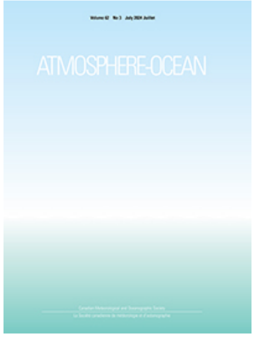

Atmosphere-Ocean

ISSN: (Print) (Online) Journal homepage: www.tandfonline.com/journals/tato20

Assessing Potential Evapotranspiration Methods in Future Drought Projections across Canada

Benita Tam, Barrie Bonsal, Xuebin Zhang, Qinxiao Zhang & Robin Rong

To cite this article: Benita Tam, Barrie Bonsal, Xuebin Zhang, Qinxiao Zhang & Robin Rong (2024) Assessing Potential Evapotranspiration Methods in Future Drought Projections across Canada, Atmosphere-Ocean, 62:3, 193-205, DOI: 10.1080/07055900.2023.2288632

To link to this article: https://doi.org/10.1080/07055900.2023.2288632

Published online: 11 Dec 2023.

Assessing Potential Evapotranspiration Methods in Future Drought Projections across Canada

Benita Tam[1,*], Barrie Bonsal[1], Xuebin Zhang[1], Qinxiao Zhang[2], and Robin Rong[1]

[1]*Science and Technology Branch, Environment and Climate Change Canada, 4905 Dufferin Street, North York, ON M3H 5T4, Canada*
[2]*CBCL Limited, Nova Scotia, Halifax, Canada*

[Original manuscript received 23 June 2023; accepted 10 November 2023]

ABSTRACT *Recently, concerns have arisen as to whether temperature-based proxy methods used to estimate potential evapotranspiration (PET) are reliable when examining future drought severity, especially in the context of a warmer climate. The objective of this study was to assess the effect of different PET approaches, focusing on proxies for radiation and humidity, on future Standardized Precipitation Evapotranspiration Index (SPEI) calculations across Canada. Using output from 22 CMIP6 global climate models (GCMs), seasonal and annual SPEI comparisons were carried out between the physically-based Penman-Monteith (PM) method and two approaches that incorporate temperature proxies to calculate radiation and/or humidity. These included the temperature-based Hargreaves (HG) approach and a PM method with derived humidity (PM-m). Results revealed that although the general patterns of SPEI projections across Canada were consistent among the methods, notable spatial and temporal differences were apparent. Specifically, both median and extreme SPEI projections based on the two temperature proxy methods revealed less annual and summer drying in much of central, eastern, and northern regions of Canada when compared to the physically based SPEI-PM. In extreme western regions (British Columbia, Yukon) these two methods, particularly HG, projected drier conditions. Differences of using temperature derived radiation and humidity were also most apparent in spring (and to a lesser degree, autumn), where the HG approach overestimated spring drying (and autumn wetting) over large regions of the country. Overall, differences tended to be more pronounced for the fully temperature-based HG approach during all periods considered. Results from this study strongly suggest that when possible, a physically-based approach be used when estimating PET to assess future drought projections. If a temperature proxy is used, the differences to a physically-based method should be understood and resultant implications be evaluated.*

RÉSUMÉ *[Traduit par la rédaction] Ces derniers temps, on s'est demandé si les méthodes de substitution basées sur la température utilisées pour estimer l'évapotranspiration potentielle (ETP) étaient fiables pour examiner la gravité des sécheresses futures, notamment dans le contexte d'un climat plus chaud. Cette étude visait à évaluer l'effet de différentes approches d'ETP, en se concentrant sur les approximations du rayonnement et de l'humidité, sur les calculs futurs de l'indice normalisé d'évapotranspiration des précipitations (INEP) à travers le Canada. En utilisant les résultats de 22 modèles climatiques mondiaux (MCM) CMIP6, des comparaisons saisonnières et annuelles de l'INEP ont été effectuées entre la méthode Penman-Monteith (PM) à base physique et deux approches qui intègrent des approximations de température pour calculer le rayonnement et/ou l'humidité. Il s'agit de l'approche de Hargreaves (HG) basée sur la température et d'une méthode PM avec humidité dérivée (PM-m). Les résultats ont révélé que, bien que les modèles généraux des projections de l'INEP à travers le Canada soient cohérents entre les méthodes, des différences spatiales et temporelles notables sont apparues. Plus précisément, les projections médianes et extrêmes de l'INEP fondées sur les deux méthodes d'approximation de la température ont révélé un assèchement annuel et estival moins important dans une grande partie des régions du centre, de l'est et du nord du Canada, par rapport à l'INEP-PM à base physique. Dans les régions de l'extrême ouest (Colombie-Britannique, Yukon), ces deux méthodes, notamment l'approche HG, ont projeté des conditions plus sèches. Les différences liées à l'utilisation du rayonnement et de l'humidité dérivés de la température étaient également plus apparentes au printemps (et dans une moindre mesure, en automne), où l'approche HG a surestimé l'assèchement printanier (et l'humidification automnale) dans de vastes régions du pays. Dans l'ensemble, les différences ont eu tendance à être plus prononcées pour l'approche HG entièrement basée sur la température pendant toutes les périodes considérées. Les résultats de cette étude suggèrent fortement que, dans la mesure du possible, une approche*

*Corresponding author's email: benita.tam@ec.gc.ca

à base physique soit utilisée lors de l'estimation de la TEP pour évaluer les projections de sécheresses ultérieures. Si une approximation de la température est utilisée, les différences par rapport à une méthode à base physique doivent être comprises et les répercussions qui en résultent doivent être évaluées.

KEYWORDS CMIP6; SPEI; droughts; Canada; potential evapotranspiration; radiation; humidity

1 Introduction

Droughts are among the greatest natural hazards across Canada, often affecting more people and frequently resulting in more loss and damage than any other natural disaster (e.g. Bonsal et al., 2020). Persistent, large-area events often stress water availability by depleting soil moisture, reducing stream flows, lowering lake and reservoir levels, and diminishing groundwater supplies. This ultimately causes major impacts on most sectors, including agriculture, energy production, industry, forestry, recreation, aquatic ecosystems, human health, and society. For example, during the 2001 and 2002 drought years over Canada, the country's Gross Domestic Product fell by an estimated $5.8 billion CAD, while previously reliable water supplies, such as streams, wetlands, dugouts, reservoirs, and groundwater, were placed under stress and often failed (Wheaton et al., 2005; Wheaton et al., 2008). Furthermore, the environmental impacts from major drought episodes also include reduced water quality, wetland loss, soil erosion and degradation, increased risk of forest fires and wildfires, and ecological habitat destruction (Bonsal et al., 2011).

Droughts are complex phenomena with a multitude of definitions mainly dependent on their timing/duration and associated impacts. In general, they refer to prolonged periods of time with abnormally below average moisture conditions, during which limitations in water availability result in negative impacts for various components of natural systems and economic sectors (Ault, 2020; Wilhite & Pulwarty, 2017; Zhou et al., 2023). However, each drought is different depending on factors such as area affected, duration, intensity, frequency, antecedent conditions, and the region's capability to adapt to water shortages. Drought types begin as lack of precipitation (meteorological) and propagate through to agricultural (decreased soil moisture), ecological (related to plant water stress that causes e.g. tree mortality), hydrological (water shortage in streams or storages such as reservoirs, lakes, and groundwater), and finally socio-economic.

