataset: The Japanese 55-year Reanalysis (JRA-55) - snow*

Overview

This document provides an overview of the snow-related data from JRA-55. JRA-55 is a third-generation reanalysis developed by Japanese Meteorological Agency (JMA). It is spanning 1958 to present period and represent an update of the previous Japanese 25-year Reanalysis (JRA-25). The analysis period starts in 1958, when regular radiosonde observation began on a global basis. Many of the deficiencies of JRA-25 are alleviated in JRA-55 because the Data Assimilation (DA) system used for the project featured a variety of improvements.

Provider's contact information

JRA-55 is developed by the Japanese Meteorological Agency (JMA). Contact JMA at the email address below with any questions on JRA-55:

Climate Prediction Division, Global Environment and Marine Department,

Japan Meteorological Agency,

Email: jra@met.kishou.go.jp

Contact DIAS Office at the email address below with any questions on JRA-55 stored at DIAS:

DIAS Office

Japan Agency for Marine-Earth Science and Technology

Email: dias-office@diasjp.net

Licensing and citation

The intellectual property rights of the datasets belong exclusively to JMA.

JRA-55 data are provided by collaborative organizations that are separate entities from JMA. User registration and agreement to terms and conditions of data service usage are required individually for each organization. Data at NCAR RDA is licensed under a Creative Commons Attribution 4.0 International Licence.

Individual users should provide JMA (jra@met.kishou.go.jp) with a copy of their scientific or technical papers, publications, press releases or other communications regarding these datasets. The source of the products should be duly acknowledged in scientific or technical

papers, publications, press releases or other communications regarding the products. This includes information on the provider of data and of the collaborative organizations from where the data was downloaded.

Example for data downloaded from DIAS Office:

" In this study, the Japanese 55-year Reanalysis (JRA-55) provided by the Japan Meteorological Agency (JMA) was utilized. This dataset was also collected and provided under the Data Integration and Analysis System (DIAS), which was developed and operated by a project supported by the Ministry of Education, Culture, Sports, Science and Technology. "

Example for downloaded from NCAR RDA:

Japan Meteorological Agency/Japan. 2013, updated monthly. JRA-55: Japanese 55-year Reanalysis, Daily 3-Hourly and 6-Hourly Data. Research Data Archive at the National Center for Atmospheric Research, Computational and Information Systems Laboratory. https://doi.org/10.5065/D6HH6H41. Accessed† dd mmm yyyy.

†Please fill in the "Accessed" date with the day, month, and year (e.g., - 5 Aug 2011) you last accessed the data from the RDA.

Spatial coverage and resolution:

JRA-55 data, is a global dataset. Data is available at two spatial resolutions: (1) data on pressure levels at 1.25 degree spatial resolution and (2) data on model TL319L60 grid (~55 km) that was processed to a regular latitude-longitude Gaussian grid (320 latitudes by 640 longitudes, nominally 0.5625 degrees) and is available on NCAR RDA.

Variable name and units:

The following table summarizes the snow-related variables available at NCAR RDA a regular latitude-longitude Gaussian grid (320 latitudes by 640 longitudes, nominally 0.5625 degrees) and the name of the set of data including each of them.

Notation (name)	Units	Dataset product
Snowfall rate water equivalent	mm day-1	JRA-55 **3-Hourly** Model Resolution 2-Dimensional **Average Diagnostic Fields (fcst_phy2m)**
Snow depth	m	JRA-55 **3-Hourly** Model Resolution Land **Surface Forecast Fields (fcst_land)** JRA-55 Model Resolution **Snow Depth Analysis Fields (anl_snow)**

Water equivalent of accumulated snow depth	kg m-2	JRA-55 **3-Hourly** Model Resolution Land **Surface Forecast Fields (fcst_land)** JRA-55 **6-Hourly** Model Resolution Land **Surface Analysis Fields (anl_land)**

Two-dimensional average diagnostic fields (fcst_phy2m) are produced every three hours. The parameters shown in Table 4-11 are averaged from the beginning of forecasts up to three hours for 00 - 03, 06 - 09, 12 - 15 and 18 - 21 UTC, and from three to six hours for 03 -06, 09 - 12, 15 - 18 and 21 - 24 UTC. Dates in file names indicate the beginning of the averaging period.

Temporal coverage and resolution:

JRA-55 is covering 1958 to present period. The Forecast and Diagnostic fields are available at 3h time step, while the Analysis Fields are available just at 6h time step.

Monthly statistics are computed as averages and variances for the whole month using only six-hourly data for analyzed and instantaneous forecast fields and averages from the beginning of forecasts up to six hours for average diagnostic fields.

The data is updated on a monthly base.

Information about observations (number, homogeneity)

Most of the observational data employed in JRA-55 are those used in JRA-25. Additionally, newly reprocessed METEOSAT and GMS data were supplied by EUMETSAT and MSC/JMA respectively. From 1958 to 2002, JRA-55 is using the same conventional data as ECMWF ERA-40 reanalysis. The table below summarizes the conventional data assimilate in JRA-55.

Table 1. Conventional data assimilated in JRA-55

Obs type	Parameter	Level
SYNOP	P	surface
SHIP	P	surface
BUOY	P	surface
Upper-level	T	~100 hPa
Upper-level	T	100~1000 hPa
Upper-level	u	~100 hPa
Upper-level	u	100~1000 hPa
Upper-level	Rh	100~1000 hPa
Aircraft	u	100~1000 hPa
Profiler (US)	u	100~1000 hPa

Quality control of conventional data is basically the same as the one used for JRA-25, and it includes a climatological check, track check, removal of duplicates, consistency check and gross error check.

In the snow depth analysis component, Snow depth data over the United States, Russia and Mongolia (that were supplied by UCAR, RIHMI and IMH respectively) and daily snow cover retrievals from the Special Sensor Microwave/Imager (SSM/I) and the Special Sensor Microwave Imager Sounder (SSMIS) are used.

Methodology

JRA-55 has been produced with the TL319 version of the Japan Meteorological Agency (JMA) operational data assimilation system (as of December 2009), which features numerous improvements made since the Japanese 25-year Reanalysis (JRA-25). These include a revised longwave radiation scheme, 4D-Var and variational bias correction for satellite radiances. It also incorporates several newly available observational datasets produced as a result of ongoing efforts to improve quality of past observations, including homogenization of radiosonde temperature observations (Haimberger *et al*. 2008, 2012) and reprocessing of satellite data at major meteorological satellite centers.

The analysis of screen-level variables (2 m temperatures, 2 m relative humidities and 10 m winds) is performed separately with a univariate 2-dimensional optimal interpolation (2D-OI). Land surface analysis fields are generated by driving an offline version of the JMA Simple Biosphere (SiB) model with forcing fields from the atmospheric model. **Snow depth analysis fields** are generated once a day with 2D-OI using SYNOP snow depth observations. First-guess fields are derived for each grid point using (A) snow depth of the land surface analysis and (B) satellite snow covers. Satellite snow covers are retrieved in the 0.25° × 0.25° latitude/longitude grid from microwave imager radiances.

The forecast model used for JRA-55 is based on the TL319 spectral resolution version of the JMA global spectral model (GSM) as of December 2009 (JMA 2007, 2013b), which has been extensively improved since JRA-25.

The reanalysis period was divided into two streams (A002, B002) which have been producing three discontinuities: at 00 UTC on 1 July 1958, 00 UTC on 1 September 1980, and 00 UTC on 1 October 1992. JRA-55 is presently operated on a near-real-time basis and provides monthly updates for the data.

Information about the technical and scientific quality

One important realization in jRA-55 is the increase in the model resolution (T319L60 vs T106L40 in JRA-25). Among the improvements in the product are reduced biases in stratospheric temperature and Amazonian rainfall, and greater temporal consistency of the temperature analysis. Some notable biases persist, including a dry bias in the upper and middle troposphere, and a warm bias in the upper troposphere. The impacts of changes in the observing system on the forecast error are generally more evident in the Southern Hemisphere than the Northern Hemisphere.

The data is updated on a monthly base. JMA provide a webpage where the issues with JRA-55 are described: JRA-55 Quality Issues

Limitations and strengths for application in North Canada

GENERAL KEY STRENGTHS:

- Longest-running full observing system reanalysis with and advanced assimilation methodology.

GENERAL KEY LIMITATIONS:

- The impact of changes in observing systems is particularly apparent for July 2006, when Global Navigation Satellite System-Radio Occultation (GNSS-RO) refractivity data were introduced into JRA-55.
- There are issues with JRA-55 snow depth analysis that are documented in following documentation: Impact of snow depth analysis bugs on the JRA-55 product for the period from 2015 to 2016 and Areas and periods shown with unrealistically deep snow (1958-2016) .
    - List of areas and periods shown with unrealistically deep snow: JRA-55_snow_bugs_list1_update_en.txt (28 July 2016 updated)

- Masking data for reference in determining grid points and periods affected by the bugs: JRA-55_mask_update_en.zip (28 July 2016 updated)

References to documents describing the methodology or/and the dataset

Kobayashi, S., Y. Ota, Y. Harada, A. Ebita, M. Moriya, H. Onoda, K. Onogi, H. Kamahori, C. Kobayashi, H. Endo, K. Miyaoka, and K. Takahashi, 2015: The JRA-55 Reanalysis: General specifications and basic characteristics. Journal of the Meteorological Society of Japan. Ser. II, 93(1), 5-48, doi:10.2151/jmsj.2015-001.

Harada, Y., H. Kamahori, C. Kobayashi, H. Endo, S. Kobayashi, Y. Ota, H. Onoda, K. Onogi, K. Miyaoka, and K. Takahashi, 2016: The JRA-55 Reanalysis: Representation of atmospheric circulation and climate variability, J. Meteor. Soc. Japan, 94, 269-302, doi:10.2151/jmsj.2016-015.

