Government of
Northwest Territories

Compendium of NWT Climate Change Knowledge

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Introduction

In 2017, the Auditor General of Canada released an environmental audit of climate change in the Northwest Territories to the NWT Legislative Assembly. The audit included several specific recommendations, including recommendation 39B: 'Provide departments and others with access to relevant climate change information to make informed adaptation decisions. This would include collecting new information, accessing information already available, and establishing mechanisms to house and share this information. The Department should work with other government departments, agencies, communities, and research institutions to identify existing climate change-related information. This compendium responds to the recommendation.

The objective of the Compendium of NWT Climate Change Knowledge is to provide a summary and review of the latest knowledge related to climate change in the Northwest Territories. The general public, students, researchers, and governmental and non-governmental organizations can use this document to better understand the multiple, widespread impacts of climate change.

This document focuses on the impacts of climate change on climatology, fresh waters/ice, marine waters/ice, animals, vegetation, humans, ecosystems, landscape processes, archaeology/paleontology, and infrastructure/energy. These categories were selected by the Government of Northwest Territories ENR to broadly encompass the wide range of challenges experienced in the NWT. Although this compendium broadly focuses on Western knowledge (resulting from its focus on written publications), Indigenous and Traditional Knowledge are included where possible.

This compendium was completed by a group of graduate student contributors from within the NWT and across Canada. Each contributor was asked to search for and review the 25 most relevant pieces of literature in their field of expertise. Contributors were given the freedom to conduct their searches in the spaces most relevant to their fields. Although much of the literature was found through academic databases, other databases, including governmental and NGO sites, were consulted and the literature is included where applicable. Reviewed pieces may include conference proceedings, peer-reviewed articles, government publications, synthesis reports, and book chapters. They were then asked to identify a few key pieces that should be included in the Compendium on NWT Climate Change Knowledge and provide a coinciding summary and description of relevance. These key summaries (many of which were adapted from the publications themselves) and coinciding descriptions frame this document.

Table of Contents

Climatology

Lightning and weather associated with the extreme 2014 wildfire season in Canada's Northwest Territories

Keywords: Lightning; Forest Fires; Smoke; Northern Canada

Summary

The hot and dry conditions associated with a persistent high-pressure weather system during the summer of 2014 led the Northwest Territories to experience the worst fire season in its recorded history. Record numbers of cloud-to-ground (CG) flashes, lightning-initiated forest fires, and area burned were observed. Prolonged periods of smoke from the wildfires led to dramatic reductions in visibility and road closures, and reduced air quality resulted in numerous health alerts. CG flash activity and polarity patterns were noticeably different in 2014 from those occurring in previous years with, for example, far more nighttime positive flashes.

Relevance

The 2014 extreme fire season in NWT 2014 was linked to dry surface conditions in fall 2013 through spring 2014. This was combined with a persistent high-pressure system during the summer. Lightning activity was observed on a diurnal cycle (during the day) with the majority of flashes occurring in the mid-afternoon. The author suggests a potential connection between the dense smoke from fires to the continued increase in lightning flashes in 2014. The significance of this paper shows the influence of climate on the frequency of lightning-initiated forest fires. A drier fall, winter, and spring are likely to produce a more intense fire period in the summer. This information can be used to predict the severity of future fire seasons for the region and policymakers can use it to plan accordingly for the summer months.

Citation

Kochtubajda, B., Stewart, R., & Tropea, B. Lightning and weather associated with the extreme 2014 wildfire season in Canada's Northwest Territories. In Proceedings of the 24th International Lightning Detection Conference (pp. 1-4). https://doi.org/10.1038/s41586-021-03437-y

Tree-ring reconstruction of early-growing season precipitation from Yellowknife, Northwest Territories

Keywords: Pinus Banksiana; Atmospheric Patterns; Tree Rings; Precipitation Changes

Summary

Twelve jack pine (Pinus banksiana) tree-ring chronologies were developed from sites on rock outcrops near Yellowknife, Northwest Territories, Canada. The average chronology length is approximately 180 years spanning the period 1825–2005. The longest extends to 1679, whereas the shortest covers the period 1936–2005. All of the site chronologies are significantly correlated with June, total May–July, June–July, and June–August precipitation, although relations with the single month of June are strongest. June precipitation was reconstructed using a regionally averaged tree-ring chronology. The reconstruction captures 42% of the variance in the instrumental climate record and based on Rbar and EPS statistics is considered robust from 1819 to 2005. Periods of lower June precipitation occurred in 1927–1979, 1880–1893,1842–1865, 1801–1821, 1776–1796, and 1698–1739. Positive June precipitation anomalies are reconstructed for 1980–1995, 1890–1926, 1822–1841, 1756–1775, and 1687–1697. Throughout the period of reconstruction, there is strong multi-decadal agreement between June precipitation in Yellowknife and other dendro hydrological records from western North America and records of Pacific climate variability. This suggests that large-scale atmospheric patterns influenced by sea surface temperatures (SSTs) in the Pacific basin have controlled continental-scale precipitation patterns at decadal time scales in the Yellowknife region over the past three centuries or more.

Relevance

This research shows that precipitation early in the growing season may be controlled by large-scale atmospheric circulation patterns, possibly driven by set patterns in the north pacific. This is significant because it shows that precipitation in NWT is controlled by the Pacific Decadal Oscillation (PDO). By understanding the patterns of the PDO through time we can estimate precipitation changes to the NWT. If we understand how the PDO will change under a warming climate, then we can estimate changes to the precipitation cycle with climate change. Changes to precipitation will affect vegetation composition and water availability. This paper is significant because it shows the link between teleconnections and precipitation in NWT.

Citation

Michael F. J. Pisaric, Sonia M. St-Onge & Steven V. Kokelj. 2009. Tree-ring Reconstruction of Early-growing Season Precipitation from Yellowknife, Northwest Territories, Canada. *Arctic, Antarctic, and Alpine Research(41)*4, 486-496, DOI: 10.1657/1938-4246-41.4.486

Contributions of Traditional Knowledge to understanding climate change in the Canadian Arctic

Keywords: Traditional Knowledge; Local Expertise; Climate Monitoring

Summary

Despite much scientific research, a considerable amount of uncertainty exists concerning the rate and extent of climate change in the Arctic, and how change will affect regional climatic processes and northern ecosystems. The extensive use of the land and the coastal ocean in Inuit communities provides a unique source of local environmental expertise that is guided by generations of experience. Environmental change associated with variations in weather and climate has not gone unnoticed by communities that are experiencing change firsthand. Little research has been done to explore the contributions of Traditional Knowledge to climate-change research. Based in part on a collaborative research project in Sachs Harbour, western Canadian Arctic, this paper discusses five areas in which Traditional Knowledge may complement scientific approaches to understanding climate change in the Canadian Arctic. These are the use of Traditional Knowledge as local-scale expertise; as a source of climate history and baseline data; in formulating research questions and hypotheses; as insight into impacts and adaptation in Arctic communities; and for long-term, community- based monitoring. These five areas of potential convergence provide a conceptual framework for bridging the gap between Traditional Knowledge and western science, in the context of climate-change research.

Relevance

This paper presents five areas where Traditional Knowledge can be used for climate change research. The authors note that ecological and environmental expertise found in Inuit communities can highlight parameters rarely measured by scientists and help make sense of scientific findings by placing them in local context. The five convergences are:

1. Local-scale expertise
2. Climate history
3. Research hypotheses
4. Community adaptation
5. Community-based monitoring

These five convergences provide a starting point for building relationships between communities and scientists. Moreover, the impacts of climate change are complex, and best studied through a pluralistic approach that includes multiple knowledge systems and perspectives. Policymakers may want to encourage climate scientists specifically to include more Indigenous Knowledge and perspectives in their work.

Citation

Riedlinger, D., & Berkes, F. (2001). Contributions of Traditional Knowledge to understanding climate change in the Canadian Arctic. Polar record, 37(203), 315-328. https://doi.org/10.1017/S0032247400017058

Eighteen years of ecological monitoring reveals multiple lines of evidence for tundra vegetation change

Keywords: Climate Change; Community Composition; Greening; Growth; Permafrost; Phenology; Tundra; Warming.

Summary

The Arctic tundra is warming rapidly, yet the exact mechanisms linking warming and observed ecological changes are often unclear. Understanding mechanisms of change requires long-term monitoring of multiple ecological parameters. Here, the authors present the findings of a collaboration between government scientists, local people, park rangers, and academic researchers that provide insights into changes in plant composition, phenology, and growth over 18 years on Qikiqtaruk-Herschel Island, Canada. Qikiqtaruk is an important focal research site located at the latitudinal tall shrub line in the western Arctic. This unique ecological monitoring program indicates the following findings: (1) nine days per decade advance of spring phenology, (2) a doubling of average plant canopy height per decade, but no directional change in shrub radial growth, and (3) a doubling of shrub and graminoid abundance and a decrease by one-half in bare ground cover per decade. Ecological changes are concurrent with satellite-observed greening and, when integrated, suggest that indirect warming from increased growing season length and active layer depths, rather than warming summer air temperatures alone, could be important drivers of the observed tundra vegetation change. The results highlight the vital role that long-term and multi-parameter ecological monitoring plays in both the detection and attribution of global change.

Relevance

The 18 years of ecological monitoring on Qikiqtaruk indicate (1) an increase in the potential growing season length with warmer air and soil temperatures, fewer frost days and earlier snow melt, leaf emergence, and flowering of monitored plant species, yet also earlier leaf senescence; (2) an increase in canopy heights of tundra plant species; and (3) changing vegetation community composition, including increases in shrub and graminoid species and decreases in bare ground corresponding with a deepening active layer. This study is one of the first to demonstrate such a range of changes occurring simultaneously at one site over a period of decades, providing very strong evidence for ongoing, directional vegetation change and offering insight into the potential drivers of change. The study highlights the critical role that collaborations between local people, park rangers, government scientists, and academic research programs play in climate change research. It is only with the multiple lines of evidence collected through an integrated ecological monitoring program that we can synthesize observed vegetation changes and compare potential drivers, thus improving our understanding of global change responses of this tundra ecosystem.

Citation

Myers-Smith, I. H., Grabowski, M. M., Thomas, H. J., Angers-Blondin, S., Daskalova, G. N., Bjorkman, A. D., ... & Eckert, C. D. (2019). Eighteen years of ecological monitoring reveals multiple lines of evidence for tundra vegetation change. *Ecological Monographs*, 89(2), e01351. https://doi.org/10.1002/ecm.1351

Holocene climate change in Arctic Canada and Greenland

Keywords: Arctic Canada; Greenland; Holocene; Holocene Thermal Maximum; Neoglacial

Summary

This synthesis paper summarizes published proxy climate evidence showing the spatial and temporal pattern of climate change through the Holocene in Arctic Canada and Greenland. The synthesis includes 47 records from a recently published database of highly resolved Holocene paleoclimate time series from the Arctic. The authors analyze the temperature histories represented by the database and compare them with paleoclimate and environmental information from 54 additional published records, mostly from datasets that did not fit the selection criteria for the Arctic Holocene database. They review evidence from a variety of proxy archives including glaciers (ice cores and glacial geomorphology), lake sediments, peat sequences, and coastal and deep-marine sediments. The temperature-sensitive records indicate more consistent and earlier Holocene warmth in the north and east, and a more diffuse and later Holocene thermal maximum in the south and west. Principal components analysis reveals two dominant Holocene trends, one with early Holocene warmth followed by cooling in the middle Holocene, the other with a broader period of warmth in the middle Holocene followed by cooling in the late Holocene. The temperature decrease from the warmest to the coolest portions of the Holocene is 3.0 ± 1.0C on average. The Greenland Ice Sheet retracted to its minimum extent between 5 and 3.7km, consistent with many sites from around Greenland depicting a switch from warm to cool conditions around that time. The spatial pattern of temperature change through the Holocene was likely driven by the decrease in northern latitude summer insolation through the Holocene, the varied influence of waning ice sheets in the early Holocene, and the variable influx of Atlantic Water into the study region.

Relevance

This paper is a summary of multiple climate proxy records for Arctic Canada and Greenland. Climate proxies can be any biotic or abiotic element that preserves an isotope which can be used to infer climate. Types of proxies can be lake sediments, glaciers, ocean sediments, trees, ground ice and many more. They find that the records indicate more consistent and earlier Holocene warmth in the north and east, and a more diffuse and later Holocene thermal maximum in the south and west. This is relevant to policymakers because it shows that the arctic is not warming uniformly, the south-west warmed lower and at a later period than the north-east. This has implications to vegetation response, water availability, permafrost degradation and much more. A slower response allows local ecosystems the time to adapt.