Due to its complex nature, drought cannot be characterized using a single universal definition (Lloyd-Hughes, 2014). Several indices specific to certain types of droughts have therefore been devised to quantify drought duration and severity and, subsequently, assess historical trends and projected future occurrence. Although precipitation is the key variable when quantifying drought, past and projected future warming across Canada (Zhang et al., 2000) that increases evaporative demand necessitates the incorporation of evapotranspiration to determine the balance between water supply and water demand. Potential evapotranspiration (PET), in this case used to estimate reference crop evapotranspiration (Allen et al., 1998), is subtracted from precipitation to calculate a meteorological drought index (e.g. the Palmer Drought Severity Index (PDSI) (Palmer, 1965)); the Standardized Precipitation Evapotranspiration Index (SPEI) (Beguería et al., 2014; Vicente-Serrano et al., 2010). The present study focused on SPEI as it is commonly used in literature to assess meteorological drought, including previous work that examined CMIP5 SPEI projections for Canada (Tam et al., 2019). Furthermore, it is simplistic in nature and allows for spatiotemporal comparisons of the impact of different PET calculations on SPEI values across large regions.

PET represents water vapour flux under ideal conditions (i.e. the maximum amount of actual evapotranspiration that could occur if there were no limiting factors to water availability on land) (Hasiotis et al., 2007; Seneviratne et al., 2021). When estimating PET, multiple elements influencing the evaporative process should be considered, including wind speed, humidity, radiation, and air temperature (McMahon et al., 2013). The most recent sixth assessment report (AR6) of the Intergovernmental Panel on Climate Change (IPCC) (Masson-Delmotte et al., 2021; Seneviratne et al., 2021) stressed that when assessing future meteorological drought (i.e. abnormal and prolonged period of moisture deficiency [Palmer, 1965]), it is necessary to consider increased atmospheric evaporative demand (AED) (i.e. the maximum amount of actual evapotranspiration that can happen from land surfaces if they are not limited by water availability). They stated that since AED is affected by radiative and aerodynamic components, variables such as solar radiation and humidity are highly relevant, while estimates based solely on air temperature usually overestimate drought severity particularly in the context of substantial background warming. As a result, physically-based combination methods such as the Penman-Monteith (PM) equation are more adequate and recommended as the standard approach to estimating PET (McAfee, 2013; Pereira et al., 2015; Seneviratne et al., 2021; Sheffield et al., 2012). In fact, in the recent AR6 assessment, only those indices that were PM-based were assessed for future drought projections. As a result, this study uses the physically-based PM as the reference dataset to which the other methods are compared.

Still, other approaches continue to be used and preferred over PM due to fewer data requirements. The suitability of more simplistic approaches may depend on climatic zone, where greater complexity improves PET estimates in temperature and polar regions (Pimentel et al., 2023). Studies have found that the more simplistic PET approaches based solely on air temperature, such as Thornthwaite (PET-TH)

TABLE 1. List of models and realizations used in SPEI ensembles.

	Model (realization)	References
1.	ACCESS-CM2 (r1i1p1f1)	Bi et al. (2020)
2.	ACCESS-ESM1-5 (r1i1p1f1)	Ziehn et al. (2020)
3.	CanESM5 (r1i1p2f1)	Swart et al. (2019)
4.	CMCC-ESM2 (r1i1p1f1)	Cherchi et al. (2019); Lovato et al. (2022)
5.	CNRM-CM6-1 (r1i1p1f2)	Voldoire et al. (2019); Saint-Martin et al. (2021)
6.	CNRM-ESM2-1 (r1i1p1f2)	Séférian et al. (2019)
7.	EC-Earth (r4i1p1f1)	Döscher et al. (2022)
8.	EC-Earth3-Veg (r1i1p1f1)	
9.	FGOALS-g3 (r1i1p1f1)	Li et al. (2020)
10.	GFDL-ESM4 (r1i1p1f1)	Dunne et al. (2020)
11.	INM-CM4-8 (r1i1p1f1)	Volodin et al. (2018)
12.	INM-CM5-0 (r1i1p1f1)	Volodin et al. (2017)
13.	IPSL-CM6A-LR (r1i1p1f1)	Boucher et al. (2020)
14.	KIOST-ESM (r1i1p1f1)	Pak et al. (2021)
15.	MIROC6 (r1i1p1f1)	Tatebe et al. (2019)
16.	MIROC-ES2L (r1i1p1f2)	Hajima et al. (2020)
17.	MPI-ESM1-2-HR (r1i1p1f1)	Müller et al. (2018)
18.	MPI-ESM1-2-LR (r1i1p1f1)	Mauritsen et al. (2019)
19.	MRI-ESM2-0 (r1i1p1f1)	Mizuta et al. (2012); Yukimoto et al. (2019)
20.	NorESM2-LM (r1i1p1f1)	Seland et al. (2020)
21.	NorESM2-MM (r1i1p1f1)	
22.	TaiESM1 (r1i1p1f1)	Lee et al. (2020)

and Hargreaves (PET-HG), may produce inaccurate estimates (Amatya et al., 1995; Sheffield et al., 2012). PET-TH has been found to inaccurately estimate PET for a range of climates, and in particular, greatly overestimate the severity of future drought (Jensen et al., 1990; Van der Schrier et al., 2011). PET-TH, based solely on mean temperature and daylight derived from latitude, was found to overestimate the effect of temperature on evaporation leading to an exaggerated amount of projected drying (Tian-Jun & Tao, 2013). Given the shortcomings already noted in literature, this approach was not included in analyses. Incoming shortwave radiation and specifically its representation in PET equations (e.g. radiation input vs temperature-proxies), has been found to be a significant factor in estimating PET and SPEI (Lai et al., 2022; Stagge et al., 2014). Shaw and Riha (2011) found that radiation may even be a stronger driver of PET changes than temperature depending on climatic zone. Under a changing climate, projected decreases in radiation may temper the influence of projected increases in evaporative demand; which the simpler temperature-based methods may not able to capture (McAfee, 2013). Conversely, PET projections without direct humidity or wind inputs may still be reliable in regions where projected changes in wind and humidity are expected to be small (Lai et al., 2022; Sentelhas et al., 2010). In other parts of the world, derived humidity may lead to larger differences in PET projections (Kingston et al., 2009). As projections show regional decreases in radiation in the future (McAfee, 2013; Wild et al., 2015), along with decreases in relative humidity over much land regions including continental areas (Ficklin & Novick, 2017; Stocker et al., 2013), it was of interest to understand what implications this has for future droughts in Canada. Projected changes in mean wind speed, on the other hand, are highly variable and aside from western North America where there may be projected decreases, there is low confidence in the current state of knowledge for the rest of the continent (Arias et al., 2021); thus, the present study focused on radiation and humidity.