Link to download the data and format of data:

The JRA-55 data are available in GRIB-2 format and can be accessed from the following organizations:

DIAS: Data Integration & Analysis System (data from 1958 to 2012, on a grid of approx. 1.25 deg.) : http://search.diasjp.net/en/dataset/JRA55

NCAR: National Center for Atmospheric Research (USA) (data from 1958 to present, on both spatial grids):

- Daily, 3-Hourly and 6-Hourly Data http://rda.ucar.edu/datasets/ds628.0/
- Monthly Means and Variances http://rda.ucar.edu/datasets/ds628.1/
- Near Real-Time Data http://rda.ucar.edu/datasets/ds628.8/
- Near Real-Time Data -- Monthly Means and Variances http://rda.ucar.edu/datasets/ds628.9/

Publications including dataset evaluation or comparison with other data in Canada

7.5.21 *Dataset: NOAA-CIRES-DOE Twentieth Century Reanalysis (20CRv3) - snow*

Overview

This document provides an overview of snow-related data from Twentieth Century Reanalysis (20CRv3). The 20th Century Reanalysis Project is an effort led by NOAA's Physical Sciences Laboratory (PSL) and CIRES at the University of Colorado, supported by the Department of Energy (DOE), to produce reanalysis datasets spanning the entire 20th century and much of the 19th century. These reanalyses assimilate only surface observations of synoptic pressure into NOAA’s Global Forecast System, and prescribed sea surface temperature and sea ice distribution in order to estimate atmospheric variables, from the surface to the top of the atmosphere throughout the 19th and 20th centuries. 20CRv3 is version 3 of the project. For version 3, the ensemble mean and standard deviation for each value were calculated over a set of 80 analyses and short-term forecasts.

Provider's contact information

20CRv3 is developed by the NOAA's Physical Sciences Laboratory (PSL) and CIRES at the University of Colorado, supported by the Department of Energy (DOE).

For help with the dataset please contact

Gilbert P. Compo

CIRES, University of Colorado at Boulder, and Physical Sciences Laboratory, National Oceanic and Atmospheric Administration

gilbert.p.compo at noaa.gov

Laura C. Slivinski

CIRES, University of Colorado at Boulder, and Physical Sciences Laboratory, National Oceanic and Atmospheric Administration

laura.slivinski at noaa.gov

Licensing and citation

20CRv3 data are provided by several collaborative organizations. User registration and agreement to terms and conditions of data service usage are required individually for each organization.

Data at NCAR RDA is licensed under a Creative Commons Attribution 4.0 International Licence.

The following citation should be used for data downloaded from NCAR RDA:

" **Slivinski**, L. C., et al. 2019. NOAA-CIRES-DOE Twentieth Century Reanalysis Version 3. Research Data Archive at the National Center for Atmospheric Research, Computational and Information Systems Laboratory. https://doi.org/10.5065/H93G-WS83. Accessed† dd mmm yyyy.

†Please fill in the "Accessed" date with the day, month, and year (e.g., - 5 Aug 2011) you last accessed the data from the RDA. "

The following citation should be used for data downloaded from Physical Sciences Laboratory (PSL) or from National Energy Research Scientific Computing Center (NERSC):

Papers using the NOAA-CIRES-DOE Twentieth Century Reanalysis Project version 3 dataset are requested to include the following text in their acknowledgments: "Support for the Twentieth Century Reanalysis Project version 3 dataset is provided by the U.S. Department of Energy, Office of Science Biological and Environmental Research (BER), by the National Oceanic and Atmospheric Administration Climate Program Office, and by the NOAA Physical Sciences Laboratory."

If you acquire 20th Century Reanalysis V3 data products from PSL, we are asked to acknowledge PSL by including also a text such as *20th Century Reanalysis V3 data provided by the NOAA/OAR/ESRL PSL, Boulder, Colorado, USA, from their Web site at /* in any documents or publications using these data and send a copy of the relevant publications to:

Physical Sciences Laboratory: Data Management

NOAA/ESRL/PSL

325 Broadway

Boulder, CO 80305-3328

psl.data@noaa.gov

Spatial coverage and resolution:

20CRv3 data, is a global dataset. 20CRv3 has a Gaussian T-254 grid (approximately 75 km at the equator).

Variable name and units:

The following table summarizes the snow-related data.

Notation (name)	Units	Organisation (type)

WEASD (Water equivalent of accumulated snow depth)	kg/m^2	PSL; NERSC; NCAR (Analysis Fields and First Guess Forecast Fields)
SNOWC (snow cover)	%	PSL; NCAR (Analysis Fields)
SNOD (snow depth)	m	PSL; NCAR (Analysis Fields and First Guess Forecast Fields)

Temporal coverage and resolution:

On PSL website, 20CRv3.SI is available for years 1836-1980 and 20CRv3.MO is available for years 1981-2015 (the only differences between these two versions are the prescribed sea surface temperatures and dates of availability):

- 3-hourly values for 1836/01/01 0Z to 2015/12/31 21Z.
- Daily average values for 1836/01/01 to 2015/12/31.
- Monthly average values for 1836/01 to 2015/12 (Combined SI-MO).

At NCAR RDA, 20CRv3 is available from:

- 1835/12/31 18Z to 2016/01/01 0Z (Yearly Time Series 3-Hourly Analysis Fields (Gaussian T-254))
- 1806/12/31 18Z to 2015/12/31 12Z (Yearly Time Series 3-Hourly First Guess Forecast Fields (Gaussian T-254))
- 1806/12/31 21Z to 2015/12/31 15Z (Yearly Time Series 6-Hourly Analysis Fields (Gaussian T-254))

The data is updated on an irregular base.

Information about observations (number, homogeneity)

These reanalyses assimilate only surface observations of synoptic pressure. Boundary conditions of pentad sea surface temperature and monthly sea ice concentration and time-varying solar, volcanic, and carbon dioxide radiative forcings are prescribed.

The surface pressure observations: ISPD version 4.7, made available through international cooperation facilitated by the Atmospheric Circulation Reconstructions over the Earth (ACRE) initiative and working groups of the Global Climate Observing System and World Climate Research Program.

Sea Ice Concentration Boundary Condition: monthly HadISST2.3 sea ice (Slivinski *et al*. 2019; Titchner & Rayner 2014; Walsh *et al*. 2015)

Sea Surface Temperature Boundary Condition: prior to 1981(20CRv3.SI): 8 members of pentad interpolated to daily Simple Ocean Data Assimilation with Sparse Input (SODAsi) version 3 (SODAsi.3, Giese *et al*. 2016) seasonally adjusted to the 1981-2010 HadISST2.2 climatology. Regions where sea ice was ever indicated in HadISST2.3 are filled with: HadISST2.2 daily (1963+); HadISST2.1 monthly interpolated to daily (1850-1962); or the 1861–1891 HadISST2.1 climatology (1849 and earlier). **1981 and later (20CRv3.MO)**: 8 members of pentad interpolated to daily HadISST2.2 sea surface temperatures.

Methodology

20CRv3 assimilates only surface observations of synoptic pressure into an 80-member the coupled Global Forecast System land-atmospheric model with prescribed sea surface temperatures and sea ice concentration. A coupled one-dimensional thermodynamic sea-ice model is also used. Boundary conditions of pentad sea surface temperature and monthly sea ice concentration and time-varying solar, volcanic, and carbon dioxide radiative forcings are prescribed.

Forecast model: 20CRv3 uses the atmospheric model from the NCEP Global Forecast System v14.0.1 coupled with the Noah land surface model and 2.5-layer thermodynamic sea ice model (Compo et al. (2011). The forecast system is run at a resolution of T254 (approximately 75 km at the equator) with 64 vertical levels up to .3 mb and it has 80 individual ensemble members.

Assimilation model: The data assimilation algorithm is the Ensemble Square Root Filter (Whitaker and Hamill 2002) with 4D Incremental Analysis Update (4D-IAU; Bloom *et al.,* 1996, Lei & Whitaker 2016). **The snow relaxes to a monthly climatology (Saha et al. 2010) over 60 days.**

Streams: Every 5th year a stream is produced for a continuous 5 year period. Stream years are 1835, 1840, ... , 2005, 2010. Stream year 2010 will be extended beyond 2015.

Information about the technical and scientific quality

There are three previous versions of the reanalysis: V1, V2, and V2c. Several adjustments were made to the model prior to implementation in the 20CRv3 system. Updates to the parameterizations are described in Saha *et al*. (2010) and include revised solar radiation transfer, boundary layer vertical diffusion, cumulus convection, and gravity wave drag parameterizations. In addition, the cloud liquid water is a prognostic quantity with a simple cloud microphysics parameterization. Another important improvement is in the resolution and ensemble size. Previous 20CR versions were using a 56-member ensemble with a coarser spatial resolution (T62 28 levels), while the 20CRv3 is using 80 ensemble members with a finer spatial resolution (T254 64 levels). 20CRv3 also assimilates a larger set of observations, and includes an improved data assimilation system relative to its predecessor 20CRv2c.

Observations are first grossly tested for quality control: if the observation is outside the range 850 and 1090 hPa, or if the absolute difference between the observation and the first guess value is greater than 3.2 times the square root of the sum of the forecast ensemble variance and the observation error variance, the observation is rejected. (Slivinski *et al*., 2018). They are then subject to adaptive quality control and adaptive localization control.

Limitations and strengths for application in North Canada

Key Strengths: Length of record and estimates of uncertainty

Key Limitations: As with all reanalyses, users should take care in interpreting long-term trends - inconsistencies between 20CR and other data have been reported, especially on a regional scale.

References to documents describing the methodology or/and the dataset

Compo, G.P., J.S. Whitaker, P.D. Sardeshmukh, N. Matsui, R.J. Allan, X. Yin, B.E. Gleason, R.S. Vose, G. Rutledge, P. Bessemoulin, S. Brönnimann, M. Brunet, R.I. Crouthamel, A.N. Grant, P.Y. Groisman, P.D. Jones, M. Kruk, A.C. Kruger, G.J. Marshall, M. Maugeri, H.Y. Mok, Ø. Nordli, T.F. Ross, R.M. Trigo, X.L. Wang, S.D. Woodruff, and S.J. Worley, 2011: The Twentieth Century Reanalysis Project. Quarterly Journal of the Royal Meteorological Society, 137(654), 1-28, DOI: 10.1002/qj.776.

Slivinski, L. C.,G. P. Compo, P.D. Sardeshmukh, J. S. Whitaker, C. McColl, R. J. Allan, P. Brohan, X. Yin, C. A. Smith, L. J. Spencer, R. S. Vose, M. Rohrer, R. P. Conroy, D. C. Schuster, J. J. Kennedy, L. Ashcroft, S. Brönnimann, M. Brunet, D. Camuffo, R. Cornes, T. A. Cram, F. Domínguez-Castro, J. E. Freeman, J. Gergis, E. Hawkins, P. D. Jones, H. Kubota, T. C. Lee, A. M. Lorrey, J. Luterbacher, C. J. Mock, R. K. Przybylak, C. Pudmenzky, V. C. Slonosky, B. Tinz, B. Trewin, X. L. Wang, C. Wilkinson, K. Wood, and P. Wyszyński , 2021: An Evaluation of the Performance of the Twentieth Century Reanalysis Version 3. Journal of Climate 34, 4, 1417-1438, https://doi.org/10.1175/JCLI-D-20-0505.1.

Link to download the data and format of data:

20CRv3 data are available at several organizations.