Moreover, understanding past regional climate change is a very important component to understanding current climate change and the rate of change.

Citation

Briner, J. P., McKay, N. P., Axford, Y., Bennike, O., Bradley, R. S., de Vernal, A., … Wagner, B. (2016). Holocene climate change in Arctic Canada and Greenland. Quaternary Science Reviews. https://doi.org/10.1016/j.quascirev.2016.02.010

Fresh Waters/Ice

Influence of vertical and lateral heat transfer on permafrost thaw, peatland landscape transition, and groundwater flow

Keywords: Permafrost Thaw; Groundwater Flow; Lateral Heat Flow; Climate Change

Summary

Recent climate change has reduced the spatial extent and thickness of permafrost in many discontinuous permafrost regions. Rapid permafrost thaw is producing distinct landscape changes in the Taiga Plains of the Northwest Territories, Canada. As permafrost bodies underlying forested peat plateaus shrink, the landscape slowly transitions into unforested wetlands. The expansion of wetlands has enhanced the hydrologic connectivity of many watersheds through new surface and near-surface flow paths, and increased streamflow has been observed. Furthermore, the decrease in forested peat plateaus results in a net loss of boreal forest and associated ecosystems. This study investigates fundamental processes that contribute to permafrost thaw by comparing observed and simulated thaw development and landscape transition of a peat plateau-wetland complex in the Northwest Territories, Canada from 1970 to 2012. Measured climate data are first used to drive surface energy balance simulations for the wetland and peat plateau. Near surface soil temperatures simulated in the surface energy balance model are then applied as the upper boundary condition to a three-dimensional model of subsurface water flow and coupled energy transport with freeze-thaw. Simulation results demonstrate that lateral heat transfer, which is not considered in many permafrost models, can influence permafrost thaw rates. Furthermore, the simulations indicate that landscape evolution arising from permafrost thaw acts as a positive feedback mechanism that increases the energy absorbed at the land surface and produces additional permafrost thaw. The modeling results also demonstrate that flow rates in local groundwater flow systems may be enhanced by the degradation of isolated permafrost bodies.

Relevance

Climate change is driving large scale changes to isolated permafrost bodies in the Taiga Plains in the Northwest Territories, Canada. Environments that contain these rapidly degrading permafrost bodies have enhanced flow rates within the local groundwater flow systems. As groundwater systems are complex and can lead to further degradation of the local and regional landscapes, understanding the potential sources of increased or decreased groundwater flow is important.

Citation

Kurylyk, B. L., M. Hayashi, W. L. Quinton, J. M. McKenzie, and C. I. Voss (2016), Influence of vertical and lateral heat transfer on permafrost thaw, peatland landscape transition, and groundwater flow., *Water Resource*, 52, 1286–1305, doi:10.1002/2015WR018057.

Landsat-based mapping of thermokarst lake dynamics on the Tuktoyaktuk coastal plain, Northwest Territories, Canada since 1985.

Keywords: Landsat; Arctic; Thermokarst; Lake

Summary

Several remote sensing studies have documented widespread thermokarst lake expansion in continuous permafrost regions of North America over the past few decades. Other studies have found no long-term trends in water body extents, but large intra- and inter-annual changes driven by precipitation. These differences could be due to geographic variability in physical conditions (geology, climate, permafrost and hydrology) or in the data and methods used to extract water bodies. This study tested water extraction methods over the Tuktoyaktuk Coastal Plain, Northwest Territories (NWT), Canada, based on the Landsat 5 shortwave infrared (SWIR) channel and validated them using water extents obtained from 0.5 m resolution orthophoto imagery. Methods included applying thresholds to generate binary land/water classifications, as well as deriving 30 m water fractions from both linear unmixing and a new histogram breakpoint method. Results indicated that the histogram breakpoint method outperformed other methods, underestimating overall water fraction by 0.26% and overestimating the number of pure 30 m water pixels by 0.66% compared to water fractions calculated from orthophotos. The breakpoint method was then applied to a stack of 17 near peak-of-season Landsat 5 and Landsat 7 images acquired between July 4 and August 18 from 1985 to 2011 to create a water fraction time-series for examining both trends and inter-annual variation in water extent. Results showed an overall expansion of lake area along margins by 55 km² with isolated lakes experiencing rapid drainage totalling 15 km², leading to a net water area increase of 40 km² over the 26-year period.

Relevance

The impacts on thermokarst lake levels within the Northwest Territories are difficult to quantify due to the staggering number of lakes within the territory. In order to accurately and identify lake expansion or drainage of hundreds of lakes in a region, a remote sensing methodology was used via collected Landsat-5 and Landsat-7 satellite imagery. Since much of the NWT is underlain by permafrost and changes to it can lead to an increased number of thermokarst lakes, it is critical to understand whether these lakes are increasing or decreasing in size as they can affect the local and regional hydrology of the territory. By continuing to use and further update remote sensing methodologies, large areas such as the Tuktoyaktuk Coastal Plain can be analyzed efficiently and accurately more often.

Citation

Olthof, I., Fraser, R., Schmitt, C. (2015). Landsat-based mapping of thermokarst lake dynamics on the Tuktoyaktuk Coastal Plain, Northwest Territories, Canada since 1985. *Remote Sensing of Environment*. 168, 194-204. DOI: 10.1016/j.rse.2015.07.001.

Alpine ice patches and Shúhtagoťine land use in the Mackenzie and Selwyn Mountains, Northwest Territories, Canada

Keywords: Indigenous; Traditional Knowledge; Ice patch; Traditional Land Use; Mountain Dene; Shúhtagoťine

Summary

The NWT Ice Patch Study was developed in partnership with the Shúhtagoťine residents of Tulita, Northwest Territories, Canada. While knowledge of bow-and-arrow and snare technologies persists in Shúhtagoťine culture, Shúhtagoťine oral history does not contain detailed knowledge of throwing dart technology. Using data collected in a traditional land-use mapping project, the authors consider the role of ice patches in the broader context of Shúhtagoťine land use. Ultimately, they propose that resource harvesting on high alpine plateaus and adjacent ice patches in the summer was more important in late pre-contact times than it was after contact. Shúhtagoťine land-use practices involve long-distance travel in all seasons. Safe travel in the alpine landscape requires detailed knowledge of environmental conditions, such as snow and ice conditions, and respectful engagement with the spiritual entities inhabiting the landscape.

Relevance

Traditional Knowledge collected by the Prince of Wales Northern Heritage Centre in partnership and direct participation with the Shúhtagoťine residents and elders of Tulita formed the NWT Ice Patch Study. This study involved numerous outreach initiatives such as archaeological field surveys with elders, science camps, community visits with residents, and school presentations.

As well, the NWT Ice Patch Study has assisted with protecting critical components of the landscape under the Sahtu Dene and Metis land claim. As Shúhtagoťine elders pass on their knowledge of the landscape to their youth, they are providing important tools to aid in managing a changing of their landscape as a result of global warming. It is critical for policy makers within the municipal, territorial, and federal governments to read the collected Traditional Knowledge, such as from the Ice Patch Study, when making new policies in order to ensure the survival of critical and spiritual information, as well as to continue the collection of Traditional Knowledge.

Citation

Andrews, T.D., MacKay, G., Andrew, L., Stephenson, W., Barker, A., Alix, C., Shúhtagoťine Elders of Tulita. (2012). Alpine Ice Patches and Shúhtagoťine Land Use in the Mackenzie and Selwyn Mountains, Northwest Territories, Canada. ARCTIC. Vol: 65(1), 22-42. https://doi.org/10.14430/arctic4183

Marine Waters/Ice

Numerical analysis of storm surges on Canada's Western Arctic coastline

Keywords: Northwest Territories; Tuktoyaktuk; Storm Surge; Arctic; flood; Sea Ice; Coastal Hazards; Climate Change; Driftwood; Reanalysis; Hydrodynamics

Summary

Canada's arctic region, including Tuktoyaktuk, Northwest Territories, is increasingly impacted by climate change. One example of this is extreme weather events resulting in storm surges, causing flooding and impacts to shorelines and coastal communities. The authors model storm surge events using data collected from the Tuktoyaktuk tide gauge record (Station 6485), an ERA5 reanalysis dataset downloaded from the Copernicus Climate Data Store, and other sources in a hydrodynamic model, developed in TELEMAC-2D. This approach successfully verified an event in hindcast, essentially using the model to predict a past event as if it had not yet happened. Sea ice was found to dampen the impact of storm surges.

Relevance

The impacts of climate change on the Northwest Territories is increasingly apparent and mitigating these impacts is essential to the protection of the region, the Canadian Arctic, and our planet. The authors tested a modelling approach to predict weather events that would result in storm surges, and their results are promising. NWT policymakers and other interest groups could use this modelling technique or something similar to help prepare for storm

surges and protect the shorelines of the Northwest Territories from the impacts of such events. The protection of sea ice could aid in the protection of shorelines in this region, providing a barrier to dampen the impacts of flooding. These efforts would further protect the communities throughout the Northwest Territories and would safeguard an essential ecosystem for future stewardship.

Citation

Kim, J., Murphy, E., Nistor, I., Ferguson, S. & Provan, M. (2021). Numerical Analysis of Storm Surges on Canada's Western Arctic Coastline. *Journal of Marine Science and Engineering*, 9(326), 1-20. https://doi.org/10.3390/jmse9030326

Arctic climate warming and sea ice declines lead to increased storm surge activity

Keywords: Northwest Territories; Arctic Warming; Sea Ice; Storm Surges; Mackenzie Delta; Climate Change

Summary

The Mackenzie Delta is a biologically significant and resource-rich region in northwestern Canada, and is particularly vulnerable to flooding by storm surges. To properly manage the consequences of climate warming for Arctic residents, infrastructure, and ecosystems, a better understanding of the influence of climate change on storm surge activity is required. The authors use particle size analysis of lake sediment records to show that the occurrence and magnitude of storm surges in the outer Mackenzie Delta are significantly related to temperature and that the frequency and intensity of storm surges is increasing. The results demonstrate the effects of changing climate on storm surge activity and provide a cautionary example of the threat of inundation to low-lying Arctic coastal environments under future climate warming scenarios.

Relevance

The Mackenzie Delta is an ecologically and economically significant region of the Northwest Territories. Climate change is rapidly impacting this region and the results of that impact will be felt for generations to come, as well as throughout Canada and the rest of the world. Climate change, and the oil and gas projects that fuel it, are the largest hazard to the Northwest Territories. Policymakers and public servants working in and for this region must prioritize mitigating and reversing climate change and its impacts on resources in order to protect the NWT.

Citation

Vermaire, Jesse C.; Pisaric, Michael F. J.; Thienpont, Joshua R.; Courtney Mustaphi, Colin J.; Kokelj, Steven V.; Smol, John P. (2013). Arctic climate warming and sea ice declines lead to increased storm surge activity. *Geophysical Research Letters*, 40, 1386-1390. https://doi.org/10.1002/grl.50191

Changes in oceans surrounding Canada

Keywords: Marine Geology; Climate Change; Ocean Change; Storms; Coastal Erosion

Summary

Upper-ocean temperature has increased in the Northeast Pacific and most areas of the Northwest Atlantic over the last century, consistent with anthropogenic climate change (high confidence). The upper ocean has warmed in the Canadian Arctic in the summer and fall seasons as a result of increases in air temperature and declines in sea ice (medium confidence). Oceans surrounding Canada are projected to continue to warm over the 21st century in response to past and future emissions of greenhouse gases. The warming in summer will be greatest in ice-free areas of the Arctic and off southern Atlantic Canada, where subtropical water is projected to shift further north (medium confidence). During winter in the next few decades, the upper ocean surrounding Atlantic Canada will warm the most, the Northeast Pacific will experience intermediate warming rates, and the Arctic and eastern sub-Arctic ocean areas (including Hudson Bay and Labrador Sea) will warm the least (medium confidence).

Relevance

This chapter provides a big-picture perspective on warming sea surface temperatures, warming oceans, and the causes of events like coastal erosion and loss of sea ice. While jurisdiction attempts to separate oceans and landscapes into distinct regions, the reality is that they are connected to their surrounding environments and the big picture perspective on how these changes impact the Northwest Territories is essential to understanding the issues of concern (particularly storm surges, sea level change, sea ice change, coastal erosion, ocean acidification, and sea surface temperature).

Citation

Greenan, B.J.W., James, T.S., Loder, J.W., Pepin, P., Azetsu-Scott, K., Ianson, D., Hamme, R.C., Gilbert, D., Tremblay, J-E., Wang, X.L. and Perrie, W. (2019): Changes in oceans surrounding Canada; Chapter 7 in (eds.) Bush and Lemmen, Canada's Changing Climate Report; Government of Canada, Ottawa, Ontario, p. 343–423. https://bit.ly/3yO9Cpo

Social-ecological changes and implications for understanding the declining beluga whale (Delphinapterus leucas) harvest in Aklavik, Northwest Territories.