Several historical and projected future Canadian drought studies have used the PDSI and SPEI as indicators. However, most if not all incorporated PET estimates based solely on air temperature. This was mainly attributed to air temperature and precipitation being the most readily available data for long-term analyses. Regarding past drought, the majority of investigations over various regions of the country (with most focusing on the Prairie region) showed considerable multi-year variability with no discernible long-term trends (e.g. Bonsal et al., 2011, 2017; Wang et al., 2014). For future drought, most regional and Canada-wide studies revealed an overall consistency toward the increased likelihood of drought events over southern interior continental regions of Canada, especially during summer, under higher warming emission scenarios (Bonsal et al., 2013; Dibike et al., 2017; Masud et al., 2017; Tam et al., 2019, 2023). However, as alluded to previously, there is uncertainty concerning the magnitude of these changes, primarily due to shortcomings of the indices that estimated PET solely on air temperature, which may lead to an overestimation of drought intensity (e.g. Bonsal et al., 2019; Seneviratne et al., 2021).

Given this potential overestimation in future drought magnitude, the main objective of this study was to investigate the effect of various PET calculations on longer-scale (i.e. month or longer) drought projections across Canada. To do so, we looked at the effects of proxies for radiation and humidity in SPEI projections (in comparison to a physically-based approach) over various time periods and warming scenarios, focusing on the high emission scenario at the end of the twenty-first century (when greatest warming is projected). From this, an analysis of future Canadian drought occurrence was conducted including spatial differences and recommendations on which methods are most reliable to assess future drought across the country.

2 Methods

a *Data*

1 CMIP6 GCM PROJECTIONS AND SHARED SOCIOECONOMIC PATHWAYS (SSPS)

SPEI projections were calculated using monthly output from 22 Coupled Model Intercomparison Project Sixth Phase (CMIP6) (Eyring et al., 2016) global climate models (GCMs) regridded to a common 1×1 degree grid. Regridding was performed using bilinear interpolation. Bias-corrected (see below) CMIP6 minimum temperature, maximum temperature, and total precipitation simulations were used. Other CMIP6 GCM variables (variable acronym listed) downloaded from the Earth System Grid Federation (ESGF) included monthly surface downwelling shortwave radiation (rsds), surface (air) pressure (ps), near-surface relative humidity (hurs) and near-surface wind speed (sfcWind). These four GCM variables were not bias-corrected due to limited availability of credible/robust gridded observational datasets over Canada. Literature also suggests that bias-correction is most pertinent for temperature and precipitation projections and less so for radiation, humidity and wind (Haddeland et al., 2012). Monthly relative humidity means for TaiESM1 were derived from daily simulations. The GCMs (and realizations) considered in the study are listed in Table 1.

This study produced SPEI datasets for a range of emission scenarios from the Shared Socioeconomic Pathways (SSPs) to assess the degree of projected warming with projections. The SSP-based scenarios, which span a range from very ambitious mitigation to ongoing growth in emissions, served as input for CMIP6 projections (Meinshausen et al., 2020). While SPEI projections are available for download for the three SSPs, for the purposes of the present study, we focused the results and discussion under the high emission scenario (SSP5-8.5).

2 BIAS-CORRECTED TEMPERATURE AND PRECIPITATION PROJECTIONS

Bias-corrected temperature and precipitation simulations from the CMIP6: Canadian Downscaled Climate Scenarios – Multivariate method (CanDCS-M6) dataset were used (Sobie et al., 2023). For the CanDCS-M6 dataset, temperature and precipitation simulations (1950–2100) were bias-corrected using the N-dimensional Multivariate Bias Correction (MBCn) (Cannon, 2016, 2018) with a new blended observational dataset as the matching target over 1951–2012. A new target downscaling dataset was developed by the Pacific Climate Impacts Consortium (PCIC), which combined an updated version of the ANUSPLIN gridded observational dataset with the PNWNAmet gridded observations (McKenney et al., 2011; Werner et al., 2019). Preliminary analyses (results not presented) showed that SPEI results differed considerably when using bias-corrected temperature and precipitation inputs in SPEI calculations as opposed to the raw data. As the CanDCS-M6 dataset is originally produced as a statistically downscaled daily dataset at a 10 km grid spatial resolution, monthly means of minimum and maximum temperature and monthly totals of precipitation were calculated. Monthly datasets were then regridded to a common 1×1 degree grid using bilinear interpolation.

b *PET estimations*

As alluded to previously, a multitude of approaches of varying complexity have been used to estimate PET. Physically-based methods are considered more accurate but are often not used due to extensive data requirements. Instead, simpler approaches are applied by substituting one or more atmospheric variable with proxies. Some of these approaches are based solely on air temperature (mean or maximum and minimum), used in combination with other variables (e.g. daylength, latitude). It was of interest to understand what differences may result for SPEI. Therefore, in comparison to a physically-based approach, two alternative approaches were considered: a physically-based approach that uses a temperature proxy for humidity and one based solely on air temperature (derived radiation).

The physically-based approach used was the PM method (PET-PM). It is the most complex and comprehensive approach, and the sole and universally recommended standard to estimate reference crop evapotranspiration (Allen et al., 1998). This reference evapotranspiration is an accepted proxy for atmospheric evaporative demand (Allen et al., 1998; Katerji & Rana, 2011; Tomas-Burguera et al., 2019). PM requires several input variables including wind speed, solar radiation, relative humidity, and air temperature. Procedures for calculating all related components are outlined in the Food and Agriculture Organization of the United Nations (FAO) Irrigation and Drainage Paper 56 (FAO-56) (Allen et al., 1998). While PM is strongly recommended, alternative approaches to estimating unavailable variables, such as relative humidity, radiation, and wind speed, are also outlined in Allen et al. (1998). The present study followed the recommended alternative approaches in the case of unavailable variables as described in FAO-56 (Allen et al., 1998).

Unavailable humidity data were substituted with a temperature proxy, and to isolate its role, the same PET-PM approach was used with the derived humidity (PET-PM-m) (Allen et al., 1998). In the case of even more limited data availability and in particular radiation, the temperature-based Hargreaves (HG) method was considered (Droogers & Allen, 2002; Hargreaves & Samani, 1985). The HG approach (PET-HG) incorporates minimum and maximum air temperature to derive solar radiation. It has been widely used including Tam et al. (2019) who assessed twenty-first century drought projections across Canada based on SPEI results from numerous CMIP5 GCMs.“

The aforementioned PET methods generally follow this definition:

$$PET = (\Delta \cdot Rn + \gamma \cdot \text{“mass transfer term”})/(\Delta + \gamma)$$

where R_n is net radiation, γ is the psychrometric constant, and Δ is the slope of the saturation-vapour-pressure vs temperature curve at air temperature (Stagge et al., 2014). PET-PM requires shortwave radiation input, atmospheric conditions (e.g. wind speed, humidity, temperature) to calculate mass transfer, and atmospheric surface pressure to calculate the psychometric constant (Santiago & Vicente-Serrano, 2023; Stagge et al., 2014).