At NOAA/PSL, the ensemble mean and the ensemble uncertainty files are available in netCDF4 format: https://psl.noaa.gov/data/gridded/data.20thC_ReanV3.monolevel.html

At National Center for Atmospheric Research (NCAR), the ensemble mean and the ensemble uncertainty files are available in netCDF4 format: https://rda.ucar.edu/datasets/ds131.3/

At NERSC Science Gateway, data for every member of 20CRv3 are available in netCDF4 format: https://portal.nersc.gov/project/20C_Reanalysis/

Publications including dataset evaluation or comparison with other data in Canada

7.5.22 <u>Dataset</u>: *The NOAA NCEP Climate Forecast System Reanalysis (CFSR) and Climate Forecast System Version 2 (CFSv2) - snow*

Overview

This document provides an overview of the snow products from the Climate Forecast system reanalysis (CFSR) and its operational extension CFSv2. The CFSR is a third generation reanalysis product, developed by the National Oceanic and Atmospheric Administration's (NOAA) National Center for Environmental Prediction (NCEP), and it is using a global, high resolution, coupled atmosphere-ocean-land surface-sea ice system. The spatial resolution of the global atmospheric data is ~38 km (T382) and many atmospheric variables are provided at hourly temporal resolution.

Provider's contact information

CFSR is developed by the National Oceanic and Atmospheric Administration's (NOAA) National Center for Environmental Prediction (NCEP).

Contact name: DOC/NOAA/NESDIS/NCEI > National Centers for Environmental Information, NESDIS, NOAA, U.S. Department of Commerce

Contact email: Contact: cfs@noaa.gov

Licensing and citation

CFSR data is freely available

Please reference the following article when using the CFS Reanalysis (CFSR) data:

Saha, S., S. Moorthi, H.-L. Pan, X. Wu, J. Wang, S. Nadiga, P. Tripp, R. Kistler, J. Woollen, D. Behringer, H. Liu, D. Stokes, R. Grumbine, G. Gayno, J. Wang, Y.-T. Hou, H. Chuang, H. H. Juang, J. Sela, M. Iredell, R. Treadon, D. Kleist, P. Van Delst, D. Keyser, J. Derber, M. Ek, J. Meng, H. Wei, R. Yang, S. Lord, H. van den Dool, A. Kumar, W. Wang, C. Long, M. Chelliah, Y. Xue, B. Huang, J. Schemm, W. Ebisuzaki, R. Lin, P. Xie, M. Chen, S. Zhou, W. Higgins, C. Zou, Q. Liu, Y. Chen, Y. Han, L. Cucurull, Ri. W. Reynolds, G. Rutledge, and M. Goldberg, 2010: The NCEP Climate Forecast System Reanalysis. Bulletin of the American Meteorological Society 91, 8, 1015-1058, https://doi.org/10.1175/2010BAMS3001.1.

For hourly data downloaded from UCAR RDA: **Saha**, S., *et al*. 2010. NCEP Climate Forecast System Reanalysis (CFSR) Selected Hourly Time-Series Products, January 1979 to December 2010. Research Data Archive at the National Center for Atmospheric Research, Computational and Information Systems Laboratory. https://doi.org/10.5065/D6513W89. Accessed dd mmm yyyy.

For monthly data downloaded from UCAR RDA: **Saha,** S., *et al*. 2010. NCEP Climate Forecast System Reanalysis (CFSR) Monthly Products, January 1979 to December 2010. Research Data Archive at the National Center for Atmospheric Research, Computational and Information Systems Laboratory. https://doi.org/10.5065/D6DN438J. Accessed dd mmm yyyy.

Please reference the following article when using the CFS Reforecast model or data:

Saha, S., S. Moorthi, X. Wu, J. Wang, S. Nadiga, P. Tripp, D. Behringer, Y. Hou, H. Chuang, M. Iredell, M.Ek, J. Meng, R. Yang, M.P. Mendez, H. van den Dool, Q. Zhang, W. Wang, M. Chen, and E. Becker, 2014: The NCEP Climate Forecast System Version 2, Journal of Climate, 27(6), 2185-2208, doi:10.1175/JCLI-D-12-00823.1.

For hourly data downloaded from UCAR RDA: Saha, S., et al. 2011, updated monthly. NCEP Climate Forecast System Version 2 (CFSv2) Selected Hourly Time-Series Products. Research Data Archive at the National Center for Atmospheric Research, Computational and Information Systems Laboratory. https://doi.org/10.5065/D6N877VB. Accessed dd mmm yyyy.

For monthly data downloaded from UCAR RDA: Saha, S., et al. 2012. NCEP Climate Forecast System Version 2 (CFSv2) Monthly Products. Research Data Archive at the National Center for Atmospheric Research, Computational and Information Systems Laboratory. https://doi.org/10.5065/D69021ZF. Accessed dd mmm yyyy.

Variable name and units:

The following table summarizes the name of the variables available at NCAR RDA as time series.

Notation (name)	Time step	Units
SNO D (Snow depth)	6 h and monthly	m
WEASD (Water equivalent of accumulated snow depth)	Hourly and monthly	kg m-2
SWE (Snow Water Equivalent; instantaneous) in Flux set of data at NCEI	Hourly and monthly	kg m-2

SNOWC (Snow cover)	6 h and monthly	%

Note: The forecast at the first time step (f00) of 3 minutes constitutes a spin up of the model physics, and IT IS NOT THE ANALYSIS.

Spatial coverage and resolution:

CFSR data, is a global dataset. Snow-related variables are provided on the same horizontal regular latitude-longitude grid with a spatial resolution of ~38 km (T382).

Temporal coverage and resolution:

CFSR is covering 01Jan1979 - 31Mar2011 period. The product was extended beyond 2011 as an operational real-time product, using a new version: NCEP's Climate Forecast System Version 2 (CFSv2). CFSR snow products are available at an hourly or 6 hour time resolution (see below table).

The data is available also as monthly means.

Information about observations (number, homogeneity)

All available conventional and satellite observations were included in the CFSR. Satellite observations were used in radiance form and were bias corrected with "spin up" runs at full resolution, taking into account variable CO_2 concentrations. This procedure enabled smooth transitions of the climate record due to evolutionary changes in the satellite observing system.

It is extremely difficult to assimilate 2 m temperature over land in systems like the CFSR. Therefore, surface temperature from stations is not assimilated in CFSR.

The CFSR uses the NCEP operational observation quality control procedures.

Methodology

The CFSR is a third generation reanalysis product, and it is using global, high resolution, coupled atmosphere-ocean-land surface-sea ice system. It includes (1) coupling of atmosphere and ocean during the generation of the 6 hour guess field, (2) an interactive sea-ice model, and (3) assimilation of satellite radiances. The CFSR global atmosphere resolution is ~38 km (T382) with 64 levels. The global ocean is 0.25° at the equator, extending to a global 0.5° beyond the tropics, with 40 levels. The global land surface model has 4 soil levels and the global sea ice model has 3 levels. The CFSR atmospheric model contains observed variations in carbon dioxide (CO_2), together with changes in aerosols and other trace gases and solar variations.

Snow Analysis used in the CFSR (George.Gayno@noaa.gov): Snow liquid equivalent depth was updated using analysis data from the Air Force Weather Agency's SNODEP model (Kopp et al. 1996) and the NESDIS Interactive Multisensor Snow and Ice Mapping System (IMS) (Helfrich et al. 2007). SNODEP uses in situ observations, an SSM/I-based detection algorithm, and its own climatology to produce a global analysis of physical snow depth once per day at 47 km resolution. Analysts may further adjust the analysis. SNODEP has been operational since 1975 and its data were available for the entire reanalysis period. The IMS data is a manually generated northern hemisphere snow cover analysis produced once per day. Analysts use surface data, geostationary and polar orbiting imagery, and microwave-based detection algorithms to determine whether an area is either snow covered or snow free. IMS data were available at 23 km resolution starting February 1997 and at 4 km resolution starting February 2004.

Information about the technical and scientific quality

The CSFR products are superior to previous NCEP reanalyses with respect to: improved model, finer resolution, advanced assimilation schemes, atmosphere-land-ocean-sea ice coupling, assimilates satellite radiances rather than retrievals, and accounts for changing CO_2 and other trace gasses, aerosols, and solar variations.

Known CFSRR data issues are explained in the August 2011 CFSRR Known Issues Technical Document.

Problems with snow depth were noted during the following dates:

- *Dec 26, 1980*
- *Dec 25,27-28 1999*
- *All days between Jan 1, 2009, and Jan 1, 2011*
- *Jan 25, 2011*

Limitations and strengths for application in North Canada

GENERAL KEY STRENGTHS:

- Approaches the horizontal resolution of regional reanalyses like the NARR and Arctic System Reanalysis

GENERAL KEY LIMITATIONS:

- Ocean-atmosphere interactions are not used directly. Rather the information is used for background information. The actual reanalysis is uncoupled.

References to documents describing the methodology or/and the dataset

Saha, S., S. Moorthi, H.-L. Pan, X. Wu, J. Wang, S. Nadiga, P. Tripp, R. Kistler, J. Woollen, D. Behringer, H. Liu, D. Stokes, R. Grumbine, G. Gayno, J. Wang, Y.-T. Hou, H. Chuang, H. H. Juang, J. Sela, M. Iredell, R. Treadon, D. Kleist, P. Van Delst, D. Keyser, J. Derber, M. Ek, J. Meng, H. Wei, R. Yang, S. Lord, H. van den Dool, A. Kumar, W. Wang, C. Long, M. Chelliah, Y. Xue, B. Huang, J. Schemm, W. Ebisuzaki, R. Lin, P. Xie, M. Chen, S. Zhou, W. Higgins, C. Zou, Q. Liu, Y. Chen, Y. Han, L. Cucurull, Ri. W. Reynolds, G. Rutledge, and M. Goldberg, 2010: The NCEP Climate Forecast System Reanalysis. Bulletin of the American Meteorological Society 91, 8, 1015-1058, https://doi.org/10.1175/2010BAMS3001.1

Saha, S., S. Moorthi, X. Wu, J. Wang, S. Nadiga, P. Tripp, D. Behringer, Y. Hou, H. Chuang, M. Iredell, M.Ek, J. Meng, R. Yang, M.P. Mendez, H. van den Dool, Q. Zhang, W. Wang, M. Chen, and E. Becker, 2014: The NCEP Climate Forecast System Version 2, Journal of Climate, 27(6), 2185-2208, doi:10.1175/JCLI-D-12-00823.1.

Link to download the data and format of data:

The CFSR data (1979 to 2011) are available in GRIB-2 format and can be accessed in multiple ways.