Keywords: Northwest Territories; Arctic; Climate Change; Inuvialuit; Indigenous Knowledge; Subsistence; Arcticmi; sila-ungavausiqtuak; Inuvialuit; Nunaruaqqaaqtuat Ilisimayuat; Isumatuyut Ikayuqtuat Avvakuyaa

Summary

Subsistence is the basis for food access for Inuvialuit in the western Canadian Arctic and has strong economic, dietary, and cultural importance. Inuvialuit harvest beluga whale (Delphinapterus leucas) from the eastern Beaufort beluga population during summer months within parameters established through co-management. Over the past thirty years there has been a dramatic decline in the number of beluga harvested by Inuvialuit from the community of Aklavik, Northwest Territories. This paper investigates the potential drivers of change, both social and ecological, affecting the beluga harvest. Data was collected using 32 semi-directed interviews and experiential learning. Results revealed that ecological changes, notably coastal erosion at preferred whaling camps and unpredictable and severe weather have made harvesting more difficult, expensive, and often impractical. These changes are being experienced together with social changes including the loss of Elders and their knowledge, and changing values and motivations for harvesting beluga. They argue that no one driver is responsible for the decline in the beluga harvest, but rather it is the result of multiple social-ecological changes operating across scales that affect the feasibility of the harvest and motivation to participate.

Relevance

Beluga whales are an incredibly important species ecologically and culturally, and the Eastern Beaufort Sea beluga whale population is one of the largest in Canadian waters. For generations, Inuvialuit from the Mackenzie Delta in Canada’s Western Arctic and their ancestors — the Kupugmiut and Kigirktarumiut — have spent summer months harvesting beluga whales for subsistence. Inuvialuit oral tradition remembers that beluga whale harvests during early contact (late 1800s) were high, with at least 150 whales harvested at each camp along the Beaufort Sea each summer, contributing significantly to the year-round diet. Beluga whale numbers have been steadily declining, which is a concern for Inuvialuit subsistence and for the Beaufort Sea ecosystem. This paper is a call to action for Northwest Territories policy makers to take collective action to protect the lands and waters for future generations. The authors state that "collective action is needed to bring knowledge holders together with younger generations, regardless of family grouping, and to provide harvesters with a source of income to re-engage with the beluga hunt while sharing their knowledge, skills, and values of this harvesting activity with others" (p. 244).

Citation

Worden, E., Pearce, T., Gruben, M, Ross, D., Kowana, C., Loseto, L. (2020). Social-ecological changes and implications for understanding the declining beluga whale (Delphinapterus leucas) harvest in Aklavik, Northwest Territories. *Arctic Science, 6,* 229-246.dx.doi.org/10.1139/as-2019-0027

Animals

Cumulative effects and boreal Woodland Caribou: How bow-tie risk analysis addresses a critical issue in Canada's forested landscapes

Keywords: Rangifer Tarandus; Policy; Conservation; Risk; Decision Support

Summary

This paper presents the use of the ISO 31010 Bowtie Risk Assessment Tool (BRAT) to produce a visual synthesis of the cumulative effects causing the growth rate of boreal caribou herds to persistently fall below a level corresponding to a 60% chance of self-sustainability. The BRAT diagram provided the basis for a quantitative Layers of Protection Analysis (LOPA) of risk probabilities for three caribou herds. The authors combine threat assessments from the Species at Risk Act with landscape experiments to parameterize the LOPA.

Relevance

This paper reports the implications of a combination of mitigation options versus current risk conditions and the implications of uncertainty in threat prevention. A combination of mitigation scenarios will best facilitate caribou herd recovery. Barriers preventing predation threats could also aid in recovery success and compensatory predation may account for a significant proportion of both adult and juvenile female mortality across different herds. The estimated minimum annual cost for effective mitigation and recovery is $224K CDN.

Citation

Winder, R., Stewart, F. E. C., Nebel, S., McIntire, E. J. B., Dyk, A., & Omendja, K. (2020). Cumulative Effects and Boreal Woodland Caribou: How Bow-Tie Risk Analysis Addresses a Critical Issue in Canada's Forested Landscapes. *Frontiers in Ecology and Evolution*, 8, 1. https://doi.org/10.3389/fevo.2020.00001

Implications of zoonoses from hunting and use of wildlife in North American arctic and boreal biomes: Pandemic potential

Keywords: Wildlife; Hunting; Zoonotic; Boreal; Pandemic; Indigenous

Summary

Commercial wildlife trade, and associated markets, are recognized mechanisms for zoonotic disease emergence, resulting in a growing global conversation around reducing human disease risks from spillover associated with hunting, trade, and consumption of wild animals. These discussions are especially relevant to people who rely on harvesting wildlife to meet nutritional, and cultural needs, including those in Arctic and boreal regions. Global policies around wildlife use and trade can affect food sovereignty and security, especially of Indigenous Peoples. This paper reviews known zoonotic pathogens and current risks of transmission from wildlife (including fish) to humans in North American Arctic and boreal biomes, and evaluated the epidemic and pandemic potential of these zoonoses. It discusses future concerns, and considers monitoring and mitigation measures in these changing socio-ecological systems.

Relevance

Monitoring the probability of the emergence of new (and re-emergence of old) zoonoses is crucial given the rapid changes that the northern biomes are experiencing. Indigenous leadership and engagement in disease monitoring, prevention and response, is vital for the outset, and would increase the success of such efforts, as well as ensure the protection of Indigenous rights as outlined in the United Nations Declaration on the Rights of Indigenous Peoples. Collaborating with northern communities and including Indigenous Knowledge would improve the timeliness, and likelihood, of detecting emerging zoonotic risks, and contextualize risk assessments to the unique human-wildlife relationships present in northern biomes.

Citation

Keatts, L. O., Robards, M., Olson, S. H., Hueffer, K., Insley, S. J., Joly, D. O., … Walzer, C. (2021). Implications of Zoonoses From Hunting and Use of Wildlife in North American Arctic and Boreal Biomes: Pandemic Potential. *Monitoring, and Mitigation*. Frontiers in Public Health, 9, 451. https://doi.org/10.3389/fpubh.2021.627654

Colonization of the Beaufort coastal plain by Beaver (Castor canadensis): A response to shrubification of the tundra?

Keywords: American Beaver; Beaufort Coastal Plain; Castor Canadensis; Climate Change Impacts; Range Expansion; Shrubification

Summary

A consequence of rapid global warming has been the shrubification (increase in shrub abundance, cover, and biomass) of arctic and alpine tundra ecosystems. Shrubification is likely a key driver of predicted and observed changes in the biodiversity of the Arctic. The American Beaver (Castor canadensis) has a vast distributional range, covering most of North America below the tree line; however, it has not been recorded in tundra habitat of the Beaufort Coastal Plain of Yukon and Alaska. In 2015, a beaver lodge was observed, and winter food cache on the Babbage River in Ivvavik National Park, Yukon, Canada. Local Inuvialuit hunters first observed beavers on two rivers immediately east of the Babbage River in 2008 and 2009. Together, these are the first observations of beavers on the Beaufort Coastal Plain and indicate initial attempts at colonization. Colonization of the Beaufort Coastal Plain by beavers may have been facilitated by shrubification of river valleys on the tundra of northern Yukon and adjacent Alaska, which is a consequence of rapid climate warming in the western Arctic

Relevance

According to this research note, the Beaufort Coastal Plain beaver occupancy should be of interest for at least three reasons: 1) the remarkable adaptability of beaver to colonize atypical habitats; 2) changes in mammalian communities are occurring in the Arctic as a result of climate-induced shrubification of riparian areas; and 3) beavers are keystone species that modify ecosystems. Their colonization of the Beaufort Coastal Plain may induce changes in the local landscape and hydrology, thereby impacting the biodiversity of riverine and riparian ecosystems and anadromous fish. Thus, it would be prudent to monitor for changes in beaver abundance and distribution on the Beaufort Coastal Plain and other near areas, and ecological changes associated with beaver colonization.

Citation

Jung, T. S., Frandsen, J., Gordon, D. C., & Mossop, D. H. (2016). Colonization of the Beaufort Coastal Plain by Beaver (Castor canadensis): *A Response to Shrubification of the Tundra? The Canadian Field-Naturalist*, 130(4), 332–335. https://doi.org/10.22621/cfn.v130i4.1927

Vegetation

Summer warming explains widespread but not uniform greening in the Arctic tundra biome

Keywords: Tundra; Greening; Browning; Climate Change; Vegetation

Summary

Greening of the Arctic is an increasingly 'hot' topic related to the effects of climate change, with evidence suggesting increases in plant cover, growth, height, and biomass, as well as shrubification of some tundra areas. This study examines Landsat images from 1985-2016 to establish the extent of Arctic greening over this time, and cross-references these trends to changes in topography, temperature, permafrost, and fire. Results of the study indicated that greening tended to occur in areas that showed increasing summer temperature, soil temperature, and soil moisture, particularly at higher elevations, while browning was documented typically when the inverse occurred. Although greening occurred much more frequently than browning, it should be noted that permafrost degradation, extreme weather, pests, and development activities could contribute to browning in some areas. Fires, while generally playing a local role in browning and greening, were not found to be correlated to trends in greening broadly throughout the biome.

Relevance

Extensive greening was documented in the NWT by the authors between 1985-2016. Shrubification of tundra regions is a topic of concern in the NWT given the potential to affect areas hosting important forage for wildlife species (e.g., lichen for caribou). These new landscape processes have the ability to alter ecosystems.

Citation

Berner, L.T., Massey, R., Jantz, P., Forbes, B.C., Macias-Fauria, M., Myers-Smith, I., Kumpula, T., Gauthier, G., Andreu-Hayles, L. Gaglioti, B.V., ...Goetz, S.J. (2020). Summer warming explains widespread but not uniform greening in the Arctic tundra biome. *Nature Communications*, 11, 4621. https://doi.org/10.1038/s41467-020-18479-5

Moving up and over: Redistribution of plants in alpine, Arctic, and Antarctic ecosystems under global change

Keywords: Plants; Arctic/Antarctic/Alpine; Range/Distribution Shifts; Climate Change

Summary

This paper considers management implications and considerations regarding plant distribution shifts in Arctic, alpine, and Antarctic regions, in the context of climate change and increasing human development/activities. The authors recommended a focus on prevention, insofar as human-mediated species movements are concerned. With respect to climate-driven range shifts, the authors advocate for largely allowing these movements to occur unimpeded, in order to support the conservation of biodiversity globally. However, they acknowledge that these

adaptive range shifts may occasionally produce adverse ecological, economic, or social consequences, and so response should be considered on a case-by-case basis.

Relevance

Range shifts of plant species are being reported globally, especially in high latitude and high elevation regions. Considering cliome shift projections for the NWT (see Scenarios Network for Arctic Planning, 2008), substantial changes to plant communities are expected, albeit with uncertainties associated with timing and individual and community responses. Beyond articulating the distribution shifts being seen in plant communities globally (therefore putting trends in the NWT into a global context), the authors touch on a debate occurring that will need to be addressed by the NWT in the near future. That is, should climate-driven species distribution shifts (i.e., an adaptive response to changing habitat conditions) be approached as invasive species (control, management, eradication) or should they be permitted to occur? The latter then gets into topics like facilitation (e.g., strategically planting trees resistant to forest fires) which offers unique insights on ecosystem management.

Citation

Rew, L.J., McDougall, K.L., Alexander, J.M., Daehler, C.C., Essl, F., Haider, S., Kueffer, C., Lenoir, J., Milbau, A., Nunez, M.A., Pauchard, A., & Rabitsch, W. (2020). Moving up and over: Redistribution of plants in alpine, Arctic, and Antarctic ecosystems under global change. *Arctic, Antarctic, and Alpine Research*, 52(1), 651-665. https://doi.org/10.1080/15230430.2020.1845919

Status and trends in Arctic vegetation: Evidence from experimental warming and long-term monitoring

Keywords: Arctic; Experimental Warming; Long-Term Monitoring; Phenology; Vegetation Change

Summary

The authors reviewed observational and experimental evidence of abundance and phenology changes in tundra vegetation tied to climate change, reported as both the direction and significance of change. Note that p values <0.5 were used to indicate significance of a change; however, effect sizes and confidence intervals were not included in this review. The clear directionality of many species' phenological responses in experimental studies (i.e., extension of the growing season in both spring and fall) suggests some underlying sensitivity to warming, while the more variable results obtained through observational studies suggest factors other than warming are also likely contributing to responses. Observational studies showed primarily non-significant changes in abundance over time, although some grasses and shrubs increased in abundance somewhat over time. Experimental studies showed some increase in abundance in grasses and shrubs as well, but a clearer directional response of lichens and mosses, which

declined in response to warming. Leaf litter increased across both types of studies. Shrubs increased in biomass above- and below-ground in response to experimental warming. Changes in plant diversity appear to be limited in most tundra areas to date, with the exception of alpine tundra regions in Europe, which have experienced substantial increases in plant diversity.