PET-HG, on the other hand, uses a constant to estimate the mass transfer term, and a temperature proxy to estimate radiation with the following equation (Allen et al., 1998; Hargreaves & Samani, 1985; Paredes & Pereira, 2019):

$$R_s = k_{Rs}(\text{Tmax}\pm\text{Tmin})^{0.5}R_a$$

where R_s represents solar radiation, k_{Rs} as an empirical radiation adjustment coefficient (°$C^{-0.5}$), and R_a as extraterrestrial radiation. See Allen et al. (1998) for more details.

When humidity data are unavailable, this variable can be estimated with a temperature proxy (Tmin) with the assumption that dew point temperature is close to daily Tmin; thus, air is close to saturation and relative humidity is near 100%, resulting in an estimate for actual vapour pressure, as follows (Allen et al., 1998; Paredes & Pereira, 2019; Santiago & Vicente-Serrano, 2023):

$$e_a = e^o = 0.611\exp[17.27\text{Tmin}/(\text{Tmin} + 237.3)]$$

where e_a is actual vapour pressure at 2 m height and e^o is dew point temperature (^{o}C). This assumption is valid over areas that are well saturated, but less so for arid regions where the air may not be fully saturated at daily Tmin.

c *SPEI calculations and analyses*

SPEI was calculated by summing the difference between precipitation (P) and PET accumulated over *n* months, representing a simplified climatic water balance, which is then standardized to a normal (Gaussian) distribution (Beguería et al., 2014; Vicente-Serrano et al., 2010). The Pearson Type 3 probability distribution was used to fit the climatic water balance (P-PET) to yield SPEI values with a reference period of 1950–2014 for parameter calibration (Tam et al., 2023). L-Moments were used to estimate the probability distribution parameters and an unshifted rectangular kernel (i.e. equal weighting for previous *n* time steps) was applied to the accumulated water balance time series data.

SPEI results were analyzed for two time scales, which were chosen to represent different types of drought: 3-month (SPEI-3) and 12-month (SPEI-12) periods. Specifically, the 12-month SPEI was calculated for the water year (October-September) and is representative of longer-term hydrologic drought conditions. SPEI-3 was calculated for the standard seasons; spring (March to May), summer (June to August), autumn (September to November) and winter (December to February). Focus was on the summer and spring periods as they are critical for agricultural drought. SPEI results represent a relative measure of surface water surplus, i.e. positive values, or deficit, i.e. negative values, with respect to hydroclimate conditions of the chosen reference period of 1950–2014. A negative SPEI value indicates water deficit, and a positive value indicates a surplus.

Three sets of CMIP6 SPEI projections were computed and analyzed: 1. PET estimates based on PET-PM (SPEI-PM), 2. PET-PM-m (SPEI-PM-m), and 3. PET-HG (SPEI-HG). Seasonal SPEI, as well as the frequency of threshold exceedances of −1.5 and −2 of SPEI-12 were compared among SPEI-PM, SPEI-PM-m and SPEI-HG. For the study, SPEI < −1.5 and −2 represented severe and extreme water deficit, respectively (e.g. Bonsal et al., 2017).

3 Results

a *Comparison of future changes in SPEI*

Figure 1 displays boxplots of end of century Canada-wide annual and seasonal SPEI SSP5-8.5 projections of SPEI-PM, SPEI-PM-m and SPEI-HG. To gain insight into the spatial variability among the different methods, Fig. 2 maps projected median changes in annual and seasonal SPEI across Canada for all three methods. Difference maps (SPEI-PM minus SPEI-HG, and SPEI-PM minus SPEI-PM-m) are also provided. Negative differences indicate that SPEI-PM has larger moisture deficits (i.e. is drier) and positive differences reveal larger moisture surpluses. Median projected changes in PET totals shown in Table 2 were produced to further understand SPEI differences.

1 ANNUAL SPEI

Across Canada, an annual increase in drying is projected particularly over central/southern Canada including interior British Columbia, while increased wetting is found over the rest of British Columbia, the Maritimes, and coastal regions surrounding the Arctic. Although the patterns look similar among the three approaches, difference maps revealed some dissimilarities that were common to both SPEI-PM-m and SPEI-HG. Both proxy-based approaches projected slightly less drying over much of central, eastern, and northern parts of the country (with some areas approaching an absolute difference of 1.0) when compared to SPEI-PM. In extreme western Canada, there was little difference with SPEI-PM-m (derived humidity) while this region was substantially drier for SPEI-HG (nearing 1.0 in the extreme northwest). This was consistent with nation-wide SPEI values (Fig. 1) where SPEI-PM showed a SPEI median change of +0.5 while the two proxy-based methods were slightly wetter (nearly identical medians at ∼0.6). These differences were consistent with the projected changes in PET totals (Table 2), where PET-PM projected slightly greater increases in annual PET (+112 mm) (increased by 24%) compared with the other two approaches (+100–104 mm) (increased by 21–23%).

2 SUMMER SPEI

All three methods projected a predominance of summer drying across much of Canada with driest SPEI values in southern and central regions. This is consistent with projected warming and decreases in summer precipitation over southern Canada (Bush & Lemmen, 2019). Modest wetting is projected over the high Arctic islands, consistent with projected increases in precipitation in the region. Spatial differences between SPEI-PM and the two proxy methods were similar to the annual patterns (although less pronounced) with SPEI-HG showing greater differences. These findings were consistent with nation-wide values, where compared to SPEI-PM (median change of −0.7), both proxy-based approaches were less dry (both ∼−0.5). This can be attributed to greater increases in future summer PET-PM (+61 mm)