NCEI NOMADS THREDDS Data Server: URL: https://nomads.ncdc.noaa.gov/thredds/cfsr.html

NOAA NOMADS FTP access: URL: ftp://nomads.ncdc.noaa.gov/CFSR/

At UCAR RDA data is grouped as follows:

NCEP Climate Forecast System Version 2 (CFSv2) Monthly Products (ds094.2)

NCEP Climate Forecast System Version 2 (CFSv2) 6-hourly Products (ds094.0)

NCEP Climate Forecast System Version 2 (CFSv2) Selected Hourly Time-Series Products (ds094.1)

NCEP Climate Forecast System Reanalysis (CFSR) Monthly Products, January 1979 to December 2010 (ds093.2)

NCEP Climate Forecast System Reanalysis (CFSR) 6-hourly Products, January 1979 to December 2010 (ds093.0)

NCEP Climate Forecast System Reanalysis (CFSR) Selected Hourly Time-Series Products, January 1979 to December 2010 (ds093.1)

Publications including dataset evaluation or comparison with other data in Canada

7.5.23 Dataset: MODIS Snow-Covered Area Collection 6.1

Overview

The Moderate Resolution Imaging Spectro-Radiometer (MODIS) is carried on two NASA-operated satellites, *Terra* and *Aqua*. Both are in sun-synchronous, near-polar, circular low-Earth orbits at altitudes of 705 km. *Terra*, operational since 24 February 2000, crosses the equator ~10:30 (descending – travelling N to S) and 22:30 (ascending – travelling S to N) daily: *Aqua*, operational since 4 July 2002, crosses the equator ~13:30 (ascending) and 01:30 (descending) daily.

The sensor captures images in 36 spectral bands: two are at 250 m (nominal) spatial resolution, five at 500 m and the remainder at 1000 m. Its broad swath (field of view orthogonal to orbital track) of 2330 km ensures that the great majority of the Earth's surface is imaged every day.

The MODIS snow-cover datasets infer the presence of snow based on the Normalized Difference Snow Index (NDSI), using the NASA VIIRS algorithm described in Hall *et al.* (2015 – available at
https://viirsland.gsfc.nasa.gov/PDF/VIIRS_snow_cover_ATBD_2015.pdf:
see also https://nsidc.org/support/faq/what-ndsi-snow-cover-and-how-does-it-compare-fsc).
NDSI is computed as (MODIS Band 4 - MODIS Band 6) / (MODIS Band 4 + MODIS Band 6)
where MODIS Band 4 detects wavelengths in the range 545 – 565 nm (green visible light) and MODIS Band 6 covers 1628 – 1652 nm (near infrared)
A range of pixel-level quality flags are also provided, from which it is possible to infer a qualitative degree of confidence in the estimated values.

Data products are as follows (comprehensive details are available from the links in the *Link to download data* section):

MODIS *Terra* / *Aqua* Snow Cover 5-Min L2 Swath 500m **MOD10_L2 / MYD10_L2**
Estimated percentage snow cover within pixel, inferred from NDSI
This dataset provides the basis for the Level 3 products described below
Each granule contains one scene, the full swath-width view acquired during five minutes of orbital travel
Nominal spatial resolution is 500 m at the nadir: referenced to the WGS84 datum (unprojected)

MODIS *Terra* / *Aqua* Snow Cover Daily L3 Global 500m SIN Grid **MOD10A1 / MYD10A1**
Estimated percentage snow cover within pixels, inferred from NDSI: albedo

Each granule is a 10°x10° tile projected onto a sinusoidal grid
Nominal spatial resolution is 500 m: true pixel dimensions are 463.313 m

MODIS *Terra* / *Aqua* CGF Snow Cover Daily L3 Global 500m SIN Grid MOD10A1F / MYD10A1F

As for MOD10A1 and MYD10A1, but with any cloud-obscured pixels filled using values from previous days. The dataset also provides the number of days between the granule's nominal date and that on which the most recent unobscured view of each pixel was available.

MODIS *Terra* / *Aqua* Snow Cover 8-Day L3 Global 500m SIN Grid MOD10A2 / MYD10A2

Pixel values represent the maximum estimated percentage snow cover derived from MOD10A1 / MYD10A1 from granules observed over the prior eight days.

MODIS *Terra* / *Aqua* Snow Cover Daily L3 Global 0.05Deg CMG MOD10C1 / MYD10C1

Provides estimated percentage snow-covered area within 0.05° cells in the MODIS Climate Modelling Grid (CMG), computed from MOD10A1 / MYD10A1

MODIS *Terra* / *Aqua* Snow Cover 8-Day L3 Global 0.05Deg CMG MOD10C2 / MYD10C2

Pixel / cell values represent the maximum estimated percentage snow cover within 0.05° cells in the MODIS Climate Modelling Grid (CMG), derived from MOD10A1 / MYD10A2 from granules observed over the prior eight days.

MODIS *Terra* / *Aqua* Snow Cover Monthly L3 Global 0.05Deg CMG MOD10CM / MYD10CM

Pixel / cell values represent the monthly mean estimated percentage snow cover within 0.05° cells in the MODIS Climate Modelling Grid (CMG), derived from the corresponding MOD10C1 / MYD10C1 daily granules.

Provider contact information

Terra and *Aqua* platforms operated by NASA: data distributed by US National Snow and Ice Data Center (NSIDC) – https://nsidc.org

Licensing

See http://nsidc.org/about/use_copyright.html

Variable name and units

Principally, estimated percentage snow-covered area: MOD10A1 and MYD10A1 also provide albedo

Spatial coverage and resolution

All datasets provide global coverage

Nominal 500 m pixel-size, unprojected, referenced to WGS84 datum:

MODIS *Terra* / *Aqua* Snow Cover 5-Min L2 Swath 500m	MOD10_L2 / MYD10_L2

Gridded in MODIS sinusoidal projection (true pixel dimensions are 463.313 m):

MODIS *Terra* / *Aqua* Snow Cover Daily L3 Global 500m SIN Grid	MOD10A1 / MYD10A1
MODIS *Terra* / *Aqua* CGF Snow Cover Daily L3 Global 500m SIN Grid	MOD10A1F / MYD10A1F
MODIS *Terra* / *Aqua* Snow Cover 8-Day L3 Global 500m SIN Grid	MOD10A2 / MYD10A2

Upscaled to 0.05°cells within MODIS Climate Modelling Grid (CMG):

MODIS *Terra* / *Aqua* Snow Cover Daily L3 Global 0.05Deg CMG	MOD10C1 / MYD10C1
MODIS *Terra* / *Aqua* Snow Cover 8-Day L3 Global 0.05Deg CMG	MOD10C2 / MYD10C2
MODIS *Terra* / *Aqua* Snow Cover Monthly L3 Global 0.05Deg CMG	MOD10CM / MYD10CM

Temporal coverage and resolution

Terra since 2000-02-24, *Aqua* since 2002-07-04

Information about related datasets

n/a

Limitations and strengths for application

Daily return intervals are assured at high latitudes.

Overlap in the sensor's field of view at high latitudes also means that a greater fraction of the pixels in any given scene are observed at angles of view closer to nadir on any given day. The nadir along-track view covers 10 km per scene.

Snow is not detected in pixels experiencing where the solar zenith angle at the time of image capture ≥ 85°: this includes Polar Night.

The relationship between NDSI values and percentage now-cover was derived empirically – but this may not hold reliably in all contexts (e.g., as a result of the influence of topography, vegetation, clouds).

References

For product-specific details, see links provided below

Original introductory paper:

Hall et al. (2002) MODIS snow-cover products *Remote Sensing of Environment* 83(1–2), pp. 181-194
https://doi.org/10.1016/S0034-4257(02)00095-0

Guide to latest collection (Collection 6.1):

Riggs *et al.* (2019) MODIS Snow Products Collection 6.1 User Guide
https://modis-snow-ice.gsfc.nasa.gov/uploads/snow_user_guide_C6.1_final_revised_april.pdf

NASA overview of MODIS snow products
https://modis.gsfc.nasa.gov/data/dataprod/mod10.php

Link to download data (and format)

Distributed by the US National Snow and Ice Data Center (NSIDC) Distributed Active Archive Center (DAAC)
https://nsidc.org/data/MOD10A1/versions/6

MODIS *Terra* Snow Cover 5-Min L2 Swath 500m https://nsidc.org/data/MOD10_L2/versions/61	MOD10_L2
MODIS *Aqua* Snow Cover 5-Min L2 Swath 500m https://nsidc.org/data/MYD10_L2/versions/61	MYD10_L2
MODIS *Terra* Snow Cover Daily L3 Global 500m SIN Grid https://nsidc.org/data/MOD10A1	MOD10A1
MODIS *Aqua* Snow Cover Daily L3 Global 500m SIN Grid https://nsidc.org/data/MYD10A1	MYD10A1
MODIS *Terra* CGF Snow Cover Daily L3 Global 500m SIN Grid https://nsidc.org/data/MOD10A1F/versions/61	MOD10A1F
MODIS *Aqua* CGF Snow Cover Daily L3 Global 500m SIN Grid https://nsidc.org/data/MYD10A1F/versions/61	MYD10A1F
MODIS *Terra* Snow Cover 8-Day L3 Global 500m SIN Grid https://nsidc.org/data/MOD10A2/versions/61	MOD10A2
MODIS *Aqua* Snow Cover 8-Day L3 Global 500m SIN Grid https://nsidc.org/data/MYD10A2/versions/61	MYD10A2

MODIS *Terra* Snow Cover Daily L3 Global 0.05Deg CMG https://nsidc.org/data/MOD10C1/versions/61	MOD10C1
MODIS *Aqua* Snow Cover Daily L3 Global 0.05Deg CMG https://nsidc.org/data/MYD10C1/versions/61	MYD10C1
MODIS *Terra* Snow Cover 8-Day L3 Global 0.05Deg CMG https://nsidc.org/data/MOD10C2/versions/61	MOD10C2
MODIS *Aqua* Snow Cover 8-Day L3 Global 0.05Deg CMG https://nsidc.org/data/MYD10C2/versions/61	MYD10C2
MODIS *Terra* Snow Cover Monthly L3 Global 0.05Deg CMG https://nsidc.org/data/MOD10CM/versions/61	MOD10CM
MODIS *Aqua* Snow Cover Monthly L3 Global 0.05Deg CMG https://nsidc.org/data/MYD10CM/versions/61	MYD10CM

Data format for all products is HDF-EOS2

7.5.24 *<u>Dataset</u>: NASA Stand-alone Passive Microwave Snow Products*

Overview

Passive microwave brightness temperatures can be used to approximate equivalent depth of snow water (SWE). As passively sensed microwave radiation travels through snow its signal attenuates due to scatter out of the line of sight. The amount of scatter is related to the volume of snow grains, and hence to the snowpack depth but also to its density, liquid water content, microstructure characteristics (e.g., snow grain structure), and stratigraphy. Initial algorithms created to retrieve snow depth from passive microwave temperature input (e.g., Chang et al., 1987) was designed for shallow to medium depth (< 150 mm) dry snow (without liquid water in the snowpack) occurring in low relief regions with low forest cover (~< 20%). Under such conditions reasonable accuracy is obtained (e.g., Vuyovich et al., 2014). Updates to the original algorithm (Kelly et al., 2003; Tedesco and Jeyaratnam, 2016) have made use of ancillary data (e.g., forest fraction, climatological snow density fields) aiming to improve retrievals of both snow depth and SWE over a broader range of snow conditions. Nonetheless comparisons of these updated algorithms with in situ data and other gridded SWE products still identify substantial performance issues throughout the snow season (Mortimer et al., 2020). In particular their spatial patterns of hemispheric climatological snow depth and SWE, as well as sub-seasonal integrated measures (i.e. daily/monthly continental snow mass) are not realistic.