Relevance

Given the high proportion of global carbon stored in the soils of northern regions, shifts in overlying vegetation may have implications for carbon storage. For example, changes in ground insulation and soil temperatures, decomposition rates, albedo, and flammability of litter. On the other hand, increasing leaf litter from shrubs could slow decomposition and thus carbon release. The occasional positive response by shrubs and grasses to warming across both types of studies in relatively warm and moist areas of the tundra corresponds with reports of shrubification in tundra areas, including within the NWT. Changes in vegetation communities, including phenological mismatches, are likely to have implications for many species, including pollinators, breeding/migratory birds, and mammals. Unfortunately, there is a paucity of information available on these topics for northern Canada, suggesting more emphasis on monitoring these systems should be considered. This work ties into the goals of the Circumpolar Biodiversity Monitoring Programme, which identifies community composition, diversity, and phenology as monitoring priorities, and to which Canada is a party.

Citation

Bjorkman, A.D., Criado, M.G., Myers-Smith, I.H., Ravolainen, V., Jónsdóttir, I.S., Westergaard, K.B., Lawler, J.P., Aronsson, M., Bennett, B., Gardfjell, H., Hieðmarsson, S., Stewart, L., & Normand, S. (2020). Status and trends in Arctic vegetation: Evidence from experimental warming and long-term monitoring. *Ambio*, 49, 678-692. https://doi.org/10.1007/s13280-019-01161-6

Spring phenology drives range shifts in a migratory Arctic ungulate with key implications for the future

Keywords: Arctic; Caribou; Climate Change; Phenology; Distribution

Summary

This study modeled and projected the influence of spring phenological shifts (snowmelt and green-up) on the calving and post-calving distribution of the Porcupine caribou herd by mid-21st century under a high emissions scenario (RCP8.5). The Porcupine caribou herd appears to select calving and post-calving habitat strategically, based on forage quality (i.e., timing of spring green-up). The results suggest the advancement of spring snowmelt and green-up dates over time (recognizing inter-year variability), which, under the conditions of this model, would favour calving and post-calving in Alaska, versus the Yukon.

Relevance

In some respects, this study provides good news. Caribou are an ecological and cultural keystone species across northern North America. This work suggests that caribou are capable of a level of spatial adaptability that may be key to their long-term survival (although a large proportion of the increase in suitable habitat in Alaska is projected for the 1002 Area of the Alaska National Wildlife Refuge, which is currently protected from development). This study also underlines the trade-offs implicit in considering conservation globally versus regionally. That is, shifts in distribution as suggested by this study may benefit the species in the long-term and thus global biodiversity conservation. However, these same shifts in distribution may have negative long-term consequences for the people of the NWT who rely on the Porcupine caribou herd for subsistence. The results of this study also join the growing body of literature suggesting that managing to a historical baseline is likely of limited utility looking forward. Finally, this study underscores the importance of habitat changes, including to forage species, to species and people. While this study focuses largely on Alaska and the Yukon, phenological shifts are also likely to affect other ungulates in the NWT.

Citation

Severson, J.P., Johnson, H.E., Arthur, S.M., Leacock, W.B., & Suitor, M.J. (2021). Spring phenology drives range shifts in a migratory Arctic ungulate with key implications for the future. *Global Change Biology*, 27, 4546-4563. https://doi.org/10.1111/gcb.15682

Warming of subarctic tundra increases emissions of all three important greenhouse gases - carbon dioxide, methane, and nitrous oxide

Keywords: Subarctic; Tundra; Peat; Climate Change; Carbon Dioxide; Methane; Nitrous Oxide

Summary

As a result of Arctic amplification, warming in high latitude regions is expected to be more pronounced than global averages. In this context and given the large stores of carbon in peat and tundra areas throughout the region, the potential for warming to shift these sinks to sources of emissions is a topic of global concern. This study considered the effects of experimental warming (moderate warming scenario) in vegetated and unvegetated subarctic tundra/peat areas on carbon dioxide, methane, and nitrous oxide emissions. Overall, experimental warming increased carbon dioxide, methane, and nitrous oxide emissions from all sites, shifting sites from sinks to sources of emissions. Warming did not increase carbon dioxide uptake by plants (possibly reflecting increased moisture stress with increasing temperature at this fairly dry study site) but did likely result in changes at the soil surface/litter layer leading to increases in soil microbial respiration at deeper levels (suggesting downward leaching of carbon compounds).

Relevance

The increase of nitrous oxide emissions at vegetated tundra sites is the first report of this phenomenon (emissions from unvegetated tundra sites had previously been reported and was echoed in the results of this study). This is relevant to global emission projections because while unvegetated tundra sites occur over relatively limited areas, vegetated tundra is extensive and widespread. Likewise, nitrous oxide emissions were sensitive to both increasing temperature and increasing moisture, a point of potential concern in the NWT, where precipitation projections suggest increases over the medium- to long-term (albeit with strong variability and not necessarily reflective of an increase in total moisture availability if evaporation and evapotranspiration increase). Overall, given the potency of nitrous oxide as a greenhouse gas, these results suggest that the framework for projecting emissions should be extended to include nitrous oxide, as well as the possibility of surface-level changes stimulating soil microbial activity at deeper soil levels. These topics are not well-addressed in climate change projections and policymakers should spend more time thinking about them to make informed decisions.

Citation

Voigt, C., Lamprecht, R.E., Marushchak, M.E., Lind, S.E., Novakowskiy, A., Aurela, M., Martikainen, P.J., & Biasi, C. (2017). Warming of subarctic tundra increases emissions of all three important greenhouse gases - carbon dioxide, methane, and nitrous oxide. *Global Change Biology*, 23, 3121-3138. https://doi.org/10.1111/gcb.13563

Satellite observations document trends consistent with a boreal forest biome shift

Keywords: NDVI; Landsat; Boreal Forest Biome; Climate Change; Biome Shift

Summary

This study assessed indicators of vegetation productivity and mortality (greening versus browning, respectively) against indicators of biome shifts within the boreal forest using moderate resolution satellite images over a span of approximately 40 years. Broadly, results indicated greening was occurring predominantly at boreal-tundra ecotones, while browning was more common at the southern boundary of the boreal forest (although note that these patterns were not uniform). Factors associated with these patterns included tree cover (greening was more common in sparsely treed areas while browning was more common in areas with moderate tree cover), stand type (greening was more common in deciduous needleleaf forests [e.g., tamarack] while browning was more common in deciduous broadleaf [e.g., aspen] and mixed forests), air and soil temperature (greening was more common in areas with low air and soil temperatures while browning was more common in areas with warm air and soil temperatures), soil nitrogen (greening was more common in areas with high soil nitrogen while browning was more common in areas with low soil nitrogen), and elevation (greening was more common at high and low elevation while browning was more common at mid-elevation). In

contrast, few patterns of vegetation productivity/mortality were observed in the center of the boreal forest (versus the northern and southern boundaries) suggesting perhaps some degree of resiliency to the pressures of climate change to date. The trends seen at the northern and southern boundaries of the boreal forest globally, however, suggest the beginnings of a possible large-scale shift within the boreal forest, although it should be noted that this trend may have slowed over the 40-year study period. Also note that disturbances and succession may complicate interpretations of greening/browning, but in this case, the authors made efforts to remove recent disturbances from the dataset to reduce this effect. Disturbances like wildfires or harvesting can be important forces in triggering these kinds of forest shifts at local scales.

Relevance

Given the severity of warming being experienced in boreal forest relative to other global biomes and the vast amounts of carbon stored by the boreal forest, shifts in the biome are of relevance to local and global environmental managers. These shifts have the potential to affect permafrost, hydrology, species communities, and people through a positive feedback loop. In the NWT, greening was pre-dominant north of Great Slave Lake, while browning was more common south of the lake. This has implications for managers who must contend with the effects that this kind of large-scale biome shift will have on local species, communities, disturbances, and ecosystem services.

Citation

Berner, L.T. & Goetz, S.J. (2021). Satellite observations document trends consistent with a boreal forest biome shift. *Global Change Biology, 28*, 3275-3292. https://doi.org/10.1111/gcb.16121

The state of Northwest Territories forests in the wake of climate change: Baseline conditions and observed changes to forest ecosystems

Keywords: Northwest Territories; Forests; Climate Change; Baseline; Trends

Summary

This report consolidates the best available information regarding the status and trends in NWT forests and presents these conditions as a baseline against which future changes can be assessed. With respect to climate change, NWT forests are and will continue to be affected by changes in permafrost (warming, deepening active layer, thaw, potential shifts from lichen-spruce to shrub-moss community composition aboveground, tree growth in wetlands), wildfires (shifts in vegetation community composition, fire return interval, permafrost degradation), pests/diseases (potential northward expansion of spruce budworm, northern tent caterpillar, willow blotch leafminer, and mountain pine beetle (although note that NWT forests are considered less susceptible to mountain pine beetle infestation than forests in Alberta and BC), increased susceptibility of other species as phenology shifts, potential for increased impact

from pathogens (e.g., western gall rust, root disease fungi), possible interactions with wildfire), species range shifts, flooding, and droughts. In fact, disturbance projections suggest that the large majority of the NWT's forests could be at risk from one or more of wildfire, spruce budworm, mountain pine beetle, and/or drought by the end of the century, assuming a high emissions scenario.

Relevance

This report covers the major forces affecting NWT forests, and effectively explains possible interactions and uncertainties. All of these forces and consequent changes will have interacting effects, as well as implications for carbon flux, wildlife, and people. Note that the report consolidates research conducted by the Canadian Forest Service primarily, rather than being necessarily representative of all research of potential relevance to NWT forests. However, as the GNWT maintains a research relationship with the Canadian Forest Service, the work should nonetheless be relevant and provide a reasonable overview of conditions within NWT forests. One point that wasn't addressed in this paper is the issue of non-native plant establishment and spread. Of particular interest is the possibility of forest stand composition shifts following wildfires; specifically, the potential increase in deciduous trees. In general, and recognizing that this hasn't been tested to date in the NWT, invasibility can vary across habitats/forest stands, with coniferous forests expected to be less invasive than mixed or deciduous stands, and those less invasive than open areas (e.g., prairie/grassland).

Citation

Huberman, Y., Beckers, J., Brett, R., Castilla, G., Errington, R., Fraser-Reid, E.C., Goodsman, D., Hogg, E.H., Metsaranta, J., Neilson, E., Olesinski, J., Parisien, M.-A., Price, D., Ramsfield, T., Shaw, C., Thompson, D., Voicu, M.F., Whitman, E., & Edwards, J. (2022). The state of Northwest Territories forests in the wake of climate change: baseline conditions and observed changes to forest ecosystems. Information Report NOR-X-430, Northern Forestry Centre, Canadian Forest Service, Natural Resources Canada: Edmonton, AB. 158 pp. https://bit.ly/3AvV7rf

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Humans

“We hardly have any moose around here anymore”: Climate change and the barriers to food security in the Dehcho Region, Northwest Territories

Keywords: Food Security; Climate Change; Indigenous Peoples; Rural Communities; Subarctic; Food Procurement

Summary

Rural Indigenous communities across northern Canada are experiencing high rates of food insecurity as a result of complex constraints to accessing quality market foods and engaging in local food procurement. Climate change is impacting the ability of northern Indigenous communities to acquire, access, and utilize food that is culturally relevant and sustainable. This research examines the interconnected sociocultural, political, economic, and environmental challenges related to food security in the community of Fort Providence situated in the Dehcho Region of the Northwest Territories. The objective of this research was to consult with community members to understand the impacts of climate change on local food procurement and to explore the myriad challenges related to food security. The research demonstrates that changing hydrological systems and ecosystems, unpredictable weather patterns, the presence of non-local harvesters, the loss of Traditional Knowledge, and the high costs of living in a rural northern community impact local food security.

Relevance

Policy makers need to consider the pillars (outlined by the Food and Agricultural Organization of the United Nations) upon which food security relies: availability, access, utilization, stability, and quality (the fifth being added by the authors). Breaking down food systems to assess each of these pillars will highlight the various issues and needs that each food system faces. This article provides one example of how to assess food (in)securities in the era of environmental and climate changes. In doing so, the paper clearly articulates how changes to the environment-food nexus are experienced at local sociocultural, political, and economic scales, thereby showing the impact of climate and environmental change on Indigenous lifestyles. Moreover, this paper offers one way that policy makers can blend Western and Indigenous sciences to inform local policies and plans.

Citation

Ross, P., & Mason, M. We Hardly Have Any Moose Around Here Anymore: Climate Change and the Barriers to Food Security in the Dehcho Region, Northwest Territories. (2020). *Arctic(73)*3, 368–85. https://doi.org/10.14430/arctic71082

Thawing permafrost in Arctic coastal communities: A framework for studying risks from climate change

Keywords: Climate Change; Risks; Permafrost; Adaptation; Arctic; Human Exposure

Summary

Thawing permafrost creates risks to the environment, economy and culture in Arctic coastal communities. Identification of these risks and the inclusion of the societal context and the

relevant stakeholder involvement is crucial in risk management and for future sustainability, yet the dual dimensions of risk and risk perception is often ignored in conceptual risk frameworks. In this paper, the authors present a risk framework for Arctic coastal communities. The framework builds on the notion of the dual dimensions of risk, as both physically and socially constructed, and it places risk perception and the coproduction of risk management with local stakeholders as central components into the model. Central to the framework is the importance of multidisciplinary collaboration. The framework motivates coproduction of risk management with locals in the identification of these risks from permafrost thaw and the development of adaptation and mitigation strategies.

Relevance

Permafrost thaw has significant implications to the fragile relationship among people, the environment (including natural and social environments), and species. This paper offers one way to understand the lived experiences of permafrost thaw in the North by looking at the role of risk (actual or perceived) in permafrost thaw adaptation. This paper can help policy makers understand the lived experiences of permafrost thaw by including socio-economic and cultural processes into the risk management and evaluation processes. It shows how permafrost thaw is connected to human life and the human experience, and how to evaluate and understand permafrost thaw using observations, measurements (qualitative and quantitative), people, stakeholders, sectors (including business, education, NGOs, and healthcare), cost-benefit analysis, human security, and adaptive capacities.

Citation

Larsen, J.N., Schweitzer, P., Abass, K., Doloisio, N., Gartler, S., Ingeman-Nielsen, T., Ingimundarson, J.H., Jungsberg, L., Meyer, A., Rautio, A. & Vullierme, M. (2021). Thawing permafrost in Arctic coastal communities: a framework for studying risks from climate change. *Sustainability, 13*(5), 2651. https://doi.org/10.3390/su13052651

A framework for examining adaptation readiness

Keywords: Adaptation; Adaptation readiness; Climate change; Adaptive capacity; Adaptation tracking; Conceptual model; Assessment framework; Indicators

Summary

Adaptation readiness is proposed as a complementary concept to adaptive capacity that captures the strength and existence of governance structures and policy processes which determine whether adaptation takes place. As such, adaptation readiness is concerned with examining actual experiences with planning for adaptation and seeks to characterize whether human systems are prepared and ready to 'do adaptation.' Ford and King propose a framework for evaluating readiness, identifying 6 overarching factors essential for adaptation taking place: political leadership, institutional organization, adaptation decision making and stakeholder

engagement, availability of usable science, funding for adaptation, and public support for adaptation. For each readiness factor, they identify potential indicators, data sources, and considerations for analysis, outlining approaches for quantitative scoring and qualitative examination. The framework provides a systematic approach for assessing adaptation readiness, and can be used – in combination with other approaches – to inform the identification and prioritization of adaptation support, guide resources to areas where need is greatest, and serve as a proxy for adaptation tracking.

Relevance

This paper, and coinciding framework, offer policy makers a detailed explanation of the six factors that directly influence climate change adaptation planning and readiness. This paper breaks down some essential social and structural factors that policy makers are directly involved with to support and aid the adaptation process. Moreover, it will inform governing bodies and agencies as to which factors are more vulnerable to environmental and climate change. Policy makers can use this paper and the framework to evaluate what aspects of life need more attention and resources and which systems should be able to adapt or evolve on their own. It should be noted that this framework does not account for Indigenous Knowledge and perspectives in adaptation structures and approaches.

Citation

Ford, J. D., & King, D. (2015). A framework for examining adaptation readiness. *Mitigation and Adaptation Strategies for Global Change, 20*(4), 505-526. https://doi.org/10.1007/s11027-013-9505-8

The environmental consequences of climate-driven agricultural frontiers

Keywords: Climate Change; Agriculture; Arctic and Subarctic; Food Systems

Summary

Recent research has documented potential environmental impacts of shifting crop growing patterns, including impacts on water, wildlife, pollinator interaction, carbon storage and nature conservation, on national to global scales. Multiple crops will be moving in response to shifting climatic suitability, and the cumulative environmental effects of these multi-crop shifts at global scales is not known. Here the authors model multiple major global commodity crop suitability changes due to climate change to estimate the impacts of new crop suitability on water, biodiversity and carbon storage. Areas that become newly suitable for one or more crops are considered Climate-driven Agricultural Frontiers that can have substantial impacts on our food and environmental systems, including major impacts on biodiversity in tropical mountains, on water resources downstream and on carbon storage in high latitude lands.

Relevance

This paper offers an approach to Northern and cold region agriculture in the context of environmental and climate change. While the scale of the paper is focused more broadly on the North, opposed to the NWT, it explores some of the obstacles and opportunities with northern farming. Specifically, it addresses the relationships among soil health, biodiversity, and carbon cycles necessary for agricultural production and focuses on the potential of the climate crisis to help alleviate food insecurities in the North. While this environmentally transformative process helps paint climate and environmental change in a positive light, the article similarly cautions on the increased environmental impact of agricultural practices. It is relevant for policy makers as it offers a legitimate opportunity to overcome climate-related challenges in the North.

Citation

Hannah, L., Roehrdanz, P. R., KC, K. B., Fraser, E. D., Donatti, C. I., Saenz, L., ... & van Soesbergen, A. (2020). The environmental consequences of climate-driven agricultural frontiers. *PloS one, 15*(2), e0228305. https://doi.org/10.1371/journal.pone.0228305

Qualitative risk assessment of impact of Toxoplasma Gondii on health of beluga whales, Delphinapterus Leucas, from the Eastern Beaufort Sea, Northwest Territories

Keywords: Qualitative Risk Assessment; Toxoplasma Gondii; Beluga Whales; Delphinapterus leucas: Beaufort Sea.

Summary

In recent years, the protozoan parasite Toxoplasma gondii has increasingly been recognized in Arctic fauna, including beluga whales (Delphinapterus leucas) in the Eastern Beaufort Sea (EBS), Northwest Territories. This paper assesses the risks of T. gondii to the health of EBS beluga because of their importance in the livelihood of Arctic communities as well as their potential role as sentinels. This risk assessment used a standard framework including hazard identification, hazard characterization, exposure assessment, and risk characterization. The authors conclude that currently, the EBS beluga are at moderate risk of exposure to T. gondii, and low risk of developing disease associated with toxoplasmosis, based on the small amount of data available (only healthy, hunter-harvested animals have been examined). Although there was a high level of uncertainty due to limited published data and the challenges in determining prevalence and significance of disease in wild marine mammal populations, overall the EBS population was currently considered to be at a low risk for population level impacts of toxoplasmosis.

Relevance

This paper explores the impacts of toxoplasmosis on Arctic beluga. The study suggests that increasing levels of toxoplasmosis are being identified for (1) their increasing presence in marine environments and (2) an increase in testing measures. The levels of toxoplasmosis need to be strictly monitored to ensure safe harvest of Arctic beluga. While the study presents the ecosystem at low risk, it acknowledges the significant limitations to the study and that other dangerous pathogens are most likely already present in the environment. Moreover, they suggest that more research is urgently needed to better understand how environmental toxins influence human health.

Citation

Sharma, R., Loseto, L. L., Ostertag, S. K., Tomaselli, M., Bredtmann, C. M., Crill, C., ... & Jenkins, E. J. (2018). Qualitative risk assessment of impact of Toxoplasma gondii on health of beluga whales, Delphinapterus leucas, from the Eastern Beaufort Sea, Northwest Territories. *Arctic Science, 4*(3), 321-337. https://doi.org/10.1139/AS-2017-0037

Food patterns and socioeconomic indicators of food consumption amongst Inuvialuit in the Canadian Arctic

Keywords: Fruits and Vegetables; Inuvialuit; Non-nutrient-dense Foods; Socioeconomic Indicators; Traditional Foods.

Summary

Inuvialuit in the Canadian Arctic have been experiencing a nutrition transition resulting in a decrease in nutrient-dense food consumption, which may, in part, explain this population's increasing chronic disease rates. Because the available literature is limited, the present study aimed to document the extent of this transition by examining current dietary patterns and socio- economic factors affecting food group consumption. This cross-sectional study was conducted in three Inuvialuit communities in the Northwest Territories between 2007 and 2008. A validated food frequency questionnaire determined intake frequency of fruit and vegetables (FV), traditional foods (TF) and non-nutrient-dense foods (NNDF). Socioeconomic status (SES) was assessed by questions on education, ownership of items in working condition used to create a Material Style of Life (MSL) scale and residents on household income support. Daily intake frequencies were compared by gender and age group using Wilcoxon rank sum test. SES association with food group intake was determined using logistic regression. NNDF were consumed approximately seven times more frequently than TF in the present study, indicating that the dietary transition is well underway amongst Inuvialuit. Participants with higher SES were more likely to consume nutrient-dense foods, suggesting possible cost barriers.

Relevance

This research explores and confirms something that we already knew to be happening in the Inuvialuit Region: a climate-induced food reform exacerbated by environmental and climate changes. The study confirms the increasing presence of non-nutrient-dense foods in the North, further contributing to public health concerns and the loss of intergenerational knowledge transfer. The article also confirms that less than a quarter of the average adult diet in the Inuvialuit Region is traditional foods, meaning that significant food structures reform is already well underway.

Citation

Erber, E., Beck, L., Hopping, B. N., Sheehy, T., De Roose, E., & Sharma, S. (2010). Food patterns and socioeconomic indicators of food consumption amongst Inuvialuit in the Canadian Arctic. *Journal of Human Nutrition and Dietetics*, 23, 59-66. https://doi.org/10.1111/j.1365-277X.2010.01097.x

Societal implications of a changing Arctic Ocean

Keywords: Arctic Ocean; Climate change; Ecology; Geopolitics; Indigenous Peoples ; Sea ice

Summary

The Arctic Ocean is undergoing rapid change: sea ice is being lost, waters are warming, coastlines are eroding, species are moving into new areas, and so on. This paper explores the many ways that a changing Arctic Ocean affects societies in the Arctic and around the world. In the Arctic, Indigenous Peoples are again seeing their food security threatened and cultural continuity in danger of disruption. Resource development is increasing as is interest in tourism and possibilities for trans-Arctic maritime trade, creating new opportunities and also new stresses. Beyond the Arctic, changes in sea ice affect mid- latitude weather, and Arctic economic opportunities may re-shape commodities and transportation markets. Rising interest in the Arctic is also raising geopolitical tensions about the region. What happens next depends in large part on the choices made within and beyond the Arctic concerning global climate change and industrial policies and Arctic ecosystems and cultures.

Relevance

This article offers a window into some of the human dimensions of a changing Arctic Ocean. It can help contextualize some of the broad challenges communities that rely on the Arctic Ocean are facing. Some of these challenges include food (in)securities caused by fluctuating sea ice patterns and water temperatures, a growing Western tourism market challenging unique cultural protocols, resource development and extraction, and sea-level rise coupled with coastal erosion and permafrost thaw. The article raises points of concern relating to international security and conflict as well, noting that the Arctic is becoming increasingly desired for its

resource potential and strategic geographic location in times of conflict. The article strongly connects different social and political issues to provide a multi-fronted perspective of challenges and opportunities of a warming northern climate. Policymakers should use this article to help think through some of the geographic changes, challenges, and opportunities posed by climate changes.

Citation

Huntington, H. P., Zagorsky, A., Kaltenborn, B. P., Shin, H. C., Dawson, J., Lukin, M., ... & Thomas, D. N. (2022). Societal implications of a changing Arctic Ocean. *Ambio, 51*(2), 298-306. https://doi.org/10.1007/s13280-021-01601-2

Ecosystems

Implications of climate change for Northern Canada: Freshwater, marine, and terrestrial ecosystems

Keywords: Climate Change; NWT; Biodiversity

Summary

Climate variability and change is projected to have significant effects on the physical, chemical, and biological components of northern Canadian marine, terrestrial, and freshwater systems. As the climate continues to change, there will be consequences for biodiversity shifts and for the ranges and distribution of many species with resulting effects on availability, accessibility, and quality of resources upon which human populations rely. This will have implications for the protection and management of wildlife, fish, and fisheries resources; protected areas; and forests. The northward migration of species and the disruption and competition from invading species are already occurring and will continue to affect marine, terrestrial, and freshwater communities. Shifting environmental conditions will likely introduce new animal-transmitted diseases and redistribute some existing diseases, affecting key economic resources and some human populations. Stress on populations of iconic wildlife species, such as the polar bear, ringed seals, and whales, will continue as a result of changes in critical sea-ice habitat interactions. Where these stresses affect economically and culturally important species, they will have significant effects on people and regional economies. Further integrated, field-based monitoring and research programs, and the development of predictive models are required to allow for more detailed and comprehensive projections of change to be made, and to inform the development and implementation of appropriate adaptation, wildlife, and habitat conservation and protection strategies.

Relevance

This study assesses how climate change has and will continue to affect freshwater, marine, and terrestrial ecosystems of the Yukon, Northwest Territories and Nunavut. As the climate continues to change in the NWT, there will be consequences for biodiversity, including the ranges and distribution of many species, with resulting impacts on availability, accessibility, and quality of resources upon which communities rely. This has policy implications for the protection and management of wildlife, fish and fisheries resources, protected areas, and forests. The northward migration of species, and disruption and competition from invading species, are already occurring and will continue to alter terrestrial, marine, and aquatic communities. Shifting environmental conditions will likely introduce new animal-transmitted diseases and redistribute some existing diseases, affecting key economic resources and some human populations. Where these stresses affect economically and culturally important species, they will have significant impacts on people and regional economies. This research calls for widespread proactive adaptation to these changes in natural resource management sectors in the NWT.

Citation

Prowse, Furgal, C., Wrona, F. J., & Reist, J. D. (2009). Implications of Climate Change for Northern Canada: Freshwater, Marine, and Terrestrial Ecosystems. *Ambio*, 38(5), 282–289. https://doi.org/10.1579/0044-7447-38.5.282

Using multiple sources of knowledge to investigate Northern environmental change: Regional ecological impacts of a storm surge in the outer Mackenzie Delta, N.W.T.

Keywords: Climate Change; Inuvialuit Knowledge; Mackenzie Delta; Monitoring; Multidisciplinary; Remote Sensing; Salinization; Storm Surge; Vegetation Change

Summary

Field data, remote sensing, and Inuvialuit knowledge were synthesized to document regional ecological change in the outer Mackenzie Delta and to explore the timing, causes, and implications of this phenomenon. In September 1999, a large magnitude storm surge inundated low-lying areas of the outer Mackenzie Delta. The storm was among the most intense on record and resulted in the highest water levels ever measured at the delta front. Synthesis of scientific and Inuvialuit knowledge indicates that flooding during the 1999 storm surge increased soil salinity and caused widespread vegetation death. Vegetation cover was significantly reduced in areas affected by the surge and was inversely related to soil salinity. Change detection analysis, using remotely sensed imagery bracketing the 1999 storm event, indicates severe impacts on at least 13 200ha of terrestrial vegetation in the outer delta. Inuvialuit knowledge identifying the 1999 surge as anomalous is corroborated by geochemical profiles of permafrost and by a recently published paleo-environmental study, which indicates that storm surge impacts of this

magnitude have not previously occurred during the last millennium. Almost a decade after the 1999 storm surge event, ecological recovery has been minimal. This broad-scale vegetation change is likely to have significant implications for wildlife and must be considered in regional ecosystem planning and in the assessment and monitoring of the cumulative impacts of development.

Relevance

Rising sea levels and a greater duration of the open water season could increase the magnitude and frequency of storm surges and the impacts to Arctic coastal ecosystems. The broad-scale ecological changes to the outer Mackenzie Delta caused by the 1999 storm surge have implications for wildlife and in the assessment, monitoring, and management of the cumulative impacts of development. This study highlights the need for coordinated monitoring and research that is multidisciplinary, regionally relevant, and locally informed. Such efforts are vital to sound policy development and resource management in Canada's changing North.

Citation

Kokelj, S., Lantz, T. C., Solomon, S., Pisaric, M. F. ., Keith, D., Morse, P., Thienpont, J. R., Smol, J. P., & Esagok, D. (2012). Using Multiple Sources of Knowledge to Investigate Northern Environmental Change: Regional Ecological Impacts of a Storm Surge in the Outer Mackenzie Delta, N.W.T. *Arctic*, 65(3), 257–272. https://doi.org/10.14430/arctic4214

Ecological patterns of fish distribution in the Slave River Delta region, Northwest Territories, Canada, as relayed by Traditional Knowledge and Western science

Keywords: Cumulative Effect Monitoring; Environmental Management; Fish Habitat; Fish Migration; Traditional Knowledge; Western Science

Summary

Indigenous community members along the Slave River in Canada have voiced their concerns for the health of ecosystems under pressure from resource extraction, hydroelectric development and global climate change. This study presents a test case of Traditional Knowledge and scientific results about the spawning and migration patterns of fish in the Slave River and Delta. This dual knowledge system approach elucidates the broader connectivity of local study regions and can improve monitoring programmes by extending beyond the usual context/confines of the present or recent past, increasing the spatial and temporal range of system information.

Relevance

This project supported holistic learning about fish spawning and migration patterns in the Slave River and Slave River Delta and advanced cumulative effects monitoring methods through the

blending of western science and Traditional Knowledge. This approach provides a means for NWT scientists to track ecological change over the coming years and help support environmental management decision making in the face of cumulative impacts. When elders and local people indicate changes in fish spawning and migration, potentially brought on by changes in water level or site access, the approach taken by this study provides NWT managers with: (1) broadly informed baseline data to assess environmental change; (2) insight into priority areas for focussed monitoring, protection or potential remediation; (3) information to support the protection of sensitive species under increased pressure; and (4) trend data regarding regional fish ecology.

Citation

Baldwin, Bradford, L., Carr, M. K., Doig, L. E., Jardine, T. D., Jones, P. D., Bharadwaj, L., & Lindenschmidt, K.-E. (2018). Ecological patterns of fish distribution in the Slave River Delta region, Northwest Territories, Canada, as relayed by Traditional Knowledge and Western science. *International Journal of Water Resources Development*, 34(2), 305–324. https://doi.org/10.1080/07900627.2017.1298516

Carbon accumulation in peatlands, southwestern Northwest Territories, Canada

Keywords: Peatlands; Carbon; Radiocarbon Data; Monitoring

Summary

Northern peatlands have stored significant quantities of carbon (C) since the early Holocene at rates that vary among peatland types. Pollen concentration dating was used to provide estimates of true C accumulation and sequestration efficiency in different peatland systems in the discontinuous permafrost zone near Fort Simpson, Northwest Territories, Canada. The catotelm portions of bog, permafrost-affected peat plateau, and Sphagnum-dominated cores were interpreted to conform to Clymo's (1984) model of C accumulation, while peat deposited under conditions with high water tables (rich fen and collapse fen) did not. The model assumes a consistent surface production, yet production in fens is thought to be highly sensitive to water table changes and may have contributed to poor model fits. Decay rates measured over the past 1200 yr range from 0.0015 to 0.0004 yr-1 . True C accumulation rates (range 7.0 in peat plateau to 18.6 g C m–2 yr–1 in bog) and sequestration efficiencies (range 0.24 in peat plateau to 0.67 in poor fen) by 1200 years before the present day were low in comparison with other North American sites. Decay rates measured over 1200 yr were significantly greater than that measured over the entire life span of the peatland (0.00033 yr–1), suggesting that a true C accumulation model incorporating a decreasing rate of decay would be more applicable.

Relevance

This paper examines both apparent and true catotelm carbon accumulation rates in several different peat landforms found within the same peatland over the past 1200 years using pollen

concentration dating, as well as those from the entire peatland development history, spanning slightly greater than 8000 years, using radiocarbon dating. This paper also highlights the differences in methods used to determine carbon accumulation rates, and the dangers of using these rates interchangeably, which have important implications for future monitoring and research. The study found that several of the peat landforms presently at the surface are also found at various stages of the overall peatland development, allowing an attempt to link recent (0–1200 year) carbon accumulation rates with those of the same landform at different times in the past.

Citation

Robinson. (2006). Carbon accumulation in peatlands, southwestern Northwest Territories, Canada. *Canadian Journal of Soil Science*, 86(Special Issue), 305–319. https://doi.org/10.4141/S05-086

Landscape Processes

Decadal scale patterns of shoreline variability in Paulatuk, NWT, Canada

Keywords: Coastal change; Erosion; Storminess; Sea-ice; Shoreline; Landsat

Summary

Dynamic changes in shoreline position as a result of natural processes and the effects of climate variability increase the susceptibility of Arctic communities that reside along the coastal zone. The application of new geospatial approaches is critical to providing updated measurements of shoreline change, necessary for sustainable coastal management strategies. This research is an integration of geographic data demarcating shoreline position and its analysis to detect change using an updated modeling application – Analyzing Moving Boundaries Using R (AMBUR). Rates-of-change were evaluated over three time periods: long-term (1984–2016); and two short-term eras (1995–2005; 2006–2016). The short-term periods were specifically chosen to assess the influence of changing sea-ice regimes, increased storm intensity, and elevated air and sea-surface temperatures. Results indicate a significant alongshore increase in the rates of erosion and the spatial extent of land loss across both segments of the study area over the short-term. Mean annual rates of change increased over the most recent period (2006–2016) along the eastern segment (−0.34m/yr) of the study area, while the western shoreline retreated at a rate of −0.24 m/yr over the same interval. These are the highest erosion rates over any time period examined in this study. As air and ocean temperature increases continue to facilitate sea ice reduction and increased permafrost thawing, shoreline erosion may be exacerbated along the Paulatuk coastline in the coming years.

Relevance

This paper depicts the erosion rates for the coastline near Paulatuk, NWT, showing that erosion rates are generally increasing. The authors offer a series of factors that contribute to the increased erosion rates, all of which should be of interest to policymakers. The significance of this is that many Arctic communities are coastal and the lands upon which their communities lie is expected to recede. Aside from the emotional impacts this has on the communities, it forces them to adapt to the changes and establish coastal reinforcement techniques (i.e., sand bags, large boulders, etc). Moreover, their methodology offers one way to remotely monitor coastlines which can be applied to other coastal regions.

Citation

Sankar, R. D., Murray, M. S., & Wells, P. (2019). Decadal scale patterns of shoreline variability in Paulatuk, NWT, Canada. *Polar Geography, 42*(3), 196-213. https://doi.org/10.1080/1088937X.2019.1597395

Influence of ground ice and permafrost on coastal evolution, Richards Island, Beaufort Sea Coast, NWT

Keywords: Permafrost Thaw; Sea Level Rise; Coastal Retreat; Bank Stability

Summary

A long-term sediment budget (1947- 1985) for northern Richards Island shows that, when ground ice and offshore erosion are accounted for, there is a near balance between headland erosion and coastal deposition. Excess ice constitutes about 20% of the total volume of eroded material from the headlands, with massive ground ice contributing nearly 9% and segregated ice lenses and ice wedges making up the remainder. Coastal response to major storms in 1987 and 1993 suggests that erosion is episodic, with short periods of intense disruption followed by readjustment of cliff profiles. Processes characteristic of this environment include mechanical erosion of ice-bonded sediments creating unstable erosional niches, mechanical failure of niches along ice-wedge planes, and longer term thermal erosion of ice-bonded sediments. Where ice contents are high, localized thaw slumps initiated by coastal erosion may retreat at rates substantially higher than those observed at other sections of the coast. Cliff-top retreat rates may be out of phase with storm-event chronology.

Relevance

The most significant finding is the fact that the subsea permafrost has dropped by 1 meter in 50 years. In very cold regions, permafrost can exist beneath the ocean. This happens when the area was previously exposed to air, permafrost forms, and then sea level rise and cover the permafrost. With climate change, sea temperatures are warming - even in cold regions like the

arctic ocean. As a consequence, the perceived permafrost is subjected to thaw. Although the concerns surrounding erosion are minimal due to the fact that the permafrost is submerged under the ocean, trapped gases (such as methane) are still able to escape and previously frozen material is subject to decomposition. The positive note is that with the thaw of sub sea permafrost, the ground settles at a faster rate than sea level rise. This paper also links the high rates of coastal retreat in Tuktoyaktuk to storm surges and water level rise. They also note that regions of embankment with high ground ice content are particularly susceptible to erosion. Therefore, bank stability efforts should concentrate on regions with high ground ice content.

Citation

Dallimore, S. R., Wolfe, S. A., & Solomon, S. M. (1996). Influence of ground ice and permafrost on coastal evolution, Richards Island, Beaufort Sea coast, NWT. *Canadian Journal of Earth Sciences*, 33(5), 664-675. https://doi.org/10.1139/e96-050

Subsidence risk from thawing permafrost

Keywords: Permafrost Thaw; Hazard Potential; Thermokarst Terrain; NWT

Summary

The thawing and disappearance of permafrost has accelerated in recent decades, damaging buildings and infrastructure and causing public concern. Climate-change scenarios predict a marked warming at high latitudes. Instrumental records indicate that warming is underway in much of the Arctic, affecting sea ice, glaciers, vegetation and the duration of lake ice. Thawing of ice-rich permafrost can lead to subsidence and deformation of level surfaces into irregular ‘thermokarst’ terrain. Effects range from localized subsidence beneath individual structures, to deep and extensive depressions developed in response to long-term climate change.

Relevance

The authors created a geographic overview of the hazard potential associated with thawing permafrost in the northern hemisphere. They show that much of the northern hemisphere is vulnerable to ground subsistence. Much of the infrastructure erected in northern regions is in an area of high hazard potential and could be affected by thaw subsistence under conditions of global warming. Thawing of ice-rich permafrost can lead to ground subsistence and deformation of level surfaces into irregular thermokarst terrain. The effects of this process range from local, small-scale subsistence to deep and extensive depressions. Detrimental changes in permafrost conditions may evolve gradually and can be predicted and monitored, allowing for mitigation of negative consequences and avoidance of catastrophic events. This paper provides a general review of permafrost thaw as a hazard in the Arctic, not just the NWT.

Citation

Nelson, F. E., Anisimov, O. A., & Shiklomanov, N. I. (2001). Subsidence risk from thawing permafrost. *Nature, 410*(6831), 889-890. https://doi.org/10.1038/35073746

Hydrologic impacts of thawing permafrost—A review

Keywords: Permafrost Modeling; Characterization; Hydrology

Summary

Where present, permafrost exerts a primary control on water fluxes, flow- paths, and distribution. Climate warming and related drivers of soil thermal change are expected to modify the distribution of permafrost, leading to changing hydrologic conditions, including alterations in soil moisture, connectivity of inland waters, streamflow seasonality, and the partitioning of water stored above and below ground. The field of permafrost hydrology is undergoing rapid advancement with respect to multiscale observations, subsurface characterization, modeling, and integration with other disciplines. However, gaining predictive capability of the many interrelated consequences of climate change is a persistent challenge due to several factors. Observations of hydrologic change have been causally linked to permafrost thaw, but applications of process-based models needed to support and enhance the transferability of empirical linkages have often been restricted to generalized representations. Limitations stem from inadequate baseline permafrost and unfrozen hydrogeologic characterization, lack of historical data, and simplifications in structure and process representation needed to counter the high computational demands of cryohydrogeologic simulations. Further, due in part to the large degree of subsurface heterogeneity of permafrost landscapes and the nonuniformity in thaw patterns and rates, associations between various modes of permafrost thaw and hydrologic change are not readily scalable; even trajectories of change can differ. This review highlights promising advances in characterization and modeling of permafrost regions and presents ongoing research challenges toward projecting hydrologic and ecologic consequences of permafrost thaw at time and spatial scales that are useful to managers and researchers.

Relevance

This paper is a review of current research and methods in permafrost hydrology. They highlight some key limitations to current research. Near surface permafrost is highly sensitive to climate change, and as a result, water movement in the periglacial environment is different than in southern regions where there is no permafrost. Policy makers should be aware of the risks climate change poses to permafrost hydrology and how researchers are able to monitor it. As it is a relatively new field, more research is needed.

Citation

Walvoord, M. A., & Kurylyk, B. L. (2016). Hydrologic impacts of thawing permafrost—A review. *Vadose Zone Journal, 15*(6). https://doi.org/10.2136/vzj2016.01.0010

The active layer: A conceptual review of monitoring, modelling techniques and changes in a warming climate

Keywords: Active layer; CALM; Modelling; Permafrost; Transition zone

Summary

This paper provides a review of research and techniques that focus on the seasonally thawed portion of the Earth above permafrost terrain known as the active layer. The paper examines various different conceptual active layer systems, identifying five active layer types: bedrock (Type I), rock glacier or debris covered (Type II), mineral soil (Type III), organic mat or soil (Type IV) and submerged (Type V) active layer systems. These systems can be independent or mixed (frequently) in a permafrost environment, but all respond differently to climatic change or disturbance based on the thermal properties of the material and ice/water content. The review also highlights various active layer monitoring techniques including: probing, the Circumpolar Active Layer Monitoring Program (CALM) and frost tubes. Active layer modelling techniques are also reviewed, including the Stefan and the Kudryavtsev equations. In addition, the study highlights the active layer in a changing climate, examining the sensitivities of this layer to changes in temperature, precipitation and surface changes. Although the active layer has been well studied, knowledge gaps still exist including conflicting definitions between the thermal definition (0°C) and the physical definition (frozen water), which can become significant in areas with pore water that contains high levels of dissolved solids.

Relevance

This paper provides a succinct review of literature involving the active layer. The authors provide a background of current research, monitoring methods, and the effects of climate change on permafrost. In permafrost terrain, the active layer is the section of ground that directly interacts with the atmosphere and seasonally freezes and thaws. It is an important layer to consider. This paper is important to policymakers because the active layer controls sub surface water movement, plant growth, geochemical recycling, etc. The active layer is also an important component to the arctic ecosystem and therefore is worth understanding. This paper is significant because it provides a great review of literature surrounding the active layer.

Citation

Bonnaventure, P. P., & Lamoureux, S. F. (2013). The active layer: A conceptual review of monitoring, modelling techniques and changes in a warming climate. *Progress in Physical Geography*, 37(3), 352–376. https://doi.org/10.1177/0309133313478314

Archaeology / Paleontology

Climate change and the deteriorating archaeological and environmental archives of the Arctic

Keywords: Arctic; Climate change; Conservation; Heritage management; Archaeological Mitigation strategies

Summary

The cold, wet climate of the Arctic has led to the extraordinary preservation of archaeological sites and materials that offer important contributions to the understanding of our cultural and ecological histories. This potential, however, is quickly disappearing due to climate-related variables, including the intensification of permafrost thaw and coastal erosion, which are damaging and destroying a wide range of cultural and environmental archives around the Arctic. In providing an overview of the most important effects of climate change in this region and on archaeological sites, the authors propose the next generation of research and response strategies, and suggest how to capitalize on existing successful connections among research communities and between researchers and the public.

Relevance

This article provides an overview of archaeology in the Arctic, its potential, and the challenges it faces due to climate change. It presents various ways to continue progressing archaeological research in the face of climate change. The authors encourage developing methods to assess and manage climate-vulnerable sites. They emphasize the need for new funding models, staff education and recruitment, and research to support a response to face these challenges. They also highlight the need for publicising the research being done in the Arctic and the risk it faces from climate change. By creating awareness and engaging the public, we may be able to increase the financial and public support for future studies of these important sites.

Citation

Hollesen, J., Callanan, M., Dawson, T., Fenger-Nielsen, R., Friesen, T. M., Jensen, A. M., ... & Rockman, M. (2018). Climate change and the deteriorating archaeological and environmental archives of the Arctic. *Antiquity*, 92(363), 573-586. https://doi.org/10.15184/aqy.2018.8

The Arctic CHAR Project: Climate change impacts on the Inuvialuit archaeological record

Keywords: Archaeology; Climate change; Arctic; Inuvialuit; Mackenzie delta
Arctic; Archaeology; Climate change; Human–Environment Interactions; Long-term climate–culture; Interactions; Social-ecological systems; Fragility; Resilience; Human Ecodynamics; Indigenous Communities

Summary

Around the circumpolar North, archaeologists and heritage managers are growing increasingly concerned about the destruction of archaeological sites due to modern climate change. This paper describes the Arctic CHAR (Cultural Heritage At Risk) project, designed to address this issue in the Mackenzie Delta region of northwestern Canada. The Mackenzie Delta is home to the Inuvialuit, whose rich history is recorded in many coastal sites. Due to permafrost melt and increasing relative sea level, these sites are being destroyed at an alarming rate. Arctic CHAR consists of two main components: survey to assess the condition of heritage resources across the region, and excavation of the most important threatened sites.

Relevance

This paper provides a brief overview of the Arctic CHAR project. The Arctic CHAR project is especially relevant for the Northwest Territories since it is a research project focused on the archaeological sites of the Mackenzie Delta region. The paper summarizes the importance of the archaeological sites in the Mackenzie Delta and the progress of the research there. Additionally, they review the various threats that these sites face and what is being done to counteract them. This paper is important in understanding the work currently being conducted to study archaeological sites in the Northwest Territories that are being affected by climate change. It also provides an ideal template for future projects in other areas with archaeological sites under a similar threat.

Citation

Friesen, T. M. (2015). The Arctic CHAR Project: climate change impacts on the Inuvialuit archaeological record. *Les nouvelles de l'archéologie*, (141), 31-37. https://doi.org/10.4000/nda.3098

Arctic archaeology and climate change

Keywords: Climate Change; Arctic Archaeology; Methods; Indigenous Communities

Summary

An enduring debate in the field of Arctic archaeology has been the extent to which climate change impacted cultural developments in the past. Long-term culture change across the circumpolar Arctic was often highly dynamic, with episodes of rapid migration, regional abandonment, and— in some cases—the disappearance or wholesale replacement of entire cultural traditions. With their capacity to examine deeper cultural responses to climate change, archaeologists are in a unique position to generate human-scale climate adaptation insights that may inform future planning and mitigation efforts. The exceptionally well-preserved cultural and paleo-ecological sequences of the Arctic make it one of the best-suited regions on Earth to address such problems. Ironically, while archaeologists employ an exciting and highly promising

new generation of methods and approaches to examine long-term fragility and resilience in Arctic social-ecological systems, many of these frozen paleo-societal archives are fast disappearing due to anthropogenic warming.

Relevance

This review provides an overview of the relationship between climate change and the field of arctic archaeology. The Arctic has long been subject to the effects of a changing climate, preserving a record of the complex relationship between climate change and human cultural responses. By studying how premodern arctic communities around the world dealt with the challenges of climate-related uncertainty, we may be able to better address modern challenges affecting arctic Indigenous communities. This will hopefully aid generating effective solutions to the challenges faced by modern Arctic communities. However, these sites are becoming increasingly threatened by climate change-related factors. In the coming years, it will be paramount to document and protect these important sites.

Citation

Desjardins, S. P., & Jordan, P. D. (2019). Arctic archaeology and climate change. *Annual Review of Anthropology*, 48, 279-296. https://doi.org/10.1146/annurev-anthro-102317-045901

Looking back while moving forward: How past responses to climate change can inform future adaptation and mitigation strategies in the Arctic

Keywords: Climate change; Arctic; Social-ecological systems; Long-term; Resilience; Archaeology; Food security; Food safety; Human-Environment Interactions; Indigenous Knowledge; Inuit

Summary

Arctic Indigenous peoples face many interconnected pressures, not the least of which is anthropogenic climate change, which is emerging as one of the most dramatic drivers of social and economic change in recent memory. In this paper, the authors investigate whether or not insights into premodern strategies for coping with climate change—and especially the “deeper histories” of traditional ways-of-knowing—can play a useful role in future planning, management and mitigation efforts. They focus on three climate-driven challenges faced by Canadian Arctic Inuit: safe travel, food security and food safety. For each, they identify specific ways in which studies of past social-ecological systems intersect with modern climate adaptation. Ultimately, they conclude that since archaeological insights highlight the operation of decision-making processes within long-term culture-adaptive trajectories, they can offer unique insights into the much shorter-term processes currently underway.

Relevance

The changing climate has long been a central factor driving cultural development in the Arctic. This paper highlights the ways that archaeological data could become useful for future mitigation strategies of climate change effects. It provides multi-generational data on the adaptation of communities to past climate change, analogous to the challenges that many modern Arctic communities face. Although more work needs to be done, the incorporation of an archaeological perspective will be highly recommended for any future planning and mitigation efforts in the Northwest Territories.

Citation

Desjardins, S. P., Friesen, T. M., & Jordan, P. D. (2020). Looking back while moving forward: How past responses to climate change can inform future adaptation and mitigation strategies in the Arctic. *Quaternary International*, 549, 239-248. https://doi.org/10.1016/j.quaint.2020.05.043

Infrastructure / Energy

Climate change and the long-term viability of the world's busiest heavy haul ice road

Keywords: Arctic and sub-Arctic infrastructure; Busiest Heavy Haul Ice Road; Climate Uncertainties; Climate modeling; Tibbitt to Contwoyto Winter Road (TCWR)

Summary

Climate models project that the northern high latitudes will warm at a rate in excess of the global mean. This will pose severe problems for Arctic and sub-Arctic infrastructure dependent on maintaining low temperatures for structural integrity. This is the case for the economically important Tibbitt to Contwoyto Winter Road (TCWR)—the world's busiest heavy haul ice road, spanning 400km across mostly frozen lakes within the Northwest Territories of Canada. In this study, future climate scenarios are developed for the region using statistical downscaling methods. In addition, changes in lake ice thickness are projected based on historical relationships between measured ice thickness and air temperatures. These projections are used to infer the theoretical operational dates of the TCWR based on weight limits for trucks on the ice. Results across three climate models reveal a considerable warming trend over the coming decades. Projected changes in ice thickness reveal a trend towards thinner lake ice and a reduced time window when lake ice is at sufficient thickness to support trucks on the ice road, driven by increasing future temperatures. Given the uncertainties inherent in climate modelling and the resultant projections, caution should be exercised in interpreting the magnitude of these scenarios. More certain is the direction of change, with a clear trend towards winter warming that will reduce the operation time window of the TCWR. This illustrates the need for

planners and policymakers to consider future changes in climate when planning annual haulage along the TCWR.

Relevance

The authors raise concerns about the ongoing warming in the high-altitude areas of Canada. They argue that these regions are warming at a rate higher than the global average putting pressure on the region's infrastructure. According to the authors, the infrastructure of this region is highly dependent on the cold temperatures for their viability. The study also incorporates climate models which predict continued warming in the decades to come. The authors predict reduced ice cover which will consequently affect movement of heavy trucks along the road. There is also the likelihood of buildings collapsing and roads becoming impassible. To NWT policymakers, this study is an asset as they can use it to determine best practices when constructing winter roads, even with the increasing temperatures in the region.

Citation

Mullan, D., Swindles, G., Patterson, T., Galloway, J., Macumber, A., Falck, H., Crossley, L., Chen, J., & Pisaric, M. (2016). Climate change and the long-term viability of the World's busiest heavy haul ice road. *Theoretical and Applied Climatology, 129*(3-4), 1089–1108. https://doi.org/10.1007/s00704-016-1830-x

Changes in shipping navigability in the Canadian Arctic between 1972 and 2016

Keywords: Arctic shipping, Climate change, Navigability, Northwest Passage, Sea ice age

Summary

There have been rapid recent reductions in sea ice age and extent in the Canadian Arctic, but little previous analysis of how this has impacted the navigability of Arctic shipping. In this study the authors analyze how navigability changed over the period 1972–2016 by converting Canadian Ice Service ice charts to shipping navigability charts for different hull strength classifications based on the Arctic Ice Regime Shipping System. Analysis focuses on the southern route of the Northwest Passage, and the Arctic Bridge route across Hudson Bay, for changes in early-season (~25 June), mid-season (~3 September), and late-season (~15 October) conditions. Results reveal that there has been a marked easing in shipping navigability for all vessels over the past decade, driven by reductions in the area and age of sea ice, particularly across the southern route of the Northwest Passage. Both medium (Type B) and little (Type E) ice strengthened vessels were able to transit the full length of this route in the middle part of the shipping season in 2012–2016, but not in 1972–1976 or 1992–1996.

Relevance

This study looks into changes in the age and extent of ice cover in the Canadian Arctic that has impacted navigability. According to the authors, between 1990 and 2015, total navigable distance tripled and vessels with low hull strengthening became more preferred. The report notes that there is a significant increase in the ease of navigation across the Canadian Arctic with melting ice. However, they point to barriers to navigation for different vessel types with Type E vessels seeing increased access with time. The study warns of existent navigational risks and hazards. They note that even though navigation is easing, ice conditions remain unpredictable and poor planning can create disasters for vessels. Such findings can be used by policymakers and decisionmakers in their planning to ensure they are aware of the existing risks and try to mitigate them. Through such reports, the GNWT policymakers can come up with policies that consider the risks present and try to avert them. Policymakers should also begin to think about the socio-economic changes increase navigability may bring to the NWT.

Citation

Copland, L., Dawson, J., Tivy, A., Delaney, F., & Cook, A. (2021). Changes in shipping navigability in the Canadian Arctic between 1972 and 2016. *Facets 6*(1), 1069-1087. https://doi.org/10.1139/facets-2020-0096

Impact of 1, 2 and 4 °C of global warming on ship navigation in the Canadian Arctic

Keywords: Arctic Bridge; Climate Model Simulations; Changing Navigability; Coastal Community; Northwest Passage, Shipping Traffic, Trade Routes

Summary

Climate change-driven reductions in sea ice have facilitated increased shipping traffic volumes across the Arctic. Here, the authors use climate model simulations to investigate changing navigability in the Canadian Arctic for major trade routes and coastal community resupply under 1, 2 and 4 °C of global warming above pre-industrial levels, on the basis of operational Polar Code regulations. Profound shifts in ship-accessible season length are projected across the Canadian Arctic, with the largest increases in the Beaufort region (100–200 d at 2 °C to 200–300 d at 4 °C). Projections along the Northwest Passage and Arctic Bridge trade routes indicate 100% navigation probability for part of the year, regardless of vessel type, above 2 °C of global warming. Along some major trade routes, substantial increases to season length are possible if operators assume additional risk and operate under marginally unsafe conditions. Local changes in accessibility for maritime resupply depend strongly on community location.

Relevance

Especially in the post-COVID-19 pandemic period, economic recovery will prove essential to many regions around the world. This article looks into how changes in climate and temperature

by 1, 2, and 4 degrees celsius above the global average can impact navigability in the Arctic region. The article finds that reduced sea-ice directly causes an increase in navigation which leads to increased access to natural resources such as mines and fisheries. To NWT policymakers, this article opens an avenue for knowledge that explains what could be done to make the NWT more economically stable. Whereas other studies point to challenges of global warming, this article points to an opportunity in the same due to improved trade and transport in the region. This finding is relevant to policymakers in NWT as they can use them to exploit the effects of the changing climate in a positive way. This can be done through formulating policies that take advantage of increased navigability to connect the communities. The GNWT can also implement the recommendations in the journal article including replica research findings to augment the findings of this study and give ideas on how the challenge of climate change can be treated as an opportunity.

Citation

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The Impact of climate change on infrastructure in the Western and Central Canadian Arctic

Keywords: Climate-Induced Change; Infrastructure Sensitivity; Inuvialuit Settlement Region; Kitikmeot Region

Summary

The stability and safety of infrastructure in the Inuvialuit Settlement Region (Yukon North Slope and Northwest Territories) and the Kitikmeot region (Nunavut) are of central concern to residents, governments, and industry. Infrastructure sensitivity occurs through climate-induced change in three key areas: permafrost, hydrology and coastal conditions. Permafrost is especially susceptible to changing climate, particularly where near-surface excess ice occurs. Melting of ice and associated thaw subsidence may induce instability of various infrastructure components. Additionally, land-use changes may alter drainage patterns, with effects on infrastructure that can range from expensive repairs to failure. Hydrological changes will alter seasonal flow peaks and stress drainage infrastructure. In the coastal sector, decreased sea ice has already resulted in increased wave activity. Rising temperatures and storm waves influence coastal retreat, particularly where erosion exposes massive ground ice and the combined effects of thermal and mechanical erosion occur. Projected changes in relative sea level (RSL) in the western part of the region may increase the impact of wave erosion and thermal abrasion on coastal retreat and infrastructure. Sea level is already rising in most Inuvialuit communities and a switch from falling to rising RSL in the Kitikmeot region may increase coastal hazards there. Rising sea levels lead to higher storm-surge flooding, more frequent exceedance of historical flood levels, inundation of low-lying land, and higher wave action on eroding shores. Accelerated coastal retreat has been documented on parts of the Alaska North Slope and the

emerging evidence points to some areas of acceleration in the Canadian Beaufort region. Knowledge about the presence of ground ice and thaw-sensitive terrain, hydrological trends, sea-level rise, and coastal processes and hazards will provide the means to design appropriate infrastructure and minimize potential risk. New planning and design standards are emerging to help local decision makers improve the resilience of infrastructure, and educational initiatives are seeking to improve community knowledge of risks to infrastructure and other community assets.

Relevance

Lamoureux et al. (2015) have findings that are handy to NWT and GNWT policymakers. It sheds light on the effects of climatic changes on infrastructure in the Western and Central Canadian Arctic. Permafrost, hydrology, and coastal conditions are identified as the primary areas of concern in which infrastructure is affected by climate change. According to the authors, the integrity of infrastructure in these regions is undermined by melting ice caused by rising temperatures. Changes in drainage patterns caused by shifts in land uses are also another cause of infrastructural instability. Hydrological changes have the potential to put pressure on the drainage system. The report adds that awareness of the presence of permafrost, hydrological factors, rising sea levels, and coastal hazards can inform future infrastructural designs and minimize risks. To policymakers in the region, the report is a call to action for them to consider climatic and environmental factors in the decision-making processes about design of infrastructure in these regions.

Citation

Lamoureux, S, Forbes, D, Bell, T, Manson, G. (2015). The Impact of Climate Change on Infrastructure in the Western and Central Canadian Arctic. *ArcticNet.* https://bit.ly/3NNVIaZ

Impacts of historical and projected climate changes on ice surfaces of the Tibbitt to Contwoyto winter road, Northwest Territories, Canada

Keywords: Atmospheric Reanalysis; Climate model; Ice Cover/Phenology NWT; TCWR (Tibbitt to Contwoyto Winter Road; Winter Road

Summary

Seasonal ice and winter roads are a historically important part of the Canadian arctic transportation network. Constructed over frozen lakes, rivers, permafrost zones, and seasonally frozen ground, the roads service rural and Indigenous communities and resource extraction projects which are otherwise fly-in only for the rest of the year. The Tibbitt to Contwoyto Winter Road (TCWR) is one of the most economically significant and heavily used roads, running from outside of Yellowknife, Northwest Territories, to Contwoyto Lake, Nunavut, connecting three of Canada's largest diamond mines, with a fourth project set to open on route by 2017. The TCWR

has been constructed annually since 1982 as a joint venture between mine operators Diavik Diamond Mines Inc., BHP Billiton Diamonds Inc., and DeBeers Canada Inc., and requires a minimum ice thickness of 0.7 meters to begin operations, with an average open season of 67 days. Current projections suggest an arctic amplification of the global climate warming signal, as well as changes to arctic precipitation patterns. Both have the potential to alter lake ice conditions, with economic impacts for the long-term viability of ice roads for moving mine supplies north via land. This thesis uses a one-dimensional thermodynamic lake ice model (Canadian Lake Ice Model – CLIMo), forced with atmospheric reanalysis data (ERA-Interim) to simulate historical ice conditions, as well as regional climate model outputs (Canadian Regional Climate Model – CRCM 4.2.0), to make near-future projections for ice phenology and thickness trends. Models suggest that climatic changes in the arctic, primarily warming surface air temperatures, could pose a threat to continued operations of the TCWR. CLIMo simulations for future climate scenarios project later ice-on dates by up to 11 days later in the calendar year, ice-off events occurring up to 14 days earlier in the spring, and a net decrease in the ice cover season by up to 25 days (after v rounding), when computed as the difference between the 1961-1990 baseline and 2041-2070 future period. While winter ice cover is unlikely to disappear entirely in the near future, the number of days where the ice surface is consistently above the 0.7 meter threshold for safe operations may decrease to the point where it no longer becomes economically feasible to build the road and transport materials via land.

Relevance

Zell (2014) gives insights into the past and forecasted climate changes expected on ice surfaces of the TCW Road in the NWT. The author notes the importance of seasonal ice for winter roads regarding TCWR. Warming surface air temperatures threaten the usability of TCWR; ice cover and thickness have decreased; and a delay in ice-on dates alongside accelerated ice-off events. In the future, Zell projects a decrease in ice thickness and a decrease in the number of days for TCWR usability. The government and policymakers of NWT can exploit such findings by creating legislations and policies that align with the projections. The anticipated challenges can help policymakers to brace for such changes and hence, create counter-policies to confront the challenges.

Citation

Zell, E. (2014). Impacts of historical and projected climate changes on ice surfaces of the Tibbitt to Contwoyto Winter Road, Northwest Territories, Canada. University of Waterloo. University of Waterloo. https://bit.ly/3AwFO1Q

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