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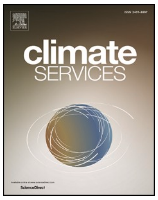

Developing user-informed fire weather projections for Canada

Laura Van Vliet [a], Jeremy Fyke [a,b,*], Sonya Nakoneczny [a], Trevor Q. Murdock [a], Pouriya Jafarpur [a]

[a] *Canadian Centre for Climate Services, Environment and Climate Change Canada, 200 Sacré-Coeur Blvd., Gatineau, QC J8X 4C6, Canada*
[b] *Department of Geography, Simon Fraser University, 8888 University Drive, Burnaby, BC V5A 1S6, Canada*

HIGHLIGHTS

- Novel fire weather projections based on bias adjusted regional climate model output.
- Substantial, robust increases in fire weather projected across most of Canada.
- User feedback informed product development and delivery mechanism.
- Fire weather projections available at https://climatedata.ca/fire-weather/.

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ABSTRACT

Increasing fire danger due to climate-driven fire weather changes has expanded demand for projections of future wildfire information for Canada. Addressing this need, we developed "CanLEAD-FWI," consisting of novel, high-resolution projections of fire weather and an associated user-facing climate services delivery mechanism. Based on the Canadian Forest Fire Weather Index (FWI) System (Van Wagner, 1987) with multivariate bias-adjusted output from the CanLEAD-CanRCM4-EWEMBI large ensemble (Cannon et al., 2021), CanLEAD-FWI provides various wildfire-relevant indicators. Comparison against two gridded observation-based datasets provides an estimate of observational uncertainty in historical FWI System component extremes, with historical CanLEAD-FWI generally situated between these two datasets. Over the 21st century, CanLEAD-FWI projects substantial, robust increases in the severity and frequency of high fire weather and a lengthening fire season across much of Canada, although the magnitude and spatial extent of increases depend on the metric and FWI System component.

To enhance data utility for decision-making and consider diverse user needs, we integrated two rounds of user engagement into product development. A web-based application was designed to address user feedback, support best practices, and reduce decision overload. CanLEAD-FWI addresses a growing need in the Canadian climate services space for both projected climate impact data and associated training and support. By combining user feedback, best practices for climate services, and expert knowledge, we aim to enhance the appropriate integration of fire weather information into long-term decision-making.

Practical implications

Increasing fire danger due to climate-driven fire weather changes (Kirchmeier-Young et al., 2017; Philip et al., 2022) is quickly becoming one of Canada's top climate change hazards (Canada's Top Climate Change Risks, 2019; Hoffman et al., 2022), and has

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Abbreviations: BC, British Columbia; BUI, Buildup Index; CanLEAD, see CanLEAD-CanRCM4-EWEMBI; CanLEAD-CanRCM4-EWEMBI, Canadian Large Ensembles Adjusted Dataset version 1, CanRCM4 simulations bias adjusted to EWEMBI; CanLEAD-FWI, Novel fire weather projections based on the CanLEAD dataset; FWI System, Canadian Forest Fire Weather Index System; DC, Drought Code; DMC, Duff Moisture Code; DSR, Daily Severity Rating; FFMC, Fine Fuel Moisture Code; FWI, Fire Weather Index; ISI, Initial Spread Index; RCP, Representative Concentration Pathway.

* Corresponding author at: Canadian Centre for Climate Services, Environment and Climate Change Canada, 200 Sacré-Coeur Blvd., Gatineau, QC J8X 4C6, Canada.

E-mail address: jeremy.fyke@ec.gc.ca (J. Fyke).

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driven growing demand for applicable, easily accessible, fire weather projections to support climate risk assessment and adaptation needs. However, until now, user-oriented projections of future fire weather conditions have not been readily available to potential users.

To address this gap, we developed a new suite of fire weather projections for Canada extending to 2100, hereafter “CanLEAD-FWI”. CanLEAD-FWI is based on the Canadian Forest Fire Weather Index (FWI) System (Van Wagner 1987), a major subsystem of the Canadian Forest Fire Danger Rating System (Stocks et al., 1989) used extensively by fire management agencies to assess and predict fire danger (Wotton, 2009). The FWI System translates four meteorological controls of fire weather – temperature, relative humidity, wind speed, and precipitation – into six standard components that quantify the meteorological contribution to overall fire danger. CanLEAD-FWI is based on input data from CanLEAD-CanRCM4-EWEMBI (CanLEAD; Cannon et al. 2021), a 50-member single model initial-condition large ensemble developed using the Canadian Regional Climate Model Version 4 (CanRCM4; Scinocca et al., 2016) bias-adjusted to the EWEMBI observational dataset (Frieler et al., 2017; Lange, 2019). CanLEAD was selected because it met the input data requirements of daily temporal resolution, suitable spatial resolution, multivariate-adjustment to an observation-based product, and included all FWI System-required input variables. Furthermore, the large ensemble provides a strong statistical basis (Maher et al., 2021) for estimating fire weather condition shifts. However, CanLEAD is a single-model, single-scenario ensemble (under Representative Concentration Pathway 8.5 [RCP8.5]; van Vuuren et al., 2011), and the approximately 50 km by 50 km resolution remains insufficient over topographically complex regions. To address this, an additional bias-adjustment to historical station-based FWI System observations was undertaken at station locations. To allow for consideration of multiple emissions scenarios, RCP-translation based on global warming levels (Sørland et al., 2020) was used to “construct” RCP2.6 and RCP4.5 from CanLEAD-provided RCP8.5.

Under constructed-RCP4.5 and RCP8.5, CanLEAD-FWI indicates substantial, robust (change greater than internal variability) increases in the frequency and severity of high fire weather conditions as well as a lengthening of the fire season across most of Canada by the end of the 21st century. The severity of high fire weather conditions is represented by the 95th percentile of daily Buildup Index (BUI) values in the May through September central wildfire season (BUIp95). Absolute change in BUIp95 and in the frequency of “high” BUI (BUI $\geq$ 60) days is greatest in southwestern and central Canada. Excluding northern regions with low baseline fire weather conditions, percentage change in fire weather severity is also greatest in southwestern Canada (British Columbia coast and interior), with increases of greater than 100 % in BUIp95 for parts of coastal British Columbia. No robust change or minor decreases in fire weather metrics are projected for some regions in northwestern Canada, where projected increases in precipitation and relative humidity in CanLEAD offset the influence of warming. This region also showed mixed results and low model agreement in previous studies (e.g., Abatzoglou et al., 2019; Quilcaille et al., 2023; Wang et al., 2015, 2017).

To facilitate the use of these data in decision-making and in consideration of the diverse user needs for fire weather information (e.g., McFayden et al., 2023), we integrated two rounds of user engagement into product development. Preliminary user engagement confirmed that the FWI System is the major tool used by Canadian wildfire experts to assess fire weather. Thus, it was important that CanLEAD-FWI be presented through the FWI System. However, users also highlighted that fire weather does not directly translate to fire activity, as the FWI System does not directly integrate information on ignition sources, local wildfire fuel availability, or other factors on potential fire behaviour. Thus, local hazard information and interpretation are required, and certain FWI System components and thresholds were indicated as more relevant depending on the region, season, fire behaviour information of interest, or other factors. Product testing within the second round of user engagement revealed the potential gap between CanLEAD-FWI-provided information and decision-making for users concerned about wildfire danger but unfamiliar with the FWI System. Feedback from both rounds of user engagement underscored the importance of providing tiered, tailored FWI System-based information to support different users.

The complexity of the product necessitated thoughtful delivery to address both the needs of wildfire experts and general practitioners. We developed a web-based application (https://climatedata.ca/fire-weather/), which provides flexible, responsive features to meet this range of needs. Integrated design features were developed to support best practices and reduce decision-overload for all users while also providing detailed projections for wildfire experts. These include: (1) Quick Start and Deep Dive sections providing two levels of complexity depending on user expertise, (2) a subset of indicators presented on the Quick Start to highlight the most intuitive and highest confidence metrics, (3) gridded data available for regional assessments, with station-based results bias-corrected to observations for expert users interested in customizable thresholds, (4) presentation of three scenarios through RCP-translation based on global warming levels, (5) guidance on interpretation of fire weather and climate change impacts, and (6) connection to an existing climate services help desk to support users in accessing, understanding, and appropriately applying the data.

CanLEAD-FWI speaks to a growing need in the Canadian climate services space for both projected climate change information and associated training and support. By including user feedback combined with expert knowledge and best practices for climate services, we aim to enhance the integration of fire weather information into long-term decision-making.

Introduction

Canada contains nine percent of the world’s forests, along with vast tracts of grasslands. Traditionally, fire has played an important ecological role in this landscape and has been central to Indigenous stewardship practices (Lake and Christianson, 2019). However, large, uncontrolled wildland fires (“wildfires”) have developed into one of Canada’s largest climate-influenced hazards (Hoffman et al., 2022). Such wildfires consume millions of hectares of forest each year and influence a significant fraction of the total Canadian land area. Most Canadian communities have some fraction of their spatial footprint closely embedded within naturally fire-prone landscapes; in total, wildland-urban interface (WUI) zones cover nearly 14 % (842 million hectares) of Canada (Johnston and Flannigan, 2018). For communities, infrastructure and industry in this WUI, wildfire presents a pervasive risk that is modulated by weather and climate, availability of fuels, and the presence of fire ignition mechanisms (Hoffman et al., 2022). Damages from wildfire events can be devastating and long-lasting (e.g., Regional Municipality of Wood Buffalo, n.d.). Recent large wildfire events demonstrate the large effects of wildfire on regional water quality (Emmerton et al., 2020), continental-scale air quality (Buchholz et al., 2022), population displacements (Anchan, 2023), economic damages (Bouchard et al., 2023), culture, and mental health (Brown et al., 2019; Dodd et al., 2018). Wildfires also have disproportionate impacts on Indigenous peoples. For example, 42 % of wildfire evacuations affect First Nation reserves or communities with largely Indigenous populations, however, these communities make up only 5 % of Canada’s population (Environment and Climate Change Canada, 2023).