While versions of these products are provided with hemispheric coverage for the entire snow season, they are not recommended for casual/non-expert use. Consider how snow conditions will limit seasonal and geographical applicability carefully.

Examples of specific products:

- AMSR-E/Aqua L3 Global Snow Water Equivalent EASE-Grids, Version 2, 2002-2011
  - Daily output, doi: 10.5067/AMSR-E/AE_DYSNO.002
  - 5-Day output, doi: 10.5067/AMSR-E/AE_5DSNO.002
  - Monthly output, doi: 10.5067/AMSR-E/AE_MOSNO.002)

- AMSR-E/AMSR2 Unified L3 Global 25 km EASE-Grid Snow Water Equivalent, Version 1, 2012-present
  - Daily output, doi: 10.5067/8AE2ILXB5SM6
  - 5-Day output, doi: 10.5067/0PX911G6417E
  - Monthly output, doi: 10.5067/43NH9LHM9YRK

- Global Monthly EASE-Grid Snow Water Equivalent Climatology, Version 1, November 1978 through May 2007, doi: 10.5067/KJVERY3MIBPS

Spatial coverage and resolution:

- Northern Hemisphere
- Products provided on EASE2 grid

Temporal coverage and resolution

- Product dependent

Limitations and strengths for application in North Canada

While large portions of snow cover in northern Canada may be dry and free of forest cover, its microstructure and stratigraphy may produce additional inaccuracies in applying the algorithms discussed above. Caution is warranted.

Note that the limitations discussed in this document pertain specifically to the determination of snow *depth* and/or *SWE* from passive microwave brightness temperature. The algorithms do accurately determine dry snow *presence*. Hence a threshold can be applied the SWE fields to determine accurate estimates of spring time variability in snow cover (e.g., Brown et al., 2007, 2010). In addition, abrupt or diurnal changes in PM brightness temperature (the source data for SWE retrievals) can be used as an indicator of melt onset/ wet snow (e.g., Semmens et al., 2013).

References to documents describing the methodology or/and the dataset

Brown, R., C. Derksen, and L. Wang, 2007: Assessment of spring snow cover duration variability over northern Canada from satellite datasets, Remote Sensing of Environment, 111, 367:381, https://doi.org/10.1016/j.rse.2006.09.035.

Brown, R., C. Derksen, and L. Wang, 2010: A multi-data set analysis of variability and change in Arctic spring snow cover extent, 1967–2008, J. Geophys. Res., 115, D16111, https://doi.org/10.1029/2010JD013975.

Chang, A.T.C., J.L. Foster and D.K. Hall, 1987: Nimbus-7 derived global snow cover parameters, Annals of Glaciology, 9, 39-44.

Kelly, Richard. E. J., A. T. C. Chang, L. Tsang, and J. L. Foster, 2003: A Prototype AMSR-E Global Snow Area and Snow Depth Algorithm. IEEE Transactions on Geoscience and Remote Sensing 41(2): 230-242.

Mortimer, C., L. Mudryk, C. Derksen, K. Luojus, R. Brown, R. Kelly, and M.Tedesco, 2020: Evaluation of long-term Northern Hemisphere snow water equivalent products, The Cryosphere, 14, 1579–1594, https://doi.org/10.5194/tc-14-1579-2020.

Tedesco, M., and J. Jeyaratnam, 2016: A New Operational Snow Retrieval Algorithm Applied to Historical AMSR-E Brightness Temperatures (ATBD). Remote Sensing, 8(12) 1037.

Semmens, K.A., J. Ramage, A. Bartsch, and G.E Liston, 2013: Early snowmelt events: detection, distribution, and significance in a major subarctic watershed. Environ. Res. Lett. 8 014020, https://doi.org/10.1088/1748-9326/8/1/014020.
Vuyovich, C. M., J. M. Jacobs, and S. F. Daly, 2014: Comparison of passive microwave and modelled estimates of total watershed SWE in the continental United States, *Water Resour. Res.*, 50, 9088– 9102, https://doi.org/10.1002/2013WR014734.

7.5.25 *<u>Dataset</u>: NOAA – Rutgers Northern Hemisphere Snow-Cover Climate Data Record*

Overview

This dataset, generated by the Global Snow Laboratory at Rutgers State University, provides a binary representation of snow-covered area across the Northern Hemisphere at weekly intervals, inferred from a range of remotely sensed imagery. The archive, which was initiated in 1966, offers the longest continuous remotely sensed record of any environmental phenomenon.

Provider contact information

Principal investigator:
Dr. David Robinson
Distinguished Professor, Department of Geography, Rutgers State University
Piscataway, New Jersey, USA

david.robinson@rutgers.edu 848-445-4741
https://climatechange.rutgers.edu/people/affiliates/robinson-david

Licensing

Use agreement provided at
https://www.ncei.noaa.gov/pub/data/sds/cdr/CDRs/Snow_Cover_Extent_Northern_Hemisphere/UseAgreement_01B-12.pdf

Dataset:

Robinson, D.A., T.W. Estilow, and NOAA CDR Program, 2012: NOAA Climate Data Record (CDR) of Northern Hemisphere (NH) Snow Cover Extent (SCE), Version 1. [indicate subset used]. NOAA National Centers for Environmental Information. doi: 10.7289/V5N014G9

Variable name and units

Presence of snow: binary flag, based on 50% threshold on last visible day nearest to end of granule-week

Spatial coverage and resolution

Published as a regular grid (88 x 88) in the Northern Polar Stereographic Projection. Note that this projection implies variation of cell area from ~10.7×10^2 km2 at the lowest latitudes to ~41.8×10^3 km^2 near the geographic North Pole.

The dataset is also available having been regridded to EASE grid (720 x 720 grid)
https://nsidc.org/data/nsidc-0046/versions/4/documentation

Temporal coverage and resolution

The archive includes representations of snow-covered area from October 1966 to the present. There are gaps of several weeks during nine months between 1968 and 1971.
Granules are generated at weekly (Tuesday to Monday) intervals.

Information about related datasets

The US National Snow and Ice Data Center (NSIDC) also publish datasets of daily Northern Hemisphere snow cover derived using the same algorithm (the Interactive Multisensor Snow and Ice Mapping System, or IMS) at spatial resolutions of 1 km, 4 km and 24 km. Details are available at
https://nsidc.org/data/G02156/versions/1

Limitations and strengths for application

The principal strength of the dataset is its long period of record and comprehensive spatial coverage.

The dataset's main limitation is that it provides only a simple binary classification of snow cover: 'snow-free' may be 0 – 49%, 'snow-covered' may be 50 – 100%. This may exaggerate estimates of trends at certain times of the year, and is compounded by the increase in cell area at higher latitudes (Allchin and Déry, 2018).

In 1999, the workflow used to generate weekly granules was upgraded from a largely manual process to a more automated system, based on higher-resolution imagery. Several authors (eg Hori et al, 2017, Mudryk et al, 2017) have raised the possibility that these new methods may have resulted in an appreciable improvement in the system's ability to detect snow cover, consequently introducing bias in trend estimations. However, those involved in generating the dataset maintain that this is not the case, based on detailed comparisons of outputs pre- / post-upgrade. It is also possible that apparently anomalous trend magnitudes, detected particularly in autumn and spring, may have been driven by assumptions adopted in inferring snow-covered area from the dataset's binary classification (Allchin and Déry, 2018).

A number of individual cells (33), mainly covering mountainous areas have also been identified as providing potentially unreliable records (Déry and Brown, 2007).

References

Descriptive references:

Estilow T.W., A.H. Young and D.A. Robinson, 2015: A long-term Northern Hemisphere snow cover extent data record for climate studies and monitoring. Earth System Science Data, 7, 137-142, doi:10.5194/essd-7-137-2015 https://essd.copernicus.org/articles/7/137/2015/essd-7-137-2015.pdf

Robinson, D.A., and A. Frei, 2000: Seasonal variability of northern hemisphere snow extent using visible satellite data. Professional Geographer, 51, 307-314, doi:10.1111/0033-0124.00226.

Robinson, D.A., K. F. Dewey and R. Heim, Jr., 1993: Global snow cover monitoring: an update. Bulletin of the American Meteorological Society, 74, 1689-1696.

NOAA landing page (includes link to algorithm description)
https://www.ncei.noaa.gov/products/climate-data-records/snow-cover-extent

General information from Rutgers University Global Snow Laboratory
http://climate.rutgers.edu/snowcover/index.php

Link to download data (and format)

NOAA CDR landing page (HTTP download available in NetCDF)
https://www.ncei.noaa.gov/products/climate-data-records/snow-cover-extent

Regridded to EASE grid
https://nsidc.org/data/nsidc-0046/versions/4/documentation

Dataset also available in legacy text format on request from Rutgers Global Snow Lab
http://climate.rutgers.edu/snowcover/index.php

7.6 River discharge

7.6.1 Dataset: Water Survey of Canada (WSC) daily streamflow observation data

Overview:

This dataset includes hydrometric observations from a network of about 2700 active and 5000 discontinued streamflow gauging stations across Canada, collected by the Environment and Climate Change Canada's Water Survey of Canada (WSC) branch in partnership with provinces, territories under National Hydrometric Program. The dataset primarily consists of flow time series derived from the stage-discharge relationship. For some stations, flow and/or water level records are available. The historical Hydrometric Data (HYDAT) is available as an Access database and could be accessed through a Windows desktop tool: EC DataExplorer (Environment Canada, 2021). Alternatively, the dataset could be downloaded from an online archive (https://wateroffice.ec.gc.ca/index_e.html; accessed: August 13, 2021) as .csv files. Metadata describes a number of attributes, including station name and number, status (active or discontinued), location (latitude and longitude), drainage area, years of record, presence of regulation, variables (flow, level and sediments), operation schedule (continues/seasonal). A subset of active stations are designated as Reference Hydrometric Basin Network (RHBN) based on the criteria of long records (+20 years) and minimal human impacts (Pellerin and Nzokou 2020). A number of symbols are used to describe the data records, which include E: Estimate; A: Partial day; B: Ice conditions; D: Dry and R: Revised (https://wateroffice.ec.gc.ca/contactus/faq_e.html; accessed: August 13, 2021).