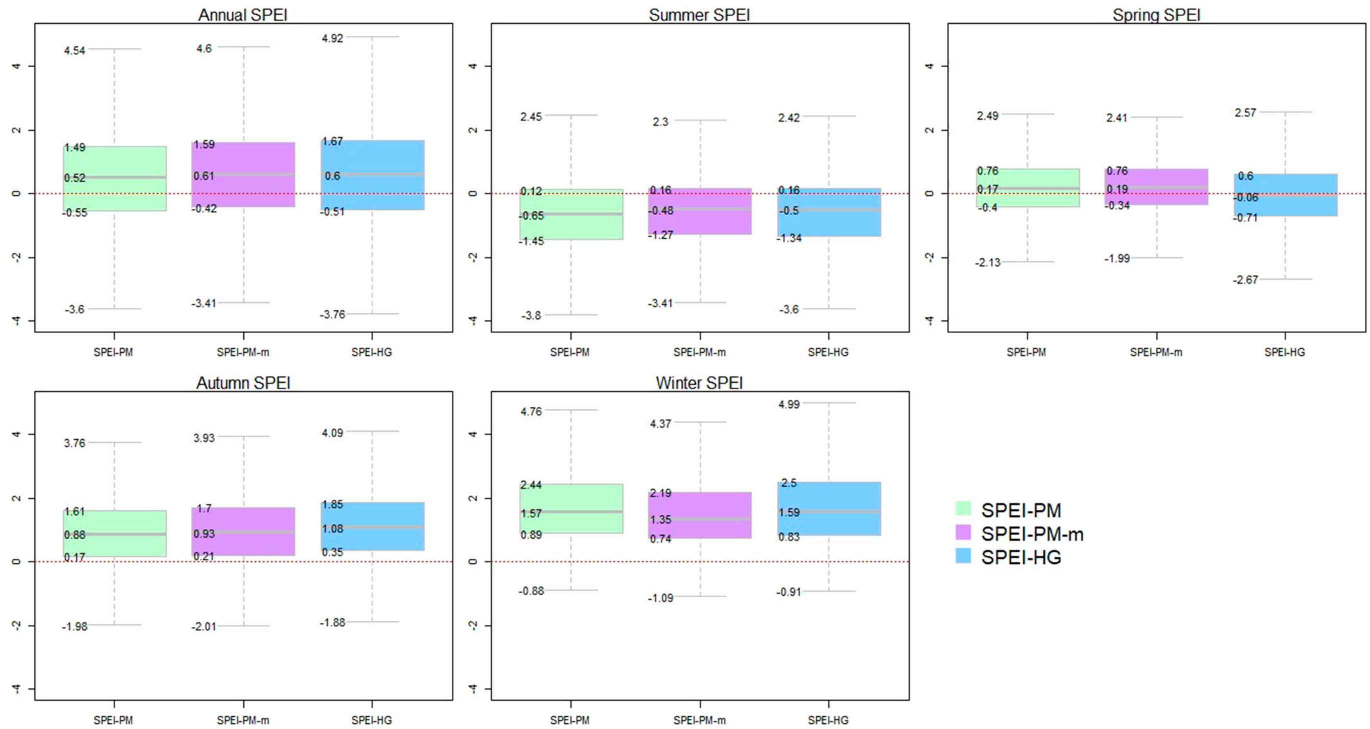

Fig. 1 CMIP6 annual and seasonal boxplots of SPEI-PM, SPEI-PM-m, SPEI-HG for the end of century (2081–2100) under a high emission scenario (SSP5-8.5). Boxplots, based on an ensemble of 22 CMIP6 GCMs, were based on Tukey with whiskers no more than 1.5 times the interquartile range. Outliers excluded.

(increased by 24%) when compared with PET-PM-m and PET-HG (both +53 mm) (increased by 19%).

3 SPRING SPEI

During spring, Canada is projected to experience both wetter and drier conditions across different regions of the country that are generally consistent among the three methods. Increased drying is found in the northwestern region that weakens in a southeastward direction through central Canada and the Prairies. For the most part, the rest of Canada is projected to become wetter. Small spatial differences were apparent between SPEI-PM and SPEI-PM-m. However, SPEI with derived radiation (SPEI-HG) projected much drier conditions over northern Canada and southwestern British Columbia. This difference is reflective of the considerably drier Canada-wide median SPEI-HG value (~−0.1) compared with the small positive SPEI medians (~0.2) for the other two approaches. This can be linked to greater projected increases in spring PET-HG (+34 mm) (increased by 32%) than PET-PM (+26 mm) and PET-PM-m (+25 mm) (increased by 20–23%).

4 AUTUMN SPEI

Projected changes in autumn SPEI were somewhat similar to annual SPEI where drying is projected to be more concentrated over the southern Prairies and extreme southern Ontario, along with increased wetting over most of the rest of Canada. Differences between SPEI-PM and the other two approaches were once again more apparent with SPEI-HG especially in the southern Prairies and western Arctic islands where this approach projected considerably less drying. Differences with SPEI-PM-m were fairly minor. Once again, these SPEI-HG differences were consistent with nation-wide autumn SPEI where SPEI-HG was wetter (median value +1.08) compared to the other two median values of ~+0.9. This was also reflected in projected PET differences (10 mm versus 17 mm) (Table 2).

5 WINTER SPEI

Winter SPEI is projected to increase over all of Canada, with intensity increasing in a southwestern to northeastern direction. The North and northeastern parts of Canada are projected to experience much more wetting than the rest of the country. Unlike the other periods, spatial differences were slightly greater for SPEI-PM-m rather than SPEI-HG. However, given the small amounts of PET during this season (Table 2) it is very likely that the choice of method has a small influence on the resultant SPEI during winter.

To summarize, all three methods showed generally similar spatial patterns in future SPEI changes during all periods considered. Some spatial differences, however, were identified. Proxy-based approaches (SPEI-HG and SPEI-PM-m) tended to show more drying in the extreme west and less drying over most of the rest of the country, particularly the North. These differences were particularly evident during annual,

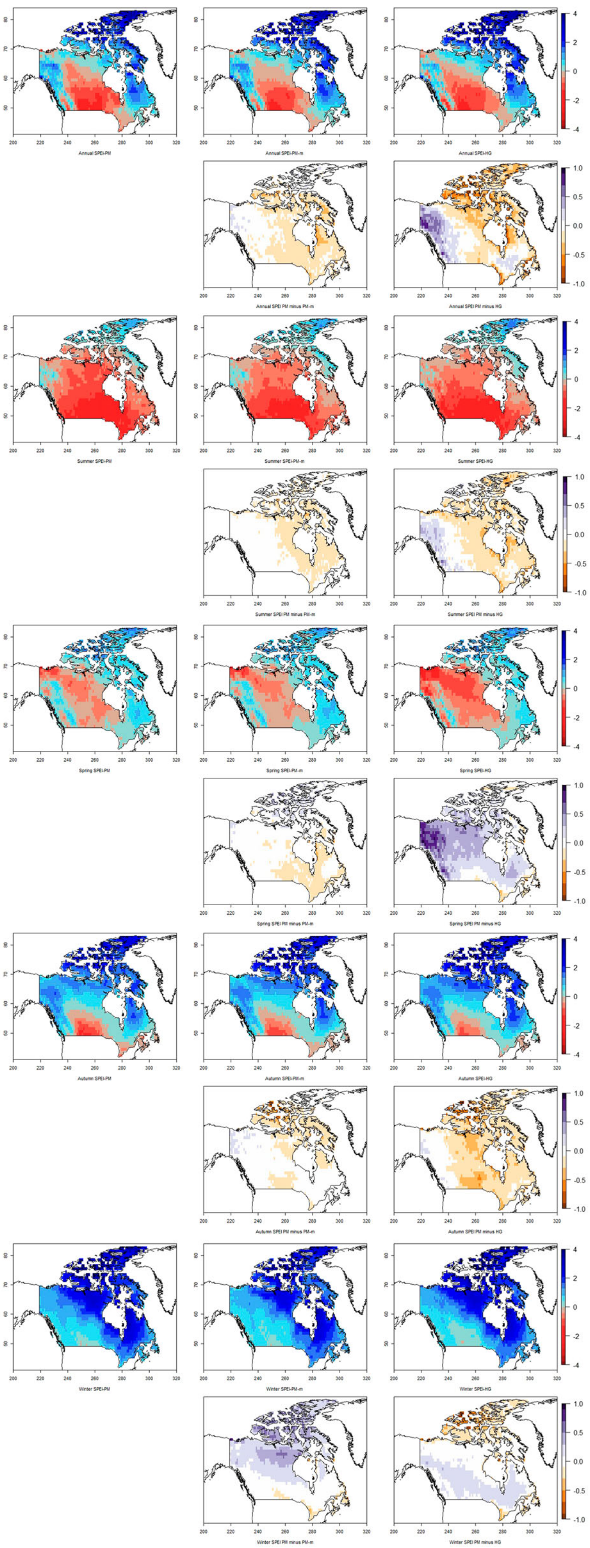

Fig. 2 Projected median annual and seasonal changes in CMIP6 SPEI-PM (left column), SPEI-PM-m (middle column) and SPEI-HG (right column), as well as the median differences to SPEI-PM-m and SPEI-HG, for the end of century (2081–2100) under a high emission scenario (SSP5-8.5). Negative differences indicate that SPEI-PM has larger moisture deficits (i.e. is drier) and positive differences reveal larger moisture surpluses. Maps are based on an ensemble of 22 CMIP6 GCMs.