Recent wildfire activity in Canada is also notable in that event-motivated retrospective detection and attribution analyses have shown human-caused climate change to be a wildfire risk multiplier. For example, Kirchmeier-Young et al. (2017) identified an anthropogenically-derived 1.5-to-6-fold increase in the likelihood of extreme wildfire-conducive meteorological conditions (“fire weather”) in Western Canada. Philip et al. (2022) found that the regional extreme temperatures responsible for the Lytton Creek wildfire in British Columbia (BC; Canada) would have been at least 150 times less likely in the absence of human-induced climate change. The observed trend towards extreme Canadian fire weather conditions will continue as the climate changes (Wang et al., 2017, 2020; Wotton et al., 2017).

Increasing fire danger due to climate-driven increases in extreme fire weather has motivated inclusion of wildfire considerations in national, provincial/territorial, and local climate risk assessments and adaptation planning in Canada (2030 NWT Climate Change Strategic Framework 2019–2023 Action Plan, 2018; Canada's Top Climate Change Risks, 2019; Vernon Climate Action Plan, 2021; Tymstra et al., 2020). However, a considerable gap still exists between this recognition of the importance of considering climate change-driven increases in wildfire danger and the availability of applicable future fire weather information. For example, currently available future projections of fire weather (Gaur et al., 2021; Park et al., 2023; Quilcaille et al., 2023; Wang et al., 2020, 2017a; Wotton et al., 2017), while extremely valuable for their intended objectives, tend to aggregate over regions that are too large to support adaptation decision-making, are limited to select demonstration locations, describe metrics of change that are not closely aligned with decision-making, or are provided via data delivery methods that are not familiar to fire management practitioners and the public. This usability gap, between scientific information and decision-maker needs, is a common theme in many applied climate impact initiatives (Baulenas et al., 2023; Beier et al., 2017; Boon et al., 2022; Findlater et al., 2021; Palutikof et al., 2019). It is a challenge that must be overcome if fire weather projections are to be integrated into wildfire management practices and adaptation planning across the country.

Motivated to narrow this gap, we present here a new user needs-driven fire weather projections dataset and associated climate services delivery mechanism: CanLEAD-FWI (Version 1.0). The goal of CanLEAD-FWI is to provide user-oriented information on future changes in Canadian Forest Fire Weather Index (FWI) System components (Van Wagner, 1987). The FWI System translates four key meteorological regulators of fire weather – temperature, relative humidity, wind speed, and precipitation – into a series of codes and indices used extensively by Canadian wildfire practitioners and others to quantify the meteorological contribution to overall fire danger (e.g., McElhinny et al. 2020; Jain et al. 2020; Wang et al. 2020). By basing CanLEAD-FWI on the FWI System, we intend to provide a climate change fire weather resource that can be integrated into established wildfire preparedness and long-term wildfire planning processes. To consider diverse user needs and enhance the pathway to decision-making, we incorporated two rounds of user engagement into product development, connecting with both fire weather experts and general practitioners. This user feedback was considered throughout development and integrated with climate services best practices to enhance product useability. We hope this will increase the appropriate integration of CanLEAD-FWI into long-term decision-making.

In this paper, we describe the development and deployment of the CanLEAD-FWI product. We first provide a detailed account of the FWI System (Section 3.1) and CanLEAD-FWI dataset methodologies (Sections 3.2 and 3.3). We then summarize the user engagement that played a central guiding role in data and delivery mechanism development (Section 3.4). The results and discussion (Section 4) provides an assessment against historical FWI System observations (Section 4.1), CanLEAD-FWI projected changes (Section 4.2), and user engagement results and user-informed product delivery (Section 4.3).

Methods

Overview of the Canadian forest fire weather index system

The Canadian Forest Fire Danger Rating System (CFFDRS; Stocks et al., 1989) is the primary system used by Canadian wildfire management agencies to operationally assess and predict key factors of fire danger and inform decision-making (Wotton, 2009). The FWI System is a major subsystem of CFFDRS, and has been used in Canada since 1970 to account for the effects of weather on fire danger (Van Wagner, 1987). The FWI System includes six standard indicators that describe different aspects of fuel dryness and potential fire behaviour (Fig. 1). The first three are based on different combinations of temperature, precipitation, wind, and relative humidity, and represent fuel moisture within three distinct layers of the forest floor assuming a "standard" pine forest: the Fine Fuel Moisture Code (FFMC) represents moisture in the surface litter layer and is related to the probability for sustained litter-layer ignition (flaming) and human-caused fire occurrence; the Duff Moisture Code (DMC) represents the moderate depth layer, which exhibits a strong control on lightning ignition; and the Drought Code (DC) represents the deep, compact organic layer and is related to the depth of burn, difficulty in extinguishing smouldering fires, and potential for holdover fires (Hanes et al., 2021; Wotton, 2009). The next three indices combine fuel moisture codes and additional wind information to represent potential fire behaviour: the Buildup Index (BUI) represents the potential fuel available for combustion; the Initial Spread Index (ISI) represents the potential ability of fire to spread without considering fuel type or quantity; and the Fire Weather Index (FWI) represents the potential frontal fire intensity (Van Wagner, 1987). An optional additional index, the Daily Severity Rating (DSR) is an exponential form of FWI that more accurately represents the non-linear difficulty in suppressing fires (Van Wagner, 1987). FWI System components increase as fuel moisture decreases and/or fire danger increases in response to higher temperatures, higher wind speeds, lower precipitation, and/or lower humidity.

FWI System components are calculated daily, with the current version of the FWI System formulated to accept daily accumulated precipitation and local noontime values of temperature, relative humidity, and wind speed. FWI System fuel moisture codes build on the previous day's conditions to account for the cumulative nature of daily weather on fuel moisture. The different effective memory of each fuel moisture code (Fig. 1) reflects their relative exposure and sensitivity to weather.

As a set of indicators based solely on meteorological conditions, the FWI System does not integrate information on ignition events (e.g., lightning strikes or human-caused ignitions), local wildfire fuel, or local topographic influences on potential fire behaviour. Thus, to develop a full view of wildfire danger, information from the FWI System must be combined with additional information about these factors (as done in other CFFDRS subsystems). For more information on the FWI System and interpretation see Wotton (2009) and Van Wagner (1987).

Gridded fire weather projections

To develop CanLEAD-FWI, we undertook the following steps: 1) identified a suitable input climate dataset; 2) pre-processed this dataset to align with FWI System assumptions; 3) configured "overwintering" methods for FWI System calculations; and 4) processed the input climate dataset through FWI System calculations and summarized using relevant statistics. These steps are described in the following sections.

Input dataset identification: CanLEAD

To develop FWI System projections suitable for regional climate impact assessment, an input dataset was required with (1) daily time series, (2) temperature, precipitation, relative humidity, and wind speed, and (3) relatively fine spatial scales. CanLEAD-CanRCM4-EWEMBI (hereafter "CanLEAD", Cannon et al., 2021) was identified as it satisfies all three conditions. This dataset is based on the Canadian Earth System Model Version 2 single model initial-condition large ensemble (CanESM2-LE; Arora et al., 2011) driven by historical (1950–2005) and upper-bound Representative Concentration Pathway 8.5 (RCP8.5, 2006–2100) scenario forcing (van Vuuren et al., 2011). Each CanESM2-LE member was dynamically downscaled to 0.44° (~50

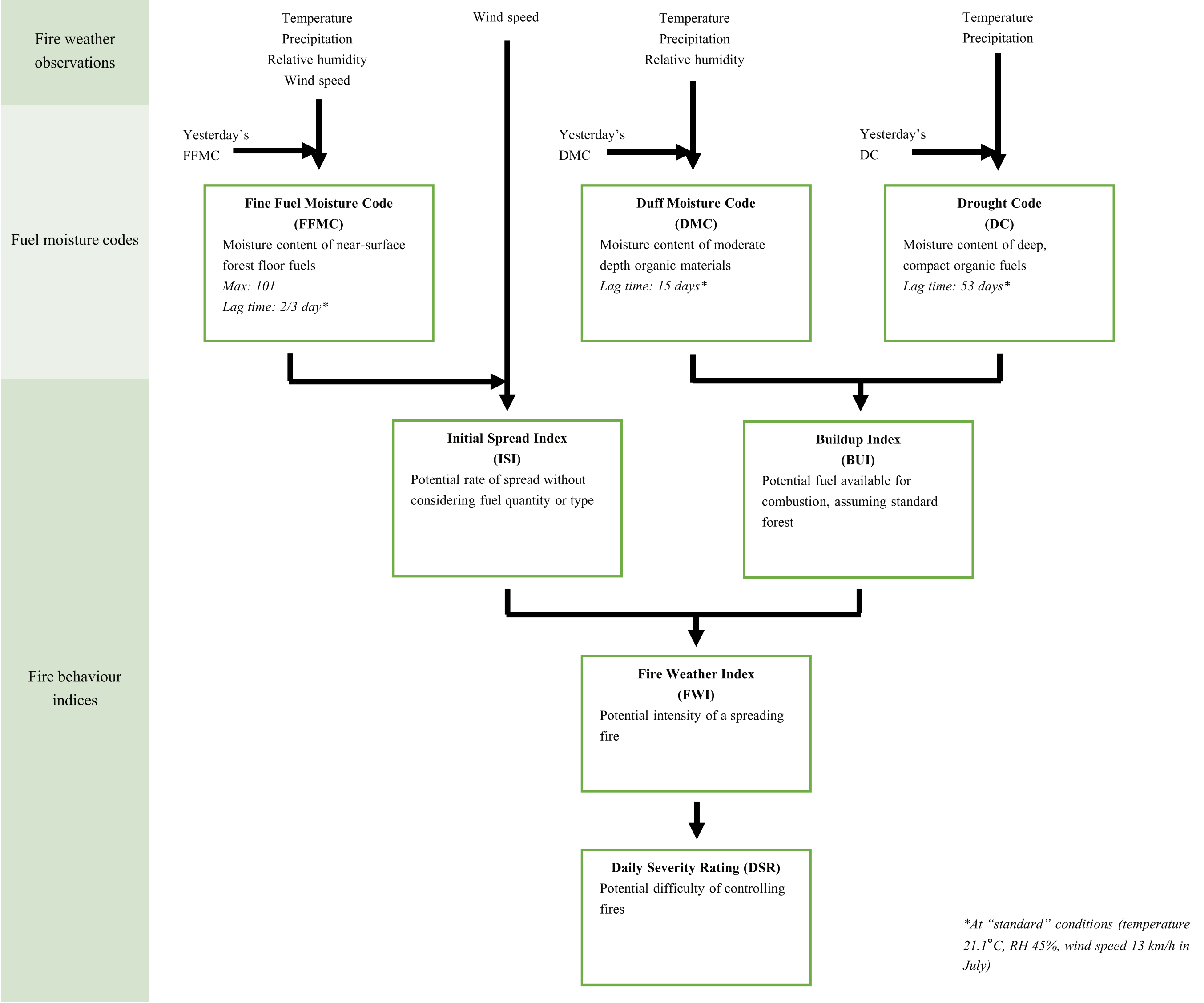

Fig. 1. The Canadian Forest Fire Weather Index System and input variables, modified from Lawson and Armitage (2008). Descriptions for each fuel code and fire behaviour index are taken from (NRCan, n.d.). Fuel code memory (time lag) information from Lawson and Armitage (2008).

km) resolution using the Canadian Regional Climate Model Version 4 (CanRCM4; Scinocca et al., 2016). Next, CanRCM4-simulated near-surface minimum and maximum daily temperatures as well as daily average precipitation rate, relative humidity, and wind speed, were adjusted using multivariate bias correction (Cannon, 2018) to the observationally constrained EWEMBI dataset (Frieler et al., 2017; Lange, 2019) after interpolation to a 0.5° latitude/longitude grid (NAM-44i).

Selection of CanLEAD involved consideration of strengths and weaknesses relative to other candidates and FWI System requirements. CanLEAD strengths include:

- A 50-member single model large ensemble, which provides a strong statistical basis (Maher et al., 2021) for estimating fire weather condition shifts and quantifying natural variability.
- Dynamical downscaling to relatively high spatial resolution, critical for assessment of regional fire weather changes (Bedia et al., 2015, 2013), and available at daily time resolution.
- Multivariate bias correction of FWI System input variables to an observational product.
- Consistency with previous Canadian climate impact assessments which employ CanRCM4 (Cannon et al., 2020) and supported by evaluations of CanLEAD (Singh et al., 2022).

Drawbacks of CanLEAD include:

- A single driving global model (CanESM2) and regional model (CanRCM4).
- A single driving climate scenario (RCP8.5).
- A 0.5° grid resolution, while much improved compared to global climate model projections, remains more coarse than ideal over topographically complex regions of Canada.
- Daily data is not provided at local noon as required by the FWI System.

These drawbacks are partially addressed by the methods described below.

CanLEAD data preprocessing for use in the FWI System

As detailed above, CanLEAD provides daily maximum temperature (T_{max}) and minimum temperature (T_{min}), as well as daily mean values of relative humidity (RH_{mean}), wind speed (WS_{mean}), and precipitation rate. However, FWI System algorithms are based on local noontime (instantaneous or 10 min) values of all variables except precipitation. WS_{mean} is typically less than, and RH_{mean} is typically greater than, their noontime counterparts. If used directly as FWI System inputs, both would bias towards underestimation of CanLEAD-FWI values. In contrast, using T_{max} would bias towards CanLEAD-FWI overestimates relative to using noontime values. To minimize these effects, adjustments were undertaken (where possible) on CanLEAD variables prior to use within the FWI System, as summarized below and in Table 1:

- Local noontime temperature was estimated from CanLEAD T_{max} and T_{min} (Beck and Trevitt, 1989). This improved on approaches taken in previous studies without access to noontime temperature, which used either T_{max} (Abatzoglou et al., 2019; Gallo et al., 2023) or T_{mean} (Fargeon et al., 2020). Noontime temperature adjustment reduced the spatially averaged climatological bias when compared to observations. See Supplementary Materials Fig. S-1 (hereafter Fig. S-1).
- Local noontime relative humidity was estimated from T_{max}, T_{min}, RH_{mean}, and noon-adjusted temperature (Allen et al. 1998, chap. 3; Beck and Trevitt 1989). This improved on approaches taken in previous studies without access to noontime relative humidity, which either used RH_{mean} (Park et al., 2023; Quilcaille et al., 2023) or daily minimum relative humidity (Abatzoglou et al., 2019; Gallo et al., 2023).
- Adjustment of WS_{mean} to noon WS was not feasible without additional information (e.g., distribution parameters; Förster et al., 2016; Tobin et al., 2015). Thus, WS_{mean} from CanLEAD was used, following previous work (Bedia et al., 2014; Wotton et al., 2017).
- For precipitation, we converted the CanLEAD mean daily precipitation rate (kg/m/s) to total daily amount (mm) assuming a water density of 1000 kg/m^3.

For further details on adjustments see Supplementary Materials Section A.1 (hereafter Section S-A.1).

Fire season and overwintering

By convention, FWI System calculations are stopped at the end of significant wildfire conditions ("winter") and restarted the following spring. We determined fire season start and end following Wotton and Flannigan (1993). "Overwintering" begins on the fourth day following three consecutive days with $T_{max} < 5$ °C. All calculations of FWI System codes are halted until spring start-up. Spring start-up begins on the fourth consecutive day following three days with $T_{max} > 12$ °C. In the spring, fuel code values are reset to default start-up values or set via overwintering calculations. We determined spring start-up fuel codes as follows:

- FFMC is set to 85 (Lawson and Armitage, 2008).
- DMC is set to 6 (Lawson and Armitage, 2008).
- DC is calculated via the total overwinter precipitation following Lawson and Armitage (2008). Following Hanes and Wotton (2024), a value of 1.0 was used for the carry-over fraction (of last autumn's moisture) and a value of 0.5 was used for the wetting efficiency fraction (effectiveness of winter precipitation in recharging moisture reserves).

Table 1
Summary of required input variables for the FWI System, corresponding CanLEAD-provided variables, and CanLEAD-FWI inputs.

FWI System-required inputs (local time)	CanLEAD-provided outputs (UTC)	CanLEAD-FWI inputs
Noontime temperature	Daily minimum and maximum temperature	Noon-adjusted temperature (local time)
Noontime relative humidity	Daily mean relative humidity	Noon-adjusted relative humidity (local time)
Noontime wind speed	Daily mean wind speed	Daily mean wind speed (UTC)
Daily total precipitation (12 h to 12 h)	Daily mean precipitation rate (00 h to 24 h)	Daily total precipitation (00 h to 24 h, UTC)

For Arctic regions, implementation of winter shutdown/spring start-up may result in some years not experiencing a fire season; the required temperature thresholds are never exceeded. Conversely, some regions of southern coastal BC may never experience a winter shutdown.

Gridded CanLEAD-FWI and metrics of change

CanLEAD-FWI was calculated in Python using the xclim 0.39.0 (Logan et al., 2022) implementation of FWI System algorithms, with inputs detailed in Table 1 and following the fire season and overwintering procedures detailed in Section 3.2.3. Prior to using the xclim-based FWI System implementation, we undertook quality control to ensure similarity of results relative to an R-based FWI System code base (Wang et al., 2017b).

CanLEAD-FWI provides daily values of all FWI System components for 1950–2100. Codes and indices are only calculated during the fire season; no values are returned during overwintering periods. The spatial domain was clipped to the Canadian land area excluding the Northern Arctic ecozone (Ecological Stratification Working Group, 1996).

We calculated relevant annual metrics from daily CanLEAD-FWI (Table 2), informed in part by engagement activities with fire management practitioners. Metrics focussed on indicators of change in the frequency and severity of high fire weather conditions, which are more strongly correlated with fire activity than average quantities (Wotton, 2009). Two threshold-based parameters count the annual number of days that exceed the two highest classifications of Canadian Forest Service (CFS) fire weather climatologies (Natural Resources Canada, n.d.), which we name "high" or "very high" fire danger. However, regionally defined thresholds for "extreme" BUI conditions vary from 60 (e.g., Ontario, Nova Scotia) to over 200 (parts of BC). Seasonal mean and percentile values of FWI System components (e.g., 95th percentile) are consistent with previous research (e.g., Wang et al. 2015; Fargeon et al. 2020). These seasonal metrics were calculated for the May to September (MJJAS) period, the approximate central fire season. Days within this period that are not considered to be within the fire season, as defined by the overwintering criteria, were set to zero to maintain a consistent sample size over the 21st century. The lengthening of the fire season is represented by the fire season length metric, following Wotton and Flannigan (1993). Full definitions of fire weather change metrics are provided in Table 2.

For each metric, we assessed change as robust when the absolute value of the climatological change from the reference period (1971–2000) (the signal) exceeded the intra-ensemble standard deviation of the reference period climatologies (the noise), that is, when the signal-to-noise ratio (SNR) exceeded one (e.g., Abatzoglou et al., 2019). Using SNR is conceptually similar to, but less sensitive than, classical statistical measures (e.g., *t*-test), with later emergence of robust changes

Table 2
List of fire weather change metrics calculated from CanLEAD-FWI daily data and their definitions. Metrics are labeled here for BUI but were calculated for each FWI System component (FWIp95, ISIp95, etc.). This applies to all metrics except fire season length. To see thresholds used for exceedance of "high" and "very high" fire danger for other components, see Figs. S-6 and S-7.

Metric code	Definition
BUIp95	95th percentile of daily BUI in the MJJAS season.
BUI60	Count of days per year with BUI values at or above 60 ("high").
BUI90	Count of days per year with BUI values at or above 90 ("very high").
BUI_{mean}	Mean BUI of the MJJAS season.
FSL	Annual count of days in the fire season, as defined in Section 3.2.3.

based on SNR > 1 (Fyke et al., 2014).

"Constructed scenarios" through RCP-translation

As described in Section 3.2.1, CanLEAD-FWI employs a single model large ensemble and a single scenario, which does not directly address emissions scenario or climate model uncertainty. Presenting projected impacts by global warming level (GWL) is an increasingly common means to circumvent issues of scenario uncertainty for the purposes of climate communication (e.g., Cannon et al., 2020; Gutiérrez et al., 2021; Sobie et al., 2021; Sørland et al., 2020). GWL approaches recast scenario uncertainty in terms of the timing of the period when a specified GWL is reached (e.g., Cannon et al. 2020). Extending this approach, GWLs can be used to "translate" (or time-shift) regionally resolved climate conditions between emissions scenarios using the GWL as a benchmark. This provides a means for addressing scenario uncertainty while retaining a standard time-period-based presentation of climate information. Adopting this approach, we developed "constructed scenarios" corresponding to warming under RCP2.6 and RCP4.5 based on the RCP8.5 CanLEAD-FWI data, closely following methods presented in Sørland et al. (2020) for developing Swiss national climate projections. For full details and a discussion on the limitations of this approach, see Section S-A.2.

Evaluation against observational products

We evaluated CanLEAD-FWI against two observation-based, gridded climatologies of FWI System components. The first provides gridded observations from interpolated noontime weather station observations, using as covariates NCEP's North American Regional Reanalysis (Mesinger et al., 2006) near-surface data and elevation (for temperature only), hereafter "CFS-OBS" (Nadeem et al. 2020). CFS-OBS has a 20-km gridded resolution for 1981–2014, and covers terrestrial areas of most Canadian provinces, excluding the Canadian territories and Prince Edward Island. The second dataset is based on ERA5 (Hersbach et al., 2020; Jain et al., 2022), hereafter "ERA5-FWI". ERA5-FWI was computed from ERA5 noontime meteorological inputs on a 31-km grid for 1979–2020. To focus on fire weather extremes, we compared the climatological annual 95th percentile of all FWI System components from ERA5-FWI and CFS-OBS to the CanLEAD-FWI ensemble mean, using the common period between datasets (1981–2014; CanLEAD-FWI follows RCP8.5 after 2005). CFS-OBS and ERA5-FWI were regridded to the NAM-44i grid using bilinear interpolation before comparison.

Station-based fire weather projections

Engagement activities indicated that fire management agencies in Canada currently use both station-based and gridded data to assess fire weather and make management decisions. Despite the use of multivariate bias adjustment within CanLEAD dataset development, biases remain in resulting gridded indices and hinder product relevance in some regions, particularly those with complex topography and/or microclimates. Thus, for the CanLEAD-FWI grid boxes where station data exists, we applied another bias-adjustment towards station-based observations of FWI System values using Quantile Delta Mapping (Cannon et al., 2015). Full details of bias adjustment methods, discussion, and validation are provided in Section S-A.3.

User engagement

To better understand user needs for future projections of fire weather information, we completed two rounds of user engagement during product development, with the goal of integrating user feedback into design and delivery of CanLEAD-FWI.

The first round ("preliminary user engagement") occurred while method development was actively underway and focused on interviews with provincial and territorial wildfire experts. Our objective was to learn from a targeted set of practitioners (Baulenas et al., 2023) about key metrics of fire weather and climate for tactical and strategic decision-making to better align project outcomes with user needs (Boon et al., 2022; Findlater et al., 2021). We identified individuals involved in wildfire management from each Canadian province and territory and conducted informal, open-ended interviews with most regions (12 participants from 11 provinces and territories across Canada). These individuals worked for provincial and territorial wildfire services as wildfire scientists, meteorologists, fire behaviour analysts, or in wildfire agency management. In this initial round of engagement, we aimed to develop a genuine person-to-person relationship, encourage honest opinion sharing, and obtain project-relevant information while avoiding influencing interviewee responses. For additional details, see Section S-A.4.

The second round ("user product testing") took place as the project was considering data presentation. Our objective was to develop a web-based interface that was as effective as possible (Palutikof et al., 2019) in delivering data and guidance to both wildfire experts and other users. To scope targeted engagement, key sectors and groups were identified (Baulenas et al., 2023). Users were categorized into two broad user types (55 total participants):

- Wildfire expert: participants working directly in provincial, territorial, or national wildfire forecasting, management, and/or wildfire research (12 participants). These participants were located across Canada, including some participants from the first round.
- General practitioner: participants not involved in the domains outlined for wildfire experts; these individuals may have had minimal experience working with wildfire information but some climate change adaptation experience (43 participants). Engaged groups included insurance experts, actuaries, provincial employees, community and municipal employees, and multi-disciplinary researchers from geographical regions across Canada. For additional details, see Section S-A.4.

We conducted nine workshops within the user product testing phase, with information collected through verbal feedback and live polling. Workshops consisted of a background presentation on fire weather information and CanLEAD-FWI, as well as an opportunity to interact with a prototype interactive web application (app). To the extent possible, engagement was tailored to each audience's expertise, aiming to improve product useability (Beier et al., 2017; Jebeile and Roussos, 2023). Questions focused on understanding of concepts, metrics of interest for decision-making, visualizations, guidance materials, understanding of uncertainty, and general opportunities and challenges. Workshops were informal and additional follow-up questions were asked.

For further information on workshops, see Section S-A.4.

Results and discussion

CanLEAD-FWI historical evaluation

To provide context for interpretation of projected future change, we first compared CanLEAD-FWI over the 1981–2014 period against two independent gridded observational products, CFS-OBS and ERA5-FWI.

Considering FWI System component extremes (95th annual percentile, 1981–2014 mean), the spatial mean difference of CanLEAD-FWI from CFS-OBS ranged from −16 % (DMC) to −31 % (DSR and DC), with most components and regions underestimated in CanLEAD-FWI (not considering FFMC; Fig. 2). FFMC, the only code with an upper bound (of 101), had a notably lower spatial mean percentage difference of < 1 % and is also the only code for which both positive and negative biases emerge in different regions of Canada. Spatial patterns of difference between CanLEAD-FWI and CFS-OBS vary by index. The greatest absolute differences in DMC, DC, and BUI are in northern Alberta, and are likely linked to precipitation differences between CanLEAD-FWI and

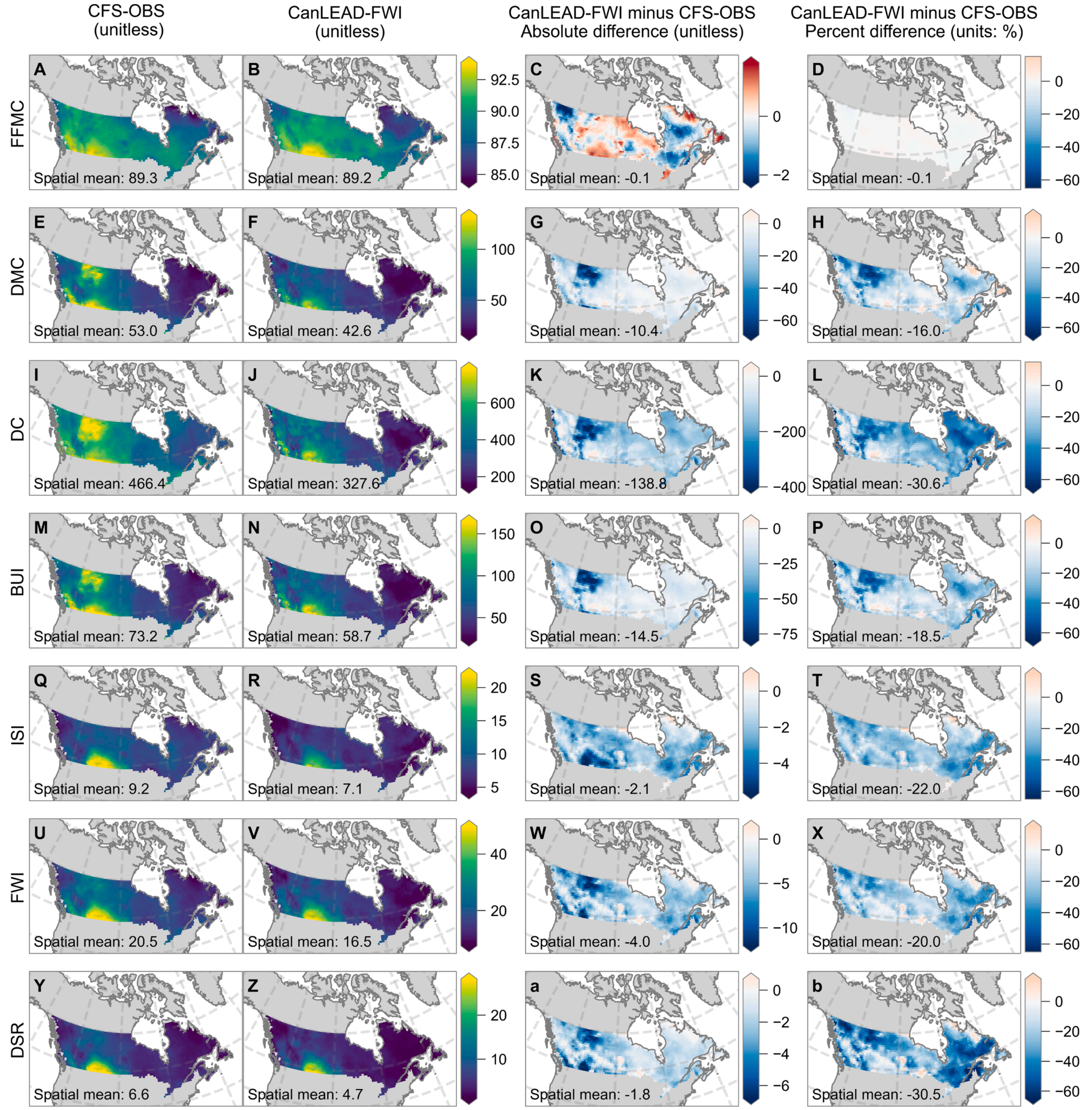

Fig. 2. Climatological mean (1981–2014) of annual 95th percentile FWI System components for CFS-OBS (column 1), CanLEAD-FWI ensemble mean (column 2; domain trimmed to match CFS-OBS), and the absolute (column 3) and percent (column 4) difference between CanLEAD-FWI and CFS-OBS over the CFS-OBS domain.

CFS-OBS. A strong high precipitation feature exists in CFS-OBS (Fig. S-3), potentially associated with a spatial artefact in the data at the British Columbia/Alberta border. More spatially consistent large negative biases exist for ISI, FWI, and DSR in CanLEAD-FWI relative to CFS-OBS. DSR is an exponential form of FWI, so spatial differences are magnified. These patterns for ISI, FWI and DSR are likely related to their dependence on wind speed. There are inherent differences between station-based data (from which CFS-OBS was generated) and modelled gridded data, which represents the grid cell in aggregate. This is especially important for wind speed, which has high spatial variability based on local characteristics. In addition, CanLEAD-FWI uses daily mean wind speed; this under-biases CanLEAD-FWI relative to CFS-OBS, which uses station-based noon wind speed as input (Fig. S-4).

The second comparison, of CanLEAD-FWI from the ERA-FWI dataset, shows spatial mean differences between −13 % (ISI) and 37 % (BUI) in the 1981–2014 climatological mean 95th annual percentile (not considering FFMC, which differs by < 1 %; Fig. 3). For most FWI System components, large differences between CanLEAD-FWI and ERA5-FWI are apparent over the mountainous regions in western Canada (parts of the Alberta, British Columbia, and the Yukon). In addition, the representation of lakes in ERA5-FWI, which are not captured in either CFS-OBS or CanLEAD-FWI, causes scattered pockets of high discrepancies.

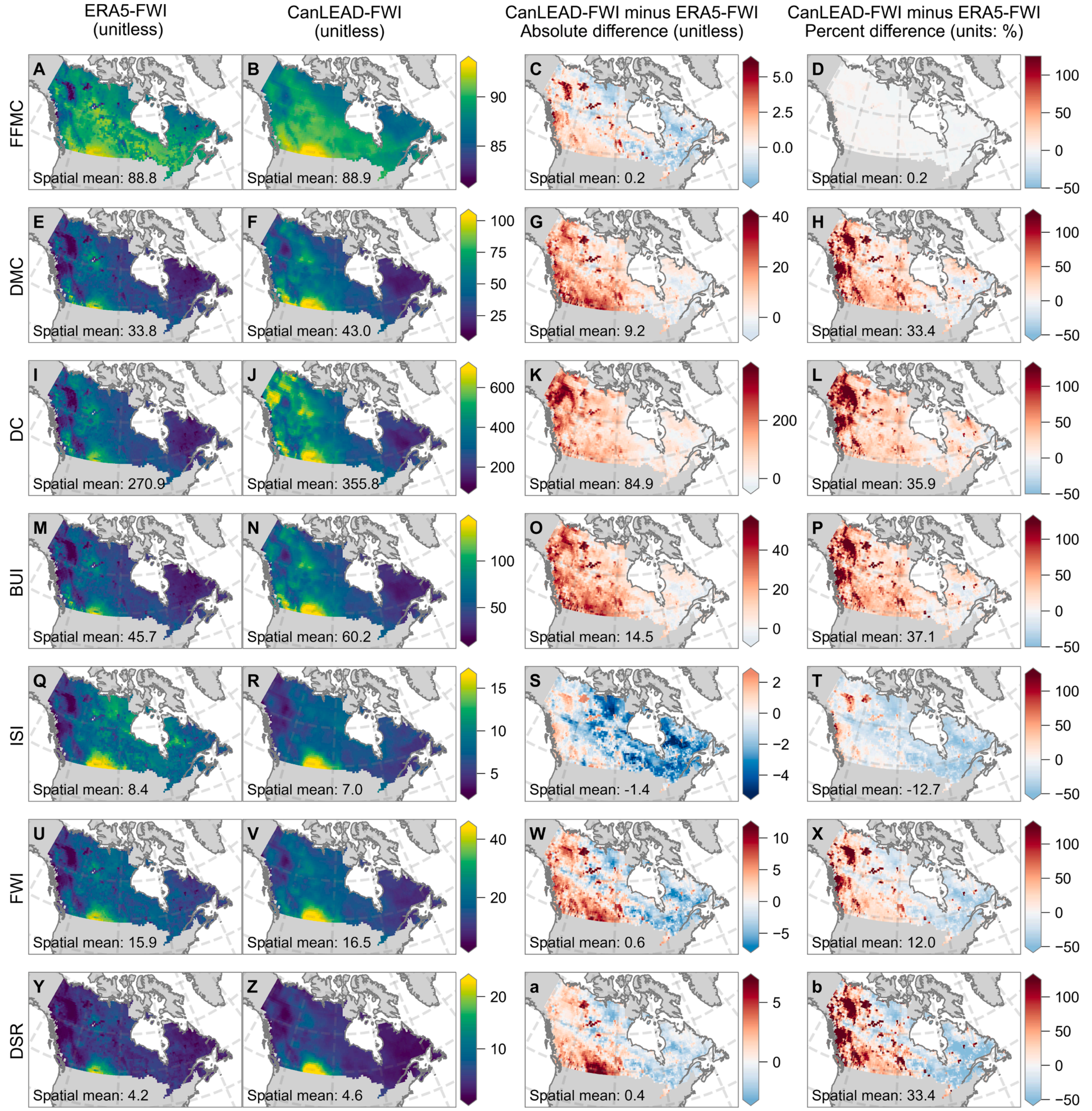

Fig. 3. Climatological mean (1981–2014) of annual 95th percentile FWI System components for ERA5-FWI (column 1), CanLEAD-FWI ensemble mean (column 2), and the absolute (column 3) and percent (column 4) difference between CanLEAD-FWI and ERA5-FWI over the study domain.

Unlike the comparison with CFS-OBS, DMC, DC, and BUI are largely overestimated across Canada in CanLEAD-FWI relative to ERA5-FWI. In general, the remaining wind-dependent FWI System components (ISI, FWI, FFMC, and DSR) tend to be overestimated in western Canada and underestimated in eastern Canada in CanLEAD-FWI. ISI, with the strongest dependence on wind, shows the largest spatial extent of underestimation in CanLEAD-FWI. This is likely attributable to differences in wind speed representation between the two datasets, as ERA5-FWI used noontime wind speed while CanLEAD-FWI used daily mean. In Western Canada, other meteorological inputs appear to counteract the dampening effect of daily mean speed on FWI System components. Note that ERA5-FWI covers the entire CanLEAD-FWI domain whereas CFS-OBS only encompasses southern Canada. Therefore, the magnitudes of spatial mean differences from CanLEAD-FWI are not directly comparable between the two observational datasets.

Overall, CanLEAD-FWI tends to be lower than CFS-OBS but higher than ERA-FWI when considering extreme FWI System component values such as the 95th annual percentile. Our assessment reveals high observational uncertainty in these historical FWI System component extremes. However, CanLEAD-FWI estimates typically lie between the observationally-based ERA5-FWI and CFS-OBS datasets in terms of index magnitudes, providing confidence in its use as a basis for future

FWI System projections.

Projected changes in fire weather

In the following evaluation, we focus on BUI-based measures of high fire weather conditions and secondarily on FSL, as these metrics were prioritized for delivery based on a combination of user input and evaluation of scientific confidence. BUI was selected due to its importance in longer-term wildfire planning, relatively high correlation with burned area (Harrington et al., 1983), and greater confidence than wind-dependent metrics such as ISI and FWI. FSL was selected as it has high certainty (it is fully temperature dependent) and was highlighted in user engagement as impactful and easily understandable.

By the 2071–2100 period under RCP8.5, CanLEAD-FWI projects substantial, robust (SNR > 1) increases in BUIp95 across most of Canada, excluding some regions in the northwest (Fig. 4). BUIp95 represents the severity of local high (95th percentile MJJAS) fire weather conditions, with projections indicating that high fire weather conditions will intensify by over 25 % across most of Canada (spatial mean 39 %; see Fig. 5 for projected percentage change in BUIp95 and other FWI System components, and Figs. S-5 to S-8 for absolute change in this and other metrics). Both absolute and relative changes are greatest in southwestern Canada (BC coast and interior), with much of BC projected to see BUIp95 increases of at least 40 %, and BUIp95 projected to more than double in Pacific coastal regions where historical fire danger is relatively low (Fig. 4; Fig. 5). Over much of the southern Arctic ecozone (including northern Quebec, much of mainland Nunavut and part of northern Northwest Territories), BUIp95 is projected to increase by over 40 %, with these sizable percentage increases stemming from low historical (baseline) values combined with moderate absolute increases. Other emissions scenarios show similar spatial patterns of change in fire weather severity, although of smaller magnitude. Constructed RCP2.6 and RCP4.5 scenarios for 2071–2100 represent 2.3 °C and 3.1 °C of warming from pre-industrial, respectively. Both scenarios demonstrate a robust (SNR > 1) increase in BUIp95 for much of Canada, except for a larger region of northwest and central Canada, with a spatial average increase in BUIp95 of 14 % and 21 %, respectively.

BUI90 provides a count of days with BUI values at or above 90, the threshold defining the highest national (CFS) fire weather class. However, regionally defined thresholds for relevant “extreme” BUI conditions vary from 60 (e.g., Ontario, Nova Scotia) to 200 (parts of BC), so BUI60 (count of days with BUI values at or above 60) is also presented in Fig. 4. Substantial increases in BUI90 and BUI60 are projected, particularly in BC and the prairies. For example, extreme southwestern BC is projected to experience increases in BUI90 of over one month by end of century under RCP8.5, with larger swaths of southern BC and Alberta projected to see increases of three weeks or more. For BUI60, most of the prairies and BC are projected to see increases of two weeks or more by 2071–2100. In some fire-prone regions of southern BC and Alberta, robust changes do not emerge by end of century because BUI60 occurrence is already frequent; this threshold is too low to fully capture the intensification of fire weather in these regions. By contrast, in Quebec, Labrador and some maritime provinces, BUI90 rarely occurs either historically or by the end of century under RCP8.5. In general, this reflects the challenge in selecting a single absolute threshold that is relevant across Canada and demonstrates the importance of considering locally relevant thresholds to assess climate change impacts on local fire danger. Emergence of robust change in BUI60 and BUI90 under constructed-RCPs 2.6 and 4.5 is more limited by end of century than emergence of BUIp95 for these same scenarios. This again is partially due to the inability of any single threshold-based index to be meaningful for the whole of Canada. Robust increases in FSL, which is fully

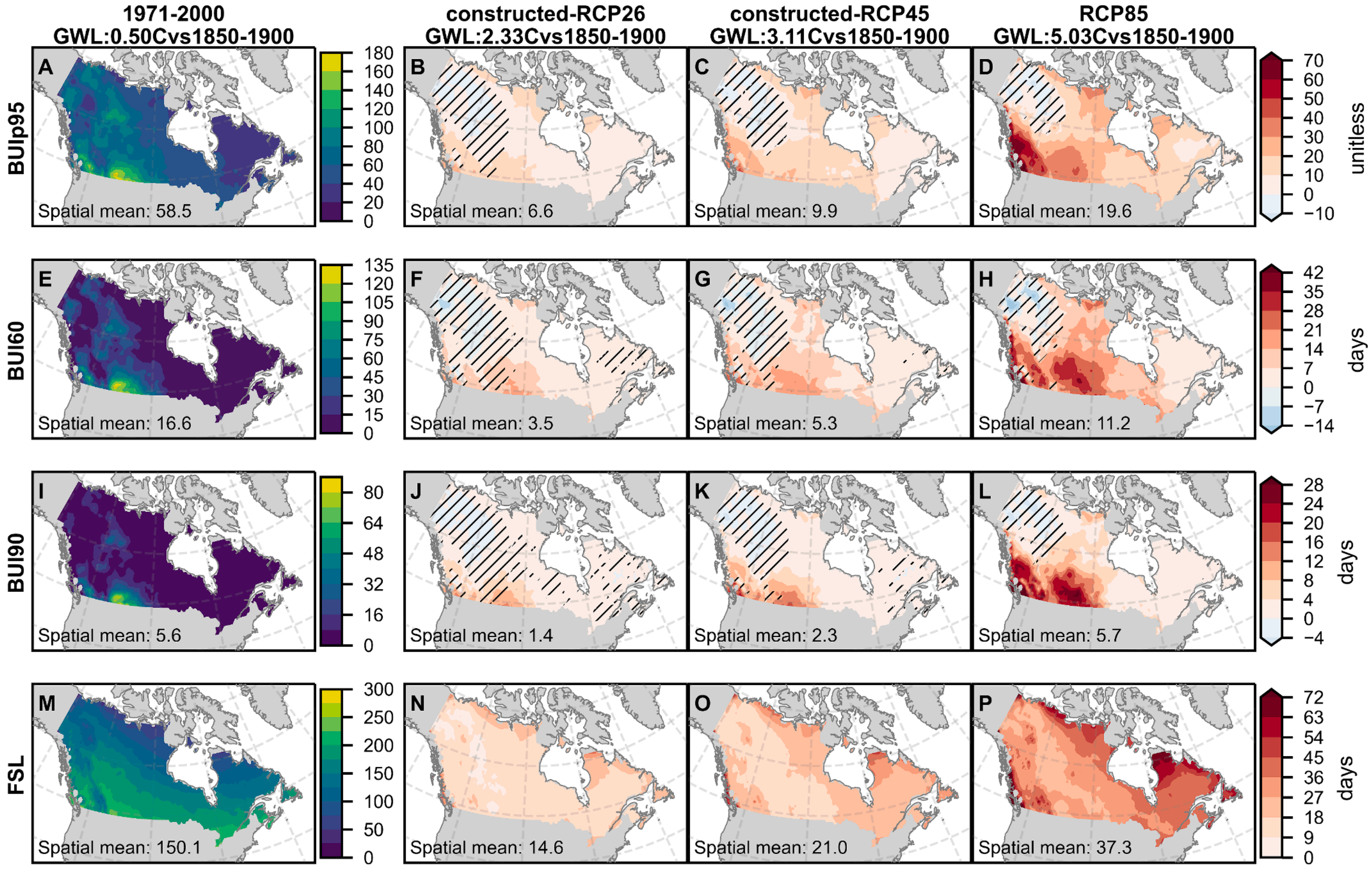

Fig. 4. Ensemble mean BUIp95 (row 1), BUI60 (row 2), BUI90 (row 3), and FSL (row 4) averaged over the 1971–2000 period (column 1) and change by 2071–2100 for constructed-RCP2.6 (column 2), constructed-RCP4.5 (column 3), and RCP8.5 (column 4). Non-robust change (SNR < 1) is masked with hatching.

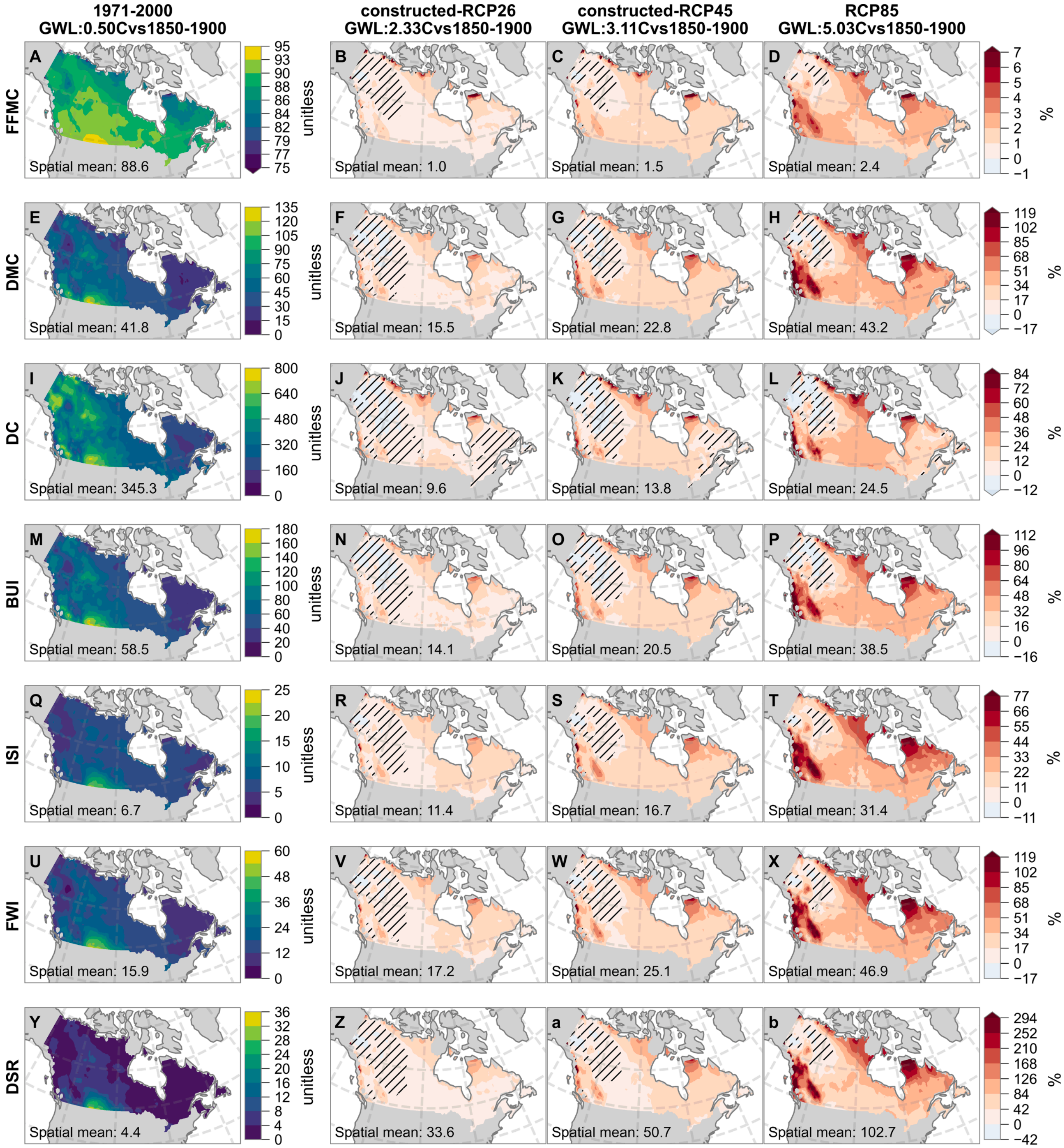

Fig. 5. Climatological mean of the 95th percentile of daily values in the MJJAS season. Columns show the ensemble mean for 1971–2000 (unitless; column 1) and percent change by 2071–2100 for constructed-RCP2.6 (column 2), constructed-RCP4.5 (column 3), and RCP8.5 (column 4). Non-robust change (SNR < 1) is masked with hatching.

temperature-dependent, are prevalent across Canada by as early as 2001–2030 under all RCPs. The domain average increase in FSL by 2071–2100 is over two weeks under constructed RCP2.6 and over 5 weeks under RCP8.5 (compared to 1971–2000; Fig. 4). FSL changes are particularly large – upwards of two months under RCP8.5 – in the Arctic coastal regions where historical fire seasons were short or not present. In the Pacific Coastal region where large changes are projected in other metrics, the fire season is projected to expand to the entire year by end of century RCP8.5, a more than 100-day increase.

The robust climate change impacts described above are apparent despite the influential role of interannual variability in FWI System components, which previous research has demonstrated can dominate total FWI uncertainty until mid-century (Fargeon et al., 2020). Fig. 6 shows the ensemble spread (mean, 10th and 90th percentile) in the change in BUIp95, BUI60, BUI90 and FSL by 2071–2100 under constructed-RCP 4.5 (3.1 °C of warming). Ensemble spread in projected

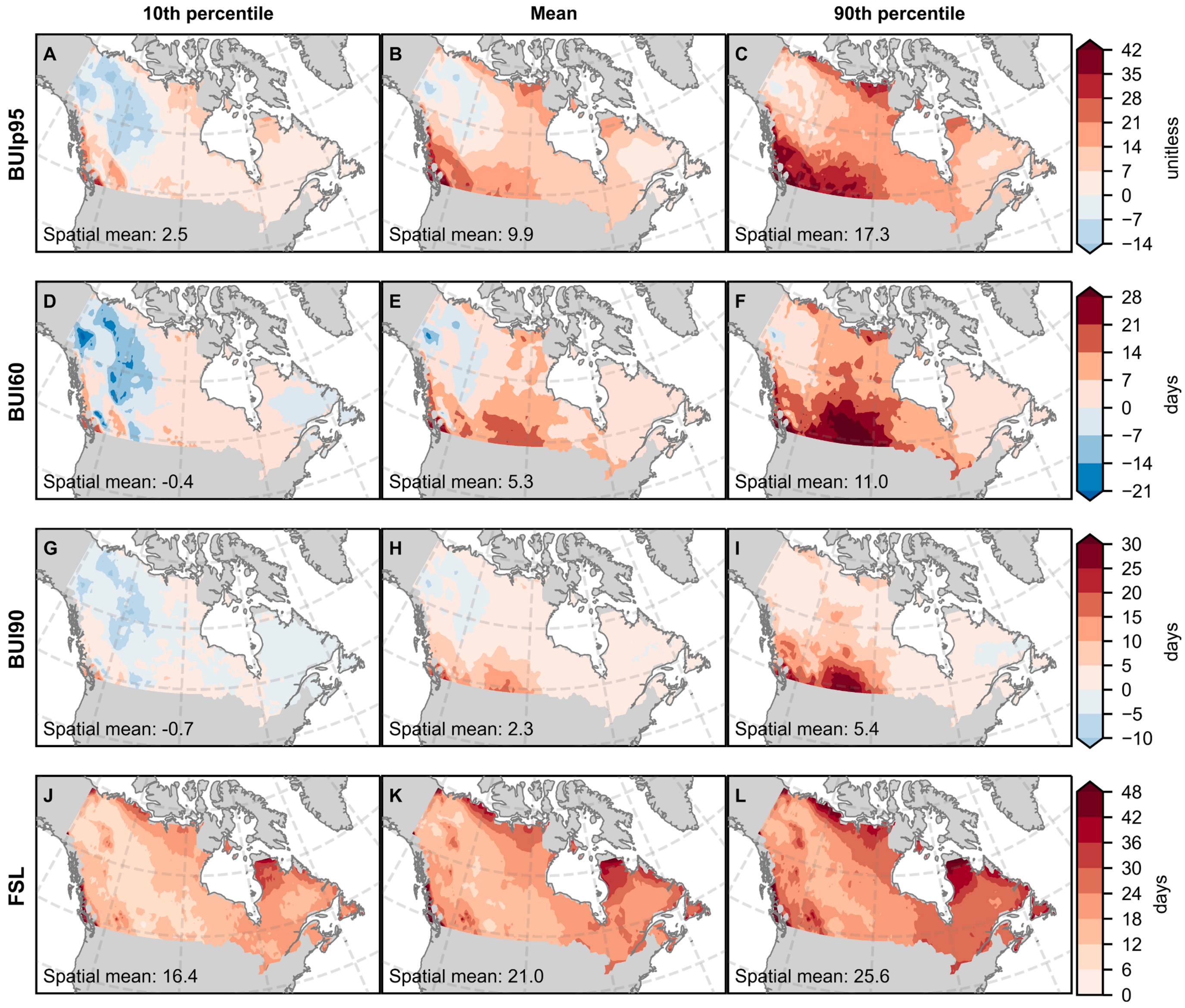

Fig. 6. Ensemble change by 2071–2100 from 1971-2000 for constructed-RCP4.5 for the ensemble 10th percentile (column 1), mean (column 2), and 90th percentile (column 3), showing BUIp95 (row 1), BUI60 (row 2), BUI90 (row 3), and FSL (row 4).

change (10th to 90th percentile, calculated by grid cell) is considerable for BUIp95, BUI60 and BUI90, with slightly larger proportional spread for threshold-based BUI60 and BUI90 (on a spatial average). For northwestern Canada where non-robust changes are projected, internal variability is apparent in the ensemble spread, with the 10th and 90th percentiles of the projected change having opposite signs. The generally lower internal variability in temperature-dependent variables (e.g., Hawkins & Sutton, 2011) is evident in FSL; as the only fully temperature-dependent metric, FSL exhibits lower ensemble spread and earlier robust change than BUI-based metrics (Fig. 4; Fig. 6).

All FWI System components are projected to undergo spatial patterns of change broadly similar to BUI-based metrics: absolute increases are greatest in southwestern and central Canada as well as some Arctic coastal regions, and no robust change or minor decreases in northwestern Canada (Fig. 5 and Figs. S-5 to S-8). However, the magnitude of both absolute and percentage change varies by component. Some key comparisons to BUIp95 and how this relates to FWI System design include:

- FFMC assesses soil moisture in the uppermost layer of forest fuel and is related to human-caused fire occurrence. FFMCp95 projects the smallest magnitude of percentage change, likely related to its cap of 101 (other components have no upper limit). In addition, CanLEAD-FWI projects the smallest extent of fire weather decrease in northwestern Canada for this component compared to others. This may be because FFMC is less sensitive to changes in precipitation compared to DC and DMC (Flannigan et al., 2016). While FFMC also considers wind speed, the CanLEAD ensemble mean projects decreasing average MJJAS wind speeds over large parts of northwestern Canada (Fig. S-4).
- DMC, typically associated with the probability of lightning-caused fires, is highly correlated with BUI due to the structure of the FWI System (Harrington et al., 1983). Of all FWI System components, spatial patterns of change in DMCp95 are most like BUIp95 (Fig. 5, see Fig. S-5 for absolute changes), including the magnitude of projected percentage increase.
- DC, which measures drought conditions in the deep soil layers, is also factored into BUI but has more influence when DMC is high. Compared to BUIp95, DCp95 projects later emergence of robust

changes and larger increases in Arctic coastal regions (relative to the spatial average). We suspect that these large Arctic increases are partially related to changing FSL, as DC typically has a low spring start-up value and rises throughout the season with a 52-day lag time at “standard” summer conditions (Van Wagner, 1987). As FSL increases, it may allow DC values to rise further. For example, near the Arctic coast, FSL increases from ~ 50 to 75 days in the past (1971–2000) to ~ 100 to 125 days by end of century (2071–2100).

- DSR is an exponential transformation of FWI intended to better capture the effort required to control wildfires. Therefore, spatial patterns of change in DSRp95 follow FWIp95 exactly but with magnified spatial differences, and a spatial mean percentage change approximately double that of FWIp95 (Fig. 5).

Our findings of projected increases in high fire weather frequency and severity across multiple metrics, as well as lengthening fire season, agrees with previous research (Abatzoglou et al., 2019; Jain et al., 2020; Park et al., 2023; Quilcaille et al., 2023; Wang et al., 2017a, 2015). However, CanLEAD-FWI-projected decreases in some regions of northwestern Canada are not apparent in most previous research. Evidence is mixed for the broader region where CanLEAD-FWI projects no robust change, which roughly corresponds to the Southwestern Yukon and Great Bear Lake homogenous fire-regime zones (Boulanger et al., 2014). Increases in fire weather severity in these regions were projected in Wang et al. (2017a, 2015), while Park et al. (2023) demonstrated that NEX-GDDP-CMIP6-projected average change is minor for the region encompassing Alaska, Yukon, and most of the Northwest Territories. Abatzoglou et al. (2019) assessed the time of emergence of anthropogenic climate change using a CMIP5 ensemble and a SNR approach, finding no emergence in this region by 2050–2080 (the last period assessed). Similarly, Quilcaille et al. (2023) used a CMIP6 ensemble, finding no robust change by end of century for average annual fire weather metrics (robustness assessed based on model agreement). In CanLEAD-FWI, lack of robust increase in BUI metrics in these regions is linked to large CanLEAD-projected increases in precipitation and relative humidity (Figs. S-2 and S-3), which are sufficient to offset the influence of warming (Fig. S1). Large increases in summer precipitation amount and frequency in northern Canada are consistent with CMIP5 and CMIP6 ensembles (Abatzoglou et al., 2019; Sobie et al., 2021) and relative humidity increases in northwestern Canada are consistent with CMIP6 (Abatzoglou et al., 2019). Since CanLEAD-FWI relies on a single model large ensemble, it cannot quantify model uncertainty that previous research has highlighted as particularly important in both historical (Gallo et al., 2023) and projected (Fargeon et al., 2020) FWI products. In the context of adaptation planning, this is particularly important for the large regions of northwestern Canada where results indicate non-robust change in fire weather. To improve interpretation of future changes, especially in these areas, future CanLEAD-FWI iterations will consider suitable (high resolution, multivariate bias-corrected) multi-model, multi-scenario ensembles as they become available. This will better constrain regional model uncertainty and reduce the need for RCP-translation.

User engagement feedback and user-informed application design

CanLEAD-FWI projections describe an increase in both the severity and frequency of high fire weather conditions across most of Canada, which we expect will provide valuable context to long-term Canadian climate risk assessments and adaptation planning. However, to be effectively integrated into these uses, dataset production alone is insufficient (Beier et al., 2017; Boon et al., 2022; Jebeile and Roussos, 2023; McFayden et al., 2023). Data delivery mechanisms and training must also be carefully considered to guide foundational knowledge development, use of best practices, and reduce barriers for users (e.g. Terrado et al., 2022). Below, we first outline the results of user engagement activities, followed by a summary on how feedback was incorporated to enhance product utility to users.

Preliminary user engagement

Through informal interviews with fire weather and management experts across Canada (Section 3.4), preliminary engagement revealed key learnings that guided both CanLEAD-FWI development and delivery:

- **The FWI System is widely applied to account for weather and climate impacts on fire danger.** Risk-based decision-making is central to wildfire management and is applied at all operational levels, from the on-the-ground tactical firefighter to provincial-scale, long-term budgeting and resourcing (Boychuk et al., 2020). When accounting for fire danger considerations related to weather and climate, the FWI System is a primary means for assessing potential impacts.
- **The FWI System is applied and interpreted differently across Canada.** There is no “one-size-fits-all” FWI System-based metric that addresses needs across the country, a point that was key to informing our subsequent data presentation approach. Canadian wildfire practitioners have a wide range of data needs: experts expressed interest in different FWI System components, threshold levels, and/or metrics depending on the region, season, or aspect of fire management.
- **CanLEAD-FWI helps address a growing need to understand the impacts of climate change on wildfire.** Climate change is already challenging existing wildfire management practices and is expected to worsen. CanLEAD-FWI projections may serve to tell a compelling narrative to decision-makers about the importance of long-term (decadal) wildfire planning.

User product testing

The second round of engagement focused on identifying effective modes for CanLEAD-FWI presentation and guidance to better serve users in climate-related decision-making (Beier et al., 2017; Boon et al., 2022). Workshops highlighted opportunities for prioritization of metrics, effective visualizations, and well-designed guidance materials:

- **FWI System component prioritization:** All FWI System components were noted by wildfire experts as useful. ISI and FFMC were highlighted for early-season planning, while some noted that BUI-based metrics were useful for long-term planning. Participants expressed interest in fire season length and made links with financial planning and interprovincial collaborations. Wildfire experts requested details on season length calculations, highlighting a primary operational concern of lengthening fire seasons. The Seasonal Severity Rating, the seasonal average of the DSR, was highlighted as a desired expert-level parameter.
- **Preferred visualizations:** Graphics describing changes to station-based indices were assessed, including time series, probability distributions, and bar graphs. Of those presented, general practitioners found it easiest to interpret stacked bar charts of fire danger ratings that reflect changes using standardized danger bins. Fire danger ratings provided a familiar point for interpretation, as ratings from “low” to “extreme” are commonly used when disseminating fire danger information to the public (Hanes et al., 2021). However, fire danger bin classification is region-specific; therefore, visuals that identify regional thresholds and interpretation was of interest to all participants.
- **Precalculated gridded information versus customizable station-based results:** Originally, the app was designed to focus on customizable, station-based projections to meet the expert need, identified through preliminary engagement, for customizable FWI System metrics. User product testing revealed an additional need for gridded data to support areas far from stations or broader regional

assessments. Additionally, some general practitioners found the customizable projections overwhelming.

- **Knowledge gaps, guidance, and interpretation:** Product testing revealed a knowledge gap between fire weather projections and decision-making for general practitioners, consistent with previous findings (McFayden et al., 2023; Tedim et al., 2021). It was unclear to many users how to navigate the different FWI System components and interpret the data and visuals for planning purposes. This ambiguity was compounded as the likelihood of fire activity, what users are ultimately interested in, depends on ignition events, local fuel characteristics, and other fire behaviour factors that the FWI System does not consider. Thus, to determine exposure to changes in frequency and intensity of wildfires due to climate change, users must obtain and interpret additional local hazard information in combination with CanLEAD-FWI projections. Gaps in understanding for general practitioners underscored the considerable training and technical knowledge required to support decision-making. Key information and guidance requested are listed below by user type.

  Wildfire experts:
  - Technical information on season length calculations, FWI System input variables, and caveats and limitations of the methods.
  - Clarification on interpretation of data presented as quantiles (e.g., BUIp95) and what this means for decision-making.

  General practitioners:
  - Explanation of differences between FWI System components, interpretation, and relationships to decision-making.
  - Clear articulation of differences between customizable station and precalculated gridded projections, and when to use them.
  - Region-specific guidance on interpreting FWI System components.
  - Summary of the limitations of information for decision-making.
- **Additional metrics:** Additional technical metrics were requested by wildfire experts beyond those originally calculated. Examples included consecutive dry days, prolonged "fire busts," seasonal fire weather (especially spring/fall shoulder seasons), and maximum annual length of the extreme fire period. These were deemed to be outside of the current project scope, but future iterations of CanLEAD-FWI will consider these as priority additions.

Table 3

Summary of challenges highlighted during user product testing, the user-feedback-driven recommendations, and implementation approach developed to address challenges.

User request or challenge	User-driven recommendation	Implementation
Lack of a clear, simple starting point challenges interpretation and app usage. General practitioners were overwhelmed by the many FWI System components. Wildfire experts expressed interest in different FWI System components, threshold levels, and/or metrics reflecting regional differences across Canada.	Develop a layered approach to information presentation, starting with a simple homepage that guides users to general or expert level information.	"Getting Started" page upon launch that outlines the basics and guides users to the appropriate level of information. "Quick Start" tab targeted at general practitioners provides three easily understandable metrics. "Deep Dive" tab targeted at experts provides additional gridded metrics and customizable station-based projections. "Guidance" tab for help and support.
Knowledge gap exists between fire weather projections and decision-making for general practitioners. Experts requested detailed technical methods to support product interpretation.	Provide easy access to foundational understanding and interpretation of the FWI System. Provide technical methods to inform expert-level work.	The "Guidance" tab provides both novice and expert-level guidance and technical information, with additional user support available by phone, email or webform if needed.
Station-based data is challenging to use for broader regional assessments or areas far from a station.	Present both station data and gridded data.	Both precalculated gridded metrics and customizable station-based data are provided.

User-informed design of CanLEAD-FWI web application

To enhance access to CanLEAD-FWI for users, we developed an online web app to provide data and guidance (https://climatedata.ca/fire-weather/) based on open-source Python tools. User needs and recommendations provided important constraints to data selection and web app design, a part of user-centred design as described in Terrado et al. (2022), with the goal of maximizing effective use of CanLEAD-FWI for decision-making. Table 3 summarizes key user challenges, feedback-driven recommendations, and actioning of that feedback within app development. Consistent with other climate service providers (e.g., Terrado et al., 2022), we found that web app design has the potential to address user concerns. One primary design choice was to employ an "onion" approach, where "layers" of information become progressively more complex with each tab, aligned to levels of user expertise (e.g. Skelton et al., 2019).

The "Quick Start" tab is targeted at general practitioners, providing three easily understandable metrics (BUIp95, BUI60, and FSL) computed from underlying variables with the highest confidence. The "Deep Dive" advanced-user tab provides additional gridded precalculated metrics, FWI System components, time periods, and emissions scenarios. It also allows for customizable metrics, where expert users can generate their own custom analyses for station-based projections. Most metrics emphasize changes in the severity and frequency of fire weather and provide graphics or data for download.

In addition to addressing user needs, other climate services best practices were considered when designing app features and guidance. For example, the emphasis on BUI-based metrics and FSL was informed by scientific confidence in input variables as well as user feedback. All FWI System metrics are important in operational wildfire management and are therefore provided in the application. However, wind-dependent FWI System components (ISI, FWI, DSR, and FFMC) are considered to have lower confidence than wind-independent components (DC, DMC, and BUI). Near-surface wind is challenging to model, as relatively coarse-scale climate models cannot resolve all mesoscale processes (Graf et al., 2019; Ranasinghe et al., 2021). Ranasinghe et al. (2021) report low confidence in the direction of projected change in mean wind speed for most of North America. Additionally, CanLEAD-FWI employs mean daily wind speed rather than the noontime wind speed required by the FWI System. For these reasons, wind speed-related aspects of CanLEAD-FWI may not be fully captured in either historical values or projected changes. BUI and other wind-independent components are emphasized in the application, while app guidance indicates that projections of FWI System components that depend on wind should be treated with more caution – for example, by considering relative change rather than absolute values, or considering them in conjunction with wind-independent components.

This and other guidance on using and interpreting CanLEAD-FWI is provided within the "Guidance" tab, with additional user support available by phone, email or webform if needed. A detailed discussion of select guidance and implementation features driven by climate services best practices and user needs is provided in Section S-B.1.

Conclusion

Climate-driven fire weather changes have increased fire danger and challenged existing wildfire management practices, resulting in an emerging demand for future wildfire information. Addressing this need, we developed the CanLEAD-FWI dataset, which provides fire weather projections for Canada based on the FWI System and multivariate bias-adjusted climate model output from the CanLEAD climate projection dataset. Assessment against two independent observation-based datasets reveals high observational uncertainty in historical FWI System component extremes. However, historical CanLEAD-FWI estimates are generally situated between the two observational datasets in terms of component magnitudes, lending confidence to use of CanLEAD-FWI for future projections extending from these historical conditions. CanLEAD-FWI projects substantial, robust increases in the severity and frequency of high fire weather conditions as well as a lengthening of the fire season across most of Canada during the 21st century, although the magnitude and spatial extent of increases depend on the selected FWI System component, metric, and emissions scenario.

CanLEAD-FWI projections and supporting guidance information are made publicly accessible via a web application (https://climatedata.ca/fire-weather/). To enhance usefulness for decision-making, product development incorporated feedback from two rounds of user engagement. Key outcomes were integrated into app design to support users in making choices consistent with best practices, reduce information overload for less technical users, and clarify appropriate data usage.

CanLEAD-FWI helps address a growing need in the Canadian climate services space for both projected climate impact data and accompanying training and support. It was developed with users' needs in mind, with their feedback considered to the extent possible given the product's strengths, limitations, and best practices for climate services. We believe that this approach will enhance the potential for appropriate integration of projected fire weather information into long-term decision-making.

CRediT authorship contribution statement

Laura Van Vliet: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Formal analysis, Data curation. **Jeremy Fyke:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Software, Methodology, Conceptualization. **Sonya Nakoneczny:** Writing – review & editing, Writing – original draft, Methodology, Investigation. **Trevor Q. Murdock:** Writing – review & editing, Methodology. **Pouriya Jafarpur:** Writing – review & editing, Investigation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cliser.2024.100505.

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