Provider's contact Information :

Water Survey of Canada Product Page: https://www.canada.ca/en/environment-climate-change/services/water-overview/quantity/monitoring/survey.html

Licensing

Disclaimer for Hydrometric Information: https://wateroffice.ec.gc.ca/disclaimer_info_e.html

Variable name and units:

River discharge [m^3 s^{-1}], water level [m]

Spatial coverage and resolution:

- Canada-wide domain consisting of point-scale hydrometric station network.
- Database consists of 2700 active and 5000 discontinued streamflow gauging stations across Canada.

- Drainage area polygons that flow into hydrometric station outlets are available for most locations (https://open.canada.ca/data/en/dataset/0c121878-ac23-46f5-95df-eb9960753375 accessed: August 13, 2021)

Temporal coverage and resolution:

Temporal coverage varies depending on site. There are nine Canadian sites prior to 1900 and about 2500 sites before 1950. Many of the stations have been discontinued (about 5000). Data are available at a daily time step.

Information about related datasets:

Other datasets are sourced on the WSC observations. WSE observations are also sourced on some of the other datasets.

Limitations and strengths for application in Northern Canada

WSC observations are quality-controlled and consistent datasets covering entire Canada. Data are readily available for download in .csv format. A major limitation is sparse station network in Northern Canada. Many stations in Northern Canada are available for a short time span or have been discontinued. Additionally, many stations have considerable number of missing records, and some of the observations are only available in the open water season.

References to documents describing the methodology and/or the dataset:

Environment Canada (2021), EC DataEXplorer, https://www.canada.ca/en/environment-climate-change/services/water-overview/quantity/monitoring/survey/data-products-services/national-archive-hydat.html (Accessed August 2021).

Pellerin and Nzokou (2020) Reference Hydrometric Basin Network Update. Environment and Climate Change Canada, Gatineau, QC. https://collaboration.cmc.ec.gc.ca/cmc/hydrometrics/www/RHBN/ (Accessed August 2021).

Link to download the data and format of data:

https://wateroffice.ec.gc.ca/index_e.html

https://wateroffice.ec.gc.ca/contactus/faq_e.html

7.6.2 Dataset: ECMWF 5th Generation Land Reanalysis (ERA5-Land) - runoff

Overview

This document provides an overview of the runoff data of ERA5-Land, in the context of the larger ERA5-Land dataset. ERA5-Land is a replay of the land component of the ERA5 atmospheric global reanalysis using a finer spatial resolution and including a series of improvements making it more accurate for all types of land applications. ERA5-Land is produced by ECMWF framed within the Copernicus Climate Change Service (C3S) of the European Commission. The data covers a period from January 1950 to the present. It provides hourly data for many near-surface atmospheric and land-surface parameters.

Provider's contact information

ERA5-Land is produced by the Copernicus Climate Change Service (C3S) at ECMWF.

Copernicus User support (copernicus-support@ecmwf.int (external to C3S)).

Licensing

Licence: Copernicus (Licence agreement information can be found here or here).

Dataset citable as: **Muñoz Sabater**, J., 2019: ERA5-Land hourly data from 1981 to present. Copernicus Climate Change Service (C3S) Climate Data Store (CDS). (Accessed on < DD-MMM-YYYY >), 10.24381/cds.e2161bac

Variable name and units:

Some water from rainfall, melting snow, or deep in the soil, stays stored in the soil. Otherwise, the water drains away, either over the surface (**surface runoff**), or under the ground (**subsurface runoff**) and the sum of these two is simply called '**runoff**'. ERA5-Land offers data for the three variables as **hourly** and **monthly** subsets:

- Runoff in m
- Subsurface runoff in m
- Surface runoff in m

There three variables represent the total amount of water accumulated from the beginning of the forecast time to the end of the forecast step. The units of the three runoff variables are depth in metres. This is the depth the water would have if it were spread evenly over the grid box. More information about how runoff is calculated is given in the IFS Physical Processes documentation.

Those products can be found by selecting their name from the 'Evaporation and Runoff' category on the pages below:

- hourly data from 1950 to present,
- monthly averaged data from 1981 to present,

Spatial coverage and resolution:

ERA5-Land is a global land-surface dataset. The atmospheric data is available on a regular latitude-longitude grid at 0.1° x 0.1° resolution (converted from native reduced-Gaussian grid resolution of approximately 9 km x 9 km), and on 4 surface layers. Oceans have been masked out with data available over landmasses and inland lakes.

Temporal coverage and resolution:

ERA5-Land data is available from 1950 to present at hourly time step. Monthly average over all hours or monthly averages by hour (24 values) for monthly data are also available from 1981 to present. The 1950 – 1980 back extension for monthly means is scheduled to be available in 2022.

ERA5-Land data updates are made synchronously with ERA5 updates, approximately 2-3 months behind real time.

Information about observations (number, homogeneity)

ERA5-Land is not directly influenced by observations, but rather, indirectly influenced through the ERA5 atmospheric forcings. ERA5's data assimilation uses observations for all geophysical quantities from about 0.75 million observations per day in 1979 and about 24 million in 2018. The 2D-OI uses surface observations at 'screen level'. The online technical documentation provides tables with the satellite and in-situ observations used as input into ERA5.

Methodology

ERA5-Land is produced under a single simulation of the land component of the ERA5 climate reanalysis, without coupling to the atmospheric module of the ECMWF's Integrated Forecasting System (IFS) and without data assimilation. The low atmospheric forcing is provided by the ERA5 reanalysis, with additional lapse-rate correction. The core of ERA5-Land is the Tiled ECMWF Scheme for Surface Exchanges over Land incorporating land surface hydrology (H-TESSEL). Because it runs without data assimilation, it makes it computationally affordable for relatively quick updates. For example, if significant improvements of the land surface model are implemented, the whole or part of the dataset can be reprocessed in a relatively short period. Updates are possible in case improved auxiliary datasets are used as input for the production.

Production of ERA5-Land is not produced as a single continuous segment, but instead as three segments: Stream-1 (2001 onwards), Stream-2 (1981-2000), and Stream-3 (1950-1980). This is because it allows parallel production of data enabling sooner public access to the data, and because the atmospheric forcings used by ERA5-Land is derived from ERA5, thus needing corresponding completed ERA5 segment. Each stream is initialized with various meteorological fields from ERA5 (temperature, precipitation, humidity, radiation, etc.). While ERA5-Land does not assimilate observations directly, they are introduced via the ERA5 atmospheric forcings. These forcings are adjusted using ERA5 derived lapse rates before being integrated with the ECMWF Carbon Hydrology-Tiled ECMWF Scheme for Surface Exchanges over Land (CHTESSEL) land surface model. This is done in 24-hour cycles, generating hourly outputs and the evolution of the land surface state and water and energy fluxes.

In the land surface hydrology H-TESSEL scheme, each land grid box is divided into fractions (tiles), with up to six fractions (bare ground, low and high vegetation, intercepted water, shaded and exposed snow). Each fraction has its own properties defining separate heat and water fluxes used in an energy balance equation solved for the tile skin temperature. New infiltration and runoff schemes are introduced with a dependency on the soil texture and standard deviation of orography. The snowpack is treated taking into account its thermal insulation properties and a more realistic representation of density, the interception of liquid rain and a revised scheme for the albedo and metamorphism aging processes. A new formulation to represent inland water bodies both for resolved lakes and sub-grid coastal water in liquid and frozen state is introduced with a dedicated new water tile. A reference document is provided at ECMWF: A revised hydrology for the ECMWF model: Verification from field site to terrestrial water storage and impact in the Integrated Forecast System.

Uncertainty estimate: Currently, ERA5-Land variable uncertainty estimates are those corresponding to ERA5. ERA5 uncertainty estimate is sampled by a 10-member lower-resolution Ensemble Data Assimilation (EDA) which provides background-error estimates for the deterministic HRES 4D-Var Data Assimilation system. The analysis method is the same for each EDA member and follows that of the HRES. Each member (except the control) is run with different random perturbations added to the observations. Likewise, the model physical tendencies are perturbed in the short forecasts that link subsequent analysis windows. Ensemble mean and spread have been pre-computed for convenience. Such uncertainty estimates are closely related to the information content of the available observing system which has evolved considerably over time. They also indicate flow-dependent sensitive areas. To facilitate many climate applications, monthly-mean averages have been pre-calculated too, though monthly means are not available for the ensemble mean and spread.

The original plan was to apply the same methodology ERA5-Land was to provide an estimate of the uncertainty fields as was done for ERA5. However, the uncertainty was estimated to be extremely low, and would have assigned unrealistically high confidence to the ERA5-Land variables. As such, it is recommended to use the corresponding ERA5 uncertainty estimates for the time being until further studies are done.

Information about the technical and scientific quality

ERA5-Land represents one of the products of the latest global atmospheric reanalysis produced by Copernicus Climate Change Service at ECMWF. It is archived at a shorter (hourly) time step, has a fine spatial resolution, uses a more advanced assimilation system and includes more sources of data than previous versions (e.g., ERA-Interim-Land). It is accompanied by extensive technical documentation and two principal scientific documentation papers. A list of 'known issues' is maintained at the online documentation (https://confluence.ecmwf.int/display/CKB/ERA5-Land%3A+data+documentation). Validation against multiple in-situ datasets is presented in the reference paper Muñoz-Sabater et al., 2021.

Information on land surface model: The land surface model of the ERA5-Land was operational in 2018 with the IFS model cycle 45r1. While most of the changes from the IFS Cy41R2 used in ERA5 are primarily technical, there were a few improvements to various fields: 1) the parameterization of the soil thermal conductivity was updated to take the ice component of frozen soil into consideration, 2) conservation of the soil-water balance was fixed and improved, and 3) rain over snow is now accounted for and is not accumulated in snow pack. Furthermore, a bug exists in IFS Cy41R2, that affects potential evapotranspiration (PET) flux calculations over forests and deserts, has been corrected in ERA5-Land, and unlike ERA5, ERA5-Land PET is an available dataset. However, PET is now determined by assuming a vegetation type of crops and no soil moisture stress. These assumptions may not be always realistic, and therefore PET should be used cautiously. More information on the CHTESSEL land surface model used in ERA5-Land can be found in Muñoz-Sabater et al. (2021, preprint) and the ERA5 document previously prepared by the CCCS

Limitations and strengths for application in North Canada

ERA5-Land is a newer land surface reanalysis and there are few available scientific evaluations of the dataset dedicated specifically to northern Canada. However, it should be noted that in northern Canada, there are currently no sub-daily records over a long historical period for many weather stations. ERA5-Land aims to provide an improved description of the water and energy cycles at surface level meeting the growing requirement from land user communities to gain access to long-term higher-resolution datasets. The high resolution improved land surface hydrology scheme incorporates surface runoff and drainage with functional dependencies on orography and soil texture, respectively.

As for all gridded data, observed values of the various parameters at local scales can differ from the values provided by the gridded dataset, which represent a statistical summary of the area surrounding a grid point. Care should be taken when comparing model variables with observations. Observations are also often taken in different units, such as mm/day, rather than the accumulated metres produced here for runoff.

As for all reanalysis' data, changes in the amounts and types of observational data that are assimilated may have an adverse impact on trends or variability.

References to documents describing the methodology or/and the dataset

Muñoz Sabater, J., 2019: ERA5-Land hourly data from 1981 to present. Copernicus Climate Change Service (C3S) Climate Data Store (CDS). (Accessed on < 25-Jun-2021 >), https://doi.org/10.24381/cds.e2161bac

Muñoz-Sabater, J., E. Dutra, A. Agustí-Panareda, C. Albergel, G. Arduini, G., Balsamo, S. Boussetta, M. Choulga, S. Harrigan, H. Hersbach, B. Martens, D. G. Miralles, M. Piles, N. J. Rodríguez-Fernández, E. Zsoter, C. Buontempo, and J.-N. Thépaut, 2021: ERA5-Land: A state-of-the-art global reanalysis dataset for land applications. Earth System Science Data, 13(9), 4349-4383. https://doi.org/10.5194/essd-2021-82

Hersbach, H., B .Bell, P. Berrisford, S. Hirahara, A. Horányi, J. Muñoz-Sabater, J. Nicolas, C. Peubey, R. Radu, D. Schepers, A. Simmons, C. Soci, S. Abdalla, X. Abellan, G. Balsamo, P. Bechtold, G. Biavati, J. Bidlot, M. Bonavita, G. Chiara, P. Dahlgren, D. Dee, M. Diamantakis, R. Dragani, J. Flemming, R. Forbes, M. Fuentes, A. Geer, L. Haimberger, S. Healy, R.J. Hogan, E. Hólm, M. Janisková, S. Keeley, P. Laloyaux, P. Lopez, C. Lupu, G. Radnoti, P. Rosnay, I. Rozum, F. Vamborg, S. Villaume, and J.-N. Thépaut, 2020: The ERA5 global reanalysis. Quarterly Journal of the Royal Meteorological Society, 146(730), 1999–2049. https://doi.org/10.1002/qj.3803**.**

Link to download the data and format of data:

Data Access: Copernicus | ECMWF (requires login)

ERA5-Land is available in GRIB and NetCDF formats

Link to download hourly and monthly data on Copernicus:

- hourly data from 1950 to present,
- monthly averaged data from 1981 to present

Publications including dataset evaluation or comparison with other data in Canada

7.6.3 *Dataset: GloFAS river discharge reanalysis*

Overview

This dataset contains global modelled daily river discharge data from the Global Flood Awareness System (GloFAS), which is part of the Copernicus Emergency Management Service (CEMS). The dataset is produced by coupling land surface model runoff component of the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA5 global reanalysis with the LISFLOOD hydrological and channel routing model (Harrigan et al. 2020). The dataset is available at 0.1° horizontal resolution and a daily time step from January 1 1979, until near real time (2 to 5 days behind real time). LISFLOOD model in GloFAS-ERA5 was calibrated against daily river discharge from 1287 observation stations worldwide, and results were found to be skilful against a mean flow benchmark for 86% of catchments, although the strength of skill varied considerably with location (Harrigan et al. 2020). Two versions of GloFAS-ERA5, legacy version (v2.1) and updated version (v3.1) are available for download in GRIB2 file format in parallel from the Copernicus Climate Change Service Climate data store (https://cds.climate.copernicus.eu/cdsapp#!/dataset/cems-glofas-historical?tab=overview; access: August 13, 2021). Additional attribute includes upstream areas for points in the river network.

Provider's contact Information :

GloFAS River Discharge Product Page: https://cds.climate.copernicus.eu/cdsapp#!/dataset/cems-glofas-historical?tab=overview

Licensing :

CEMS-FLOODS datasets licence: https://cds.climate.copernicus.eu/api/v2/terms/static/cems-floods.pdf

Variable name and units:

River discharge [$m^3 s^{-1}$]

Spatial coverage and resolution:

- Global except for Antarctica (90N-60S, 180W-180E)
- Gridded 0.1° x 0.1° data in GRIB2 format.

Temporal coverage and resolution:

January 1, 1979, to near real time at daily resolution.

Information about related datasets:

Limitations and strengths for application in Northern Canada

GloFAS dataset is available for entire Northern Canada region. Limitations include, relatively short time span (1979 present). Given that GloFAS data is based on ERA5 forcings, uncertainties associated with the ERA5 propagate into GloFAS data. The skill of GloFAS data in representing historical observations depends on location. It is not clear how many stations in Northern Canada were used for model calibration. Evaluated skills (in terms correlation, bias and variability errors) are highly variable over Northern Canada ranging for good to poor performance. While GloFAS-ERA5 reanalysis does represent major dams and reservoirs on the modelled river network, simplified reservoir operating parameters were used based on expert opinion.

References to documents describing the methodology and/or the dataset:

Harrigan, S., E. Zsoter, L. Alfieri, C. Prudhomme, P. Salamon, F. Wetterhall, C. Barnard, H. Cloke, and F. Pappenberger, 2020: GloFAS-ERA5 operational global river discharge reanalysis 1979–present, Earth Syst. Sci. Data, 12, 2043–2060, https://doi.org/10.5194/essd-12-2043-2020.

7.6.4 *<u>Dataset:</u>* ***R-ArcticNet (v4.0) river discharge***

Overview

R-ArcticNet provides a compilation of river discharge data across the entire pan-Arctic domain. This includes all major river basins of Canada draining to the Arctic Ocean, the Bering Strait, and Hudson Bay. Data are based on in-situ observations by hydrometric networks in Canada, the USA, Russia and other circumpolar countries. In Canada, data are sourced from the Water Survey of Canada and ingested into a geo-referenced platform facilitating identification of sites of interest and data downloads. Time series can be downloaded at the monthly or annual time scales in units of $m^3 s^{-1}$ or mm. Temporal coverage varies across sites with optimal coverage between 1960 and 1990.

The geo-referenced platform allows users to easily obtain site-specific information including coordinates and identification number of the hydrometric gauge, drainage area, and years of data availability. Hydrographs of the mean monthly discharge and time series graphs of monthly and total annual discharge are also provided. Summary statistics (mean, standard deviation, extremes and coefficient of variation) in monthly and annual river discharge are also tabulated.

Provider's contact information

R-ArcticNet (v4.0) Project Page: https://www.r-arcticnet.sr.unh.edu/v4.0/index.html

Licensing

Licence: N/A

Variable name and units:

River discharge [$m^3 s^{-1}$] or river runoff [mm]

Spatial coverage and resolution:

- Pan-Arctic domain including the Yukon River and Hudson Bay drainage basins
- Point-scale hydrological data representative of the watershed-scale runoff
- Number of sites in major Canadian (and American) river basins draining to the Arctic Ocean: Mackenzie – 500, Nelson – 1319, northwest Hudson Bay – 99, south and east Hudson Bay – 183, and Yukon – 96.

Temporal coverage and resolution:

Temporal coverage varies depending on site. The earliest data are prior to 1900 (for four Canadian sites), but generally from the early to mid-20th century and most time series end by 2000. Data are available at monthly or annual time scales only.

Information about related datasets

Three prior versions of the database were released. Primary data are sourced from the United States Geological Survey (USGS), Water Survey of Canada (WSC), and the State Hydrological Institute (SHI) of Russia, among other sources.

Limitations and strengths for application in Northern Canada

Observations of discharge at 2164 hydrometric gauges across northern Canada spanning the early to late 20th century. Data readily available online in a geo-referenced platform and time series can easily be downloaded in .txt format. Limitations with the dataset include no data for the 21st century (aside from 2000) and limited spatial coverage in the Canadian Arctic Archipelago among other regions. Many sites include gaps and time series are relatively short (e.g., a few years only) for some sites.

References to documents describing the methodology or/and the dataset

General description at: https://www.r-arcticnet.sr.unh.edu/v4.0/abstract.html

Lammers, R. B., A. I. Shiklomanov, C. J. Vörösmarty, B. M. Fekete, and B. J. Peterson, 2001: Assessment of contemporary Arctic river runoff based on observational discharge records. Journal of Geophysical Research: Atmospheres, 106, 3321-3334.

Link to download the data and format of data:

https://www.r-arcticnet.sr.unh.edu/v4.0/AllData/index.html

7.6.5 *Dataset: Cape Bounty Arctic Watershed Observatory*

Overview

The Cape Bounty Arctic Watershed Observatory (CBAWO) on Melville Island was established in the early 2000s by researchers at Queen's University and their collaborators. Primary motivation for establishment of CBAWO is to collect measurements on environmental conditions in an undisturbed site in the Canadian Arctic Archipelago undergoing rapid climate change. The focus is on understanding the response of high Arctic watersheds to regional warming by tracking changes in hydrology, permafrost, and landscape stability. An integrated and interdisciplinary approach is adopted to assess the cumulative impacts of environmental change at various spatial and temporal scales.

The dataset includes time series of river discharge at 10-minute intervals from the snowmelt period to late summer.

Provider's contact information

Cape Bounty Arctic Watershed Observatory Project Page: https://capebountyresearch.com/

Licensing

Licence: N/A

Variable name and units:

River discharge [m^3 s^{-1}] or river runoff [mm]

Spatial coverage and resolution:

- Cape Bounty Arctic Watershed Observatory (74º55′ N, 109º35′ W) on Melville Island, Canadian Arctic Archipelago
- Point-scale hydrological data representative of the watershed-scale runoff
- Four sites: East (8.0 km^2) and West (11.6 km^2) rivers, Goose (0.18 km^2) and Ptarmigan (0.21 km^2) creeks (unofficial names).

Temporal coverage and resolution:

Temporal coverage varies depending on site. The earliest data start in 2003 up to present.

Data are seasonal and available at 10-minute intervals.

Information about related datasets

Additional meteorological, soil, vegetation, permafrost, sediment and water data are available for these sites. Lake monitoring data and time-lapse images are also available.

Limitations and strengths for application in Northern Canada

Observations of discharge at four hydrometric gauges on Melville Island where there is an absence of Water Survey of Canada data. Data are available online at the Polar Data Catalogue. Limitations with the dataset include no data prior to 2003 and lack of cold season data.

References to documents describing the methodology or/and the dataset

General description at: https://capebountyresearch.com/scientific-infrastructure/

Beel, C. R., J. K. Heslop, J. F. Orwin, M. A. Pope, A. J. Schevers, K.Y. Hung, M. J. Lafrenière, and S. F. Lamoureux, 2021: Emerging dominance of summer rainfall driving High Arctic terrestrial-aquatic connectivity. Nature Communications, 12, 1448, https://doi.org/10.1038/s41467-021-21759-3

Lamoureux, S.F., and M.J. Lafrenière, 2017: More than just snowmelt: integrated watershed science for changing climate and permafrost at the Cape Bounty Arctic Watershed Observatory. WIREs Water, 5(1), e1255, https://doi.org/10.1002/wat2.1255.

Link to download the data and format of data:

https://polardata.ca/pdcsearch/PDCSearch.jsp?doi_id=11361

7.6.6 ***Dataset:*** ***Runoff data from Centre d'Expertise Hydrique de Québec (CEHQ) / Direction d'Expertise Hydrique (DEH)***

Overview

Since October 2003, the Centre d'expertise hydrique du Québec (CEHQ) has been disseminating water level and flow data from certain hydrometric stations operating by telemetry, commonly called "real-time stations".

In addition to this information, it is possible to obtain the complete history of daily (650 stations) and instantaneous (280 stations) water levels and flows measured at the hydrometric stations operated by the Ministère du Développement durable, de l'Environnement et des Parcs (MDDEP), an agent of the Government of Quebec, whether they are closed or open. In addition, monthly statistics (minimum, average, median and maximum) on the hydrometric stations for which validated data exist are available.

Provider's contact information

Direction de l'expertise hydrique

675, boul. René-Lévesque Est, aile Alexandre-Taschereau, 4e étage
Québec (Québec) G1R 5V7
Phone: 418 521-3993
Fax: 418 643-6900

Email: expertise.hydrique@environnement.gouv.qc.ca

More information can be found at: https://www.environnement.gouv.qc.ca/eau/hydrique-barrage/index.htm (French)

Licensing and citation

The data are made available without any liability and at the user's own risk.

The description of the conditions of use can be found: http://www.cehq.gouv.qc.ca/hydrometrie/historique_donnees/info_validite.htm

"The Centre d'Expertise Hydrique du Québec and its employees assume no responsibility for the use of this data or for any errors it may contain. Furthermore, the CEHQ and its employees cannot be held responsible for any damages, losses or direct or indirect expenses resulting from the use of this data, for any reason whatsoever."

(Currently French only Nov 2021)

Variable name and units

Historical hydrometric station runoff data are in (m^3/s) and can be obtained as

- Daily mean
- Monthly mean
- Monthly median
- Monthly minima
- Monthly maxima

Spatial coverage and resolution

The station network expands over southern and central Quebec. See download page for an overview map.

Temporal coverage and resolution

The available hydrological series contain at least three years of records for a "flow" station and at least one year for a "level" station. The oldest daily data go back to 1910 (daily data) and up to 1997 for the majority of the 280 stations with instantaneous data.

Information about observations (number, homogeneity)

Various data from more than 650 hydrometric stations, of which more than 200 are still in operation, are accessible. Note that some stations are not available online. Please contact CEHQ for information about those stations.

Methodology

DEH/CEHQ operates a network of approximately 230 hydrometric stations, almost all of which transmit data on a continuous basis, 24 hours a day, 7 days a week. Data recorded every 15 minutes by the measuring instruments are transmitted hourly to an integrated telemetry data collection system via a telephone or satellite link. On a daily basis, it is therefore possible to obtain data on water levels or flows, in particular to monitor spring floods or summer droughts, to optimize the management of dams or to know the level of certain bodies of water for outdoor activities.

Information about the technical and scientific quality

For each hydrometric station, a validation date or a message mentioning that all data are preliminary is written in the header of the data file, except for instantaneous data which are not subject to any systematic validation process. Data after this validation date is preliminary, meaning that it has not yet gone through the full-validation process and therefore changes can still be made. It should also be noted that data prior to the validation date may also be subject to change (error detection, periodic data revision, etc.). Users should ensure that they have the most recent data before using it by downloading the data they want from this website. The monthly statistics files contain only data for validated periods.

Note that a monthly statistic is not calculated when:

- five or more data are missing in the month;
- three or more consecutive pieces of data are missing in a month.

Data from active stations are validated and updated. Most recent data provided within a few days of the observations are preliminary until validated.

Limitations and strengths for application in North Canada

CEHQ maintains a comprehensive network of hydrometric stations and provides access to their data free of charge. Validation and quality flags are delivered with the data.

The dataset covers mainly southern Quebec with fewer station in the North. Note that some of the northern stations may not be available over the website.

The watershed contours and other characteristics are also made available.

References to documents describing the methodology and/or the dataset

CEHQ data access web page:

https://www.cehq.gouv.qc.ca/hydrometrie/historique_donnees/index.asp

Other data like watershed contours, flood and drought information as well as real-time data and forecasts can be found at https://www.cehq.gouv.qc.ca/hydrometrie/index.htm

Link to download the data and format of data

Data access page: https://www.cehq.gouv.qc.ca/hydrometrie/historique_donnees/default.asp

Data are in provided as ASCII files.

Publications including dataset evaluation or comparison with other data in Canada

The data from CEHQ have been used in many hydrological studies on a watershed basis. While no global comparison or evaluation is available, the data have been extensively used in the production of the Quebec Hydroclimatic Atlas.

Quebec Hydroclimatic Atlas interactive version:
https://www.cehq.gouv.qc.ca/atlas-hydroclimatique/index.htm

Quebec Hydroclimatic Atlas PDF version 2015 (English):
https://www.cehq.gouv.qc.ca/hydrometrie/atlas/Atlas_hydroclimatique_2015EN.pdf

7.6.7 *Dataset:* ***Hydro Québec Runoff (Flow rate)***

Overview

Hydro Québec provides in-situ data for northern Québec mostly south of the 55° parallel. That is data coverage corresponds mainly to Hydro Québec's area of interest, where the hydroelectric installations are. Most sites are equipped with complete weather stations (that is parameters such as temperature, humidity, wind and precipitations are covered). In the same vicinities, Hydro Quebec also has a snow data network and hydro stations (flow rate, water level, water temperatures, etc. being measured). Weather, snow and hydro sites are not necessarily situated near each other, but it can happen, especially regarding weather and snow measurements.

Provider's contact information

Open data site: https://www.hydroquebec.com/documents-donnees/loi-sur-acces/demande-acces-information.html

Licensing

Data are available under the terms of "Creative Commons Licence: Attribution-NonCommercial-ShareAlike 4.0 International". For more information, visit the Hydro-Québec webpage regarding open data licence.

https://creativecommons.org/licenses/by-nc-sa/4.0/deed.en

https://www.hydroquebec.com/documents-donnees/donnees-ouvertes/licence.html

Limitations and strengths of datasets for application in Northern Canada

As of now, open data only contains the last 10 days but upon request the complete history can be available when possible. Gaps in the datasets are common as northern sites are sensible to longer maintenance delays when there is a malfunction at the sites. Only raw datasets are offered for now and Hydro Quebec is will not be responsible for their use.

Variable name and units:

All flow data are in m^3/s. Hourly total flow rate, discharge rate, river discharge and turbinated flow.

Spatial coverage and resolution:

Flow rates and river discharges are measured over approximately 40 watersheds south of 55°N.

Temporal coverage and resolution:

Temporal coverage varies depending on site. The earliest data begin around 1960 and data coverage has increased in the 2000's.

7.6.8 *<u>Dataset</u>: Polar Bear Pass*

Overview

Polar Bear Pass National Wildlife area protects a vast wetland that forms an Arctic oasis on Bathurst Island. This area has relatively abundant tundra and wetland vegetation attracting wildlife including caribou, muskoxen and polar bears. Detailed observations of the meteorology, snowpacks, and hydrology were initiated in the mid-2000s by researchers at York University and their collaborators. Primary motivation for this effort is to better understand how Arctic wetlands are responding to climate change. Dedicated efforts are made to collect measurements on all water budget terms including precipitation, snow accumulation and melt, and runoff.

The dataset includes time series of river discharge at 30-minute intervals from the snowmelt period to late summer.

Provider's contact information

Dr. Kathy L. Young's Homepage: http://www.yorku.ca/klyoung/

Licensing

Licence: N/A

Variable name and units:

River discharge [m^3 s^{-1}] or river runoff [mm]

Spatial coverage and resolution:

- Polar Bear Pass (75.7°N, 109.5°W) on Bathurst Island, Canadian Arctic Archipelago, Nunavut
- Point-scale hydrological data representative of the watershed-scale runoff
- Two sites: Landing Strip (0.2 km^2) and Windy (4.2 km^2) creeks (unofficial names).

Temporal coverage and resolution:

Temporal coverage varies depending on site. The earliest data start in 2007 up to 2015.

Data are seasonal and available at 30-minute intervals.

Information about related datasets

Additional meteorological, soil, vegetation, and water data are available for these sites.

Limitations and strengths for application in Northern Canada

Observations of discharge at two hydrometric gauges on Bathurst Island where there is an absence of Water Survey of Canada data. Limitations with the dataset include no data prior to 2007 or post-2015 and lack of cold season data.

References to documents describing the methodology or/and the dataset

Young, K. L., J. Assini, A. Abnizova, and N.De Miranda, 2010: Hydrology of hillslope-wetland streams, Polar Bear Pass, Nunavut, Canada. Hydrological Processes, 24: 3345-3358.

Young, K. L., M. J. Lafrenière, S.F. Lamoureux, A. Abnizova, and E. A. Miller, 2015: Recent multi-year streamflow regimes and water budgets of hillslope catchments in the Canadian High Arctic: Evaluation and comparison to other small Arctic watershed studies. Hydrology Research, 46(4), 533-550.

Link to download the data and format of data:

https://polardata.ca/pdcsearch/PDCSearch.jsp?doi_id=11130