TABLE 2. Projected changes in median PET totals (mm) for end of century (2081–2100) under SSP5-8.5 from 1950 to 2014 baseline time period.

Period	PET-PM	PET-PM-m	PET-HG
Baseline PET totals for 1950–2014			
Annual	464	504	435
Summer	271	274	278
Spring	113	127	106
Autumn	68	79	44
Winter	8	18	0
Projected changes in PET totals for 2081–2100			
Annual	112	104	100
Summer	61	53	53
Spring	26	25	34
Autumn	17	17	10
Winter	3	7	2

summer, and to a lesser degree autumn time frames and more prominently for SPEI-HG. Spring differed in that SPEI-HG projected much drier conditions over much of the country compared to SPEI-PM. While in winter, greatest differences occurred between SPEI-PM and SPEI-PM-m where the latter was associated with less wetting in extreme northern Canada.

Although only scenarios under SSP5-8.5 are presented, results for SSPs 1–2.6 and 2–4.5 reflected similar spatial trends, with decreasing intensity (both positive and negative) for lower emission scenarios (not shown).

b *Future changes in severe and extreme drought*

Projected annual, summer and spring changes in severe (SPEI < -1.5) water deficits (i.e. droughts that have the greatest impacts) among SPEI-PM, SPEI-PM-m and SPEI-HG are provided in Fig. 3. Differences with respect to SPEI-PM are also provided. Note that changes in future extreme drought (SPEI < -2) were also assessed and the spatial patterns were almost identical to those using SPEI < -1.5, albeit with fewer exceedances (not shown).

Annual SPEI-PM maps revealed that the majority of extreme events are projected over the southern half of the Canadian Prairies with much of this region experiencing eight to ten more years of severe drought (~ half of the time) and four to six more years of extreme drought (latter not shown). This is substantially higher than the modelled baseline period of 1950–2014 when most of the nation was associated with ~four years of severe drought and ~one year of extreme drought (not shown). Figure 3 reveals that the rest of the country is projected to experience between zero and four more occurrences of severe and extreme drought. Differences for the two proxy-based approaches were similar over the southern Canadian Prairies and extreme southwestern Ontario where slightly lower frequencies of severe drought (one to three) were projected. As with Fig. 2, SPEI-HG showed more drying in extreme western Canada as indicated by the higher projected severe drought frequencies (one to three) in this region.

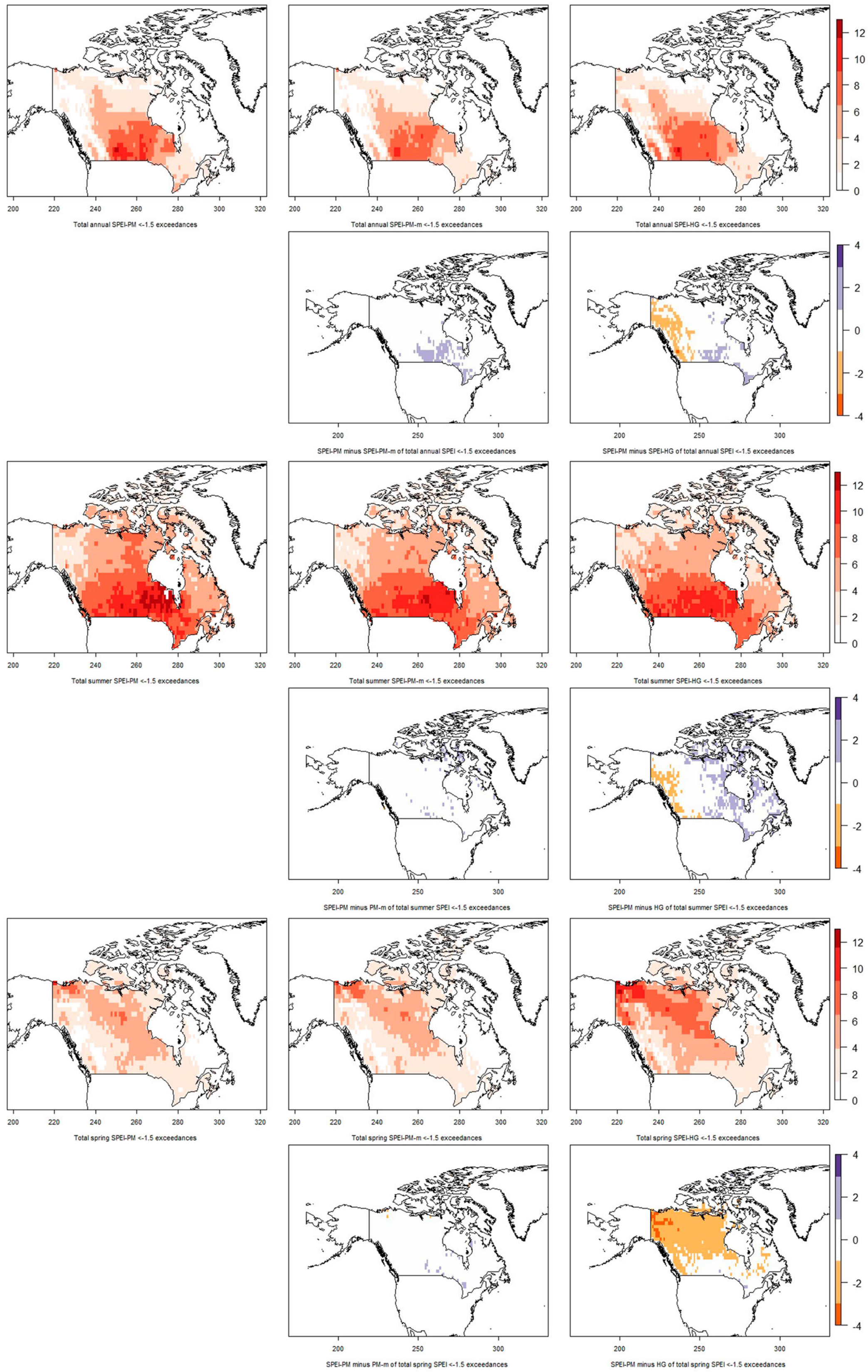

Fig. 3 Projected median total threshold exceedances of annual, summer and spring SPEI< −1.5 representing severe drought for SPEI-PM (left column), SPEI-PM-m (middle column) and SPEI-HG (right column), as well as the median differences with SPEI-PM-m and SPEI-HG for the end of century (2081–2100) under a high emission scenario (SSP5-8.5). Positive differences indicate that SPEI-PM has more threshold exceedances, i.e. more extreme dry periods, while negative differences reveal fewer threshold exceedances, i.e. fewer dry extremes. Maps are based on an ensemble of 22 CMIP6 GCMs.

Seasonal patterns for all three approaches revealed an increase in severe and extreme summer droughts over most of Canada, especially across the southern half of the country (∼eight to twelve more years of severe drought and ∼six to eight more years of extreme drought). Only the high Arctic islands may experience zero increases in the summer. Differences between the two PM approaches were almost negligible while differences for summer SPEI-HG resembled the annual severe drought differences. For spring, an increased severe and extreme drought is also expected, however, the spatial pattern differs from summer. Most occurrences are concentrated in the northwestern to northcentral region of the country with ∼six more years of severe droughts projected. The rest of Canada showed an approximate increase of two more years in severe and extreme spring droughts while the Arctic, the Maritimes and some sporadic regions in western Canada have zero increases. Compared to SPEI-PM, spring presented the most noticeable differences with HG. Similar to differences in Fig. 2, SPEI-HG projected higher frequencies of extremes (two to four more occurrences) over much of northern Canada west of Hudson Bay. Spring differences between the two PM approaches were negligible.

In summary, Fig. 3 revealed some differences in severe and extreme drought projections among the three approaches that spatially resembled those shown for average SPEI in Fig. 2 (although they tend to be less evident). Similar to Fig. 2, differences were greatest for the temperature proxy HG method and in particular in spring where differences were concentrated in more northwestern and northcentral regions of the country. Severe and extreme drought projections associated with SSPs 1–2.6 and 2–4.5 reflected similar spatial trends to SSP5-8.5, with decreasing severity for lower emission scenarios (not shown). Differences between the two PM approaches were negligible while differences with HG continue to be apparent, albeit less frequent.

4 Discussion and conclusions

The preceding assessed the effects of using temperature proxies for radiation and/or humidity in the estimation of PET and resultant annual and seasonal SPEI projections across Canada. Though beyond the scope of the present study, it's important to note that PET on daily or sub-daily time scales would require further assessment to account for other factors such as the diurnal cycle. Also, while these results are specific to SPEI, it's possible that similar patterns may be found in other indices that incorporate PET; further research exploring these differences is recommended. Comparisons were made in relation to projected SPEI medians and extremes based on PET estimations using the physically-based PM method. To show the differences clearly, results focused on projected changes at the end of the twenty-first century under the high SSP5-8.5 scenario. Although the general patterns of SPEI projections were consistent among the methods, there were some discernible differences. In particular, both median and extreme SPEI projections based on the two temperature proxy methods revealed less annual and summer drying in many regions across Canada when compared to the physically based SPEI-PM (Figs. 2 and 3). Differences of using temperature derived radiation and humidity were also more apparent in spring (and to a lesser degree, autumn), where the HG approach overestimated spring drying (and autumn wetting). As the water year is used to represent longer term hydrologic drought, and summer and spring for agricultural drought, the under/overestimation during these critical time periods can have implications on the interpretation of drought results, especially over certain regions of Canada where the differences are greatest. As alluded to previously, differences using derived humidity were more subtle and most noticeable in winter where this approach showed an underestimation of winter wetting. Given the small amounts of PET during winter, it is very likely that the choice of method has a small influence on the resultant SPEI during this season, which is primarily driven by precipitation changes. It should be noted that the present study examined differences in proxy-based SPEI projections through the use of a large multi-model ensemble, thus reducing large inter-model discrepancies. Assessment of changes were also primarily based on median SPEI projections under the high emission scenario at the end of the twenty-first century. For the most part, the other SSPs showed similar results albeit less pronounced.

The aforementioned differences in projected SPEI are directly attributable to the use of temperature proxies to derive radiation and/or humidity in the calculation of PET. The possible shortcomings of using temperature proxies have been previously assessed in numerous studies, which generally concluded that such approaches often lead to biased results. For example, differences in regional (i.e. Europe, North America) and global drought projections were more noticeable when using simpler temperature-based methods compared to PM (Kingston et al., 2009; McAfee, 2013; McKenney & Rosenberg, 1993; Shaw & Riha, 2011). In fact, the simplest empirical approaches, such as Thornthwaite or Hamon, have been found to greatly overestimate drying (Kingston et al., 2009; Lofgren et al., 2011; McAfee, 2013; Shaw & Riha, 2011), which is why such methods were not considered here. In this analysis, nation-wide comparisons yielded relatively minor differences in SPEI, with the exception of spring where derived radiation SPEI (SPEI-HG) was much drier (Fig. 1) and as expected, spring PET-HG changes were substantially higher (Table 2). This difference is possibly due to projected decreases in shortwave radiation across Canada that are not captured in the HG method. These decreases are greatest in spring when much of Canada is projected to experience a more noticeable decline in shortwave radiation (∼30%) compared to other seasons or annually (McAfee, 2013). Projected decreases in radiation in summer and annually are also found over the Arctic and extreme western Canada (Saenz & Huang, 2015), though to a lesser extent (∼10–20%)

(McAfee, 2013); possibly explaining why SPEI-HG projected greater drying over extreme west during these periods (Fig. 2). However, greater SPEI-HG drying is not observed in the Arctic region, which suggests that this region is more highly impacted by the differences in humidity (see Figs. 2 and 3). For most periods (with the exception of winter), the proxy-based approach underestimates drying across approximately the eastern half of Canada. As shown in the IPCC AR6 report, central to eastern Canada is also projected to experience reductions in summer relative humidity (4–6%) by the end of century under SSP3-7.0, with southern regions having slightly larger decreases (Lee et al., 2021). Though the projected changes in humidity may seem small, it's possible that they do have an effect on drought projections. Further research is required to determine the interrelated impacts of projected changes of both humidity and radiation on future drought in Canada.

It is important to consider that the extent of differences in proxy-based approaches varied considerably across Canada. During the water year and summer, proxy-based approaches projected fewer severe and extreme drought occurrences over the southern Prairies and southwestern Ontario. The southern Canadian Prairies are already more prone to droughts and many studies suggest that conditions will worsen under a warmer climate with an increase in the frequency, severity and duration of droughts, including multi-year and extreme droughts (Bonsal et al., 2013, 2020; Masud et al., 2017; PaiMazumder et al., 2013). As most of these studies used a temperature proxy for PET calculation, it is possible that future changes in drought and resultant impacts in this region may have been underestimated based on the results from this study. For spring, temperature proxy (HG) SPEI revealed more severe and extreme droughts over northwestern and northcentral Canada. Several regional investigations in extreme western and northern Canada have examined future drought impacts on forestry and vegetation and determined that increased temperatures will likely lead to a shift or disturbance of vegetation and tree growth, loss of forest cover, and increased risk to forest fires (Hogg & Hurdle, 1995; Reid et al., 2022; Wang et al., 2014; Xiao & Zhuang, 2007). As most of these studies also used a temperature proxy, it's possible that such projected changes and the related risks may be less than originally anticipated.

In conclusion, even though the general, large-scale patterns of SPEI projections were consistent among the different PET methods assessed in this study, the identified temporal and spatial differences warrant caution when using temperature-based proxies for radiation and to a lesser extent, humidity. It should be noted that the present study considers the PM method as the most robust approach to estimating PET. While the PM approach is widely recommended, further research to compare ground-based measurements to the PM approach may provide additional insight on the interpretation of PET projections. Nonetheless, based on the findings of the present study and those from other studies (e.g. Amatya et al., 1995; Lai et al., 2022; Liljedahl et al., 2011; Stagge et al., 2014) it is recommended that, when possible, a physically-based approach and a multi-model ensemble be used when assessing future drought projections based on indices such as the SPEI. When variables such as radiation and humidity are not available, or when assessing previous studies that used temperature proxy methods, implications need to be evaluated depending on the scale, season, and impacts being considered.

All CMIP6 datasets described here are available for download through Environment and Climate Change Canada's Canadian Climate Data and Scenarios (CCDS) site (Environment and Climate Change Canada, 2023). Next steps are to expand the assessment on the suite of drought types by incorporating projected agricultural (soil moisture) and hydrological (runoff) changes. This comprehensive drought assessment will inform anticipated impacts and vulnerabilities on water resources, ecosystems, agriculture, and Canadians.

Acknowledgements

We thank Dae Il Jeong and Rajesh Shrestha for their review and constructive comments that helped improve the manuscript. We acknowledge the international modelling centres, the Program for Climate Model Diagnosis and Intercomparison, the World Climate Research Program, and the Coupled Model Intercomparison Project for their roles in making available global climate model (GCM) datasets.

Disclosure statement

No potential conflict of interest was reported by the author(s).

References

Allen, R. G., Pereira, L. S., Raes, D., & Smith, M. (1998). Crop evapotranspiration-Guidelines for computing crop water requirements-FAO Irrigation and drainage paper 56. *Fao, Rome*, *300*(9), D05109.

Amatya, D. M., Skaggs, R. W., & Gregory, J. D. (1995). Comparison of methods for estimating REF-ET. *Journal of Irrigation and Drainage Engineering*, *121*(6), 427–435. https://doi.org/10.1061/(ASCE)0733-9437(1995)121:6(427)

Arias, P., Bellouin, N., Coppola, E., Jones, R., Krinner, G., Marotzke, J., Naik, V., Palmer, M., Plattner, G.-K., & Rogelj, J. (2021). *Climate change 2021: The physical science basis. Contribution of working group I to the sixth assessment report of the intergovernmental panel on climate change; technical summary*.

Ault, T. R. (2020). On the essentials of drought in a changing climate. *Science*, *368*(6488), 256–260. https://doi.org/10.1126/science.aaz5492

Beguería, S., Vicente-Serrano, S. M., Reig, F., & Latorre, B. (2014). Standardized precipitation evapotranspiration index (SPEI) revisited: Parameter fitting, evapotranspiration models, tools, datasets and drought monitoring. *International Journal of Climatology*, *34*(10), 3001–3023. https://doi.org/10.1002/joc.3887

Bi, D., Dix, M., Marsland, S., O'Farrell, S., Sullivan, A., Bodman, R., Law, R., Harman, I., Srbinovsky, J., Rashid, H. A., Dobrohotoff, P., Mackallah, C., Yan, H., Hirst, A., Savita, A., Dias, F. B., Woodhouse, M., Fiedler, R., & Heerdegen, A. (2020). Configuration and spin-up of ACCESS-CM2, the new generation Australian community climate and earth system simulator coupled model. *Journal of Southern Hemisphere Earth Systems Science*, *70*(1), 225–251. https://doi.org/10.1071/ES19040

Bonsal, B. R., Aider, R., Gachon, P., & Lapp, S. (2013). An assessment of Canadian prairie drought: Past, present, and future. *Climate Dynamics*, *41*(2), 501–516. https://doi.org/10.1007/s00382-012-1422-0

Bonsal, B. R., Cuell, C., Wheaton, E., Sauchyn, D. J., & Barrow, E. (2017). An assessment of historical and projected future hydro-climatic variability and extremes over southern watersheds in the Canadian Prairies. *International Journal of Climatology*, *37*(10), 3934–3948. https://doi.org/10.1002/joc.4967

Bonsal, B. R., Liu, Z., Wheaton, E., & Stewart, R. (2020). Historical and projected changes to the stages and other characteristics of severe Canadian Prairie droughts. *Water*, *12*(12), 3370. https://doi.org/10.3390/w12123370

Bonsal, B. R., Peters, D. L., Seglenieks, F., Rivera, A., & Berg, A. (2019). Changes in freshwater availability across Canada. *Canada's Changing Climate Report*, 261–342.

Bonsal, B. R., Wheaton, E. E., Chipanshi, A. C., Lin, C., Sauchyn, D. J., & Wen, L. (2011). Drought research in Canada: A review. *Atmosphere-Ocean*, *49*(4), 303–319. https://doi.org/10.1080/07055900.2011.555103

Boucher, O., Servonnat, J., Albright, A. L., Aumont, O., Balkanski, Y., Bastrikov, V., Bekki, S., Bonnet, R., Bony, S., Bopp, L., Braconnot, P., Brockmann, P., Cadule, P., Caubel, A., Cheruy, F., Codron, F., Cozic, A., Cugnet, D., D'Andrea, F., … Vuichard, N. (2020). Presentation and evaluation of the IPSL-CM6A-LR climate model. *Journal of Advances in Modeling Earth Systems*, *12*(7), e2019MS002010. https://doi.org/10.1029/2019MS002010

Bush, E., & Lemmen, D. S. (2019). *Canada's changing climate report*. Government of Canada.

Cannon, A. J. (2016). Multivariate bias correction of climate model output: Matching marginal distributions and intervariable dependence structure. *Journal of Climate*, *29*(19), 7045–7064. https://doi.org/10.1175/JCLI-D-15-0679.1

Cannon, A. J. (2018). Multivariate quantile mapping bias correction: An N-dimensional probability density function transform for climate model simulations of multiple variables. *Climate Dynamics*, *50*(1–2), 31–49. https://doi.org/10.1007/s00382-017-3580-6

Cherchi, A., Fogli, P. G., Lovato, T., Peano, D., Iovino, D., Gualdi, S., Masina, S., Scoccimarro, E., Materia, S., Bellucci, A., & Navarra, A. (2019). Global mean climate and main patterns of variability in the CMCC-CM2 coupled model. *Journal of Advances in Modeling Earth Systems*, *11*(1), 185–209. https://doi.org/10.1029/2018MS001369

Dibike, Y., Prowse, T., Bonsal, B., & O'Neil, H. (2017). Implications of future climate on water availability in the western Canadian river basins. *International Journal of Climatology*, *37*(7), 3247–3263. https://doi.org/10.1002/joc.4912

Döscher, R., Acosta, M., Alessandri, A., Anthoni, P., Arsouze, T., Bergman, T., Bernardello, R., Boussetta, S., Caron, L.-P., Carver, G., Castrillo, M., Catalano, F., Cvijanovic, I., Davini, P., Dekker, E., Doblas-Reyes, F. J., Docquier, D., Echevarria, P., Fladrich, U., … Zhang, Q. (2022). The EC-Earth3 earth system model for the coupled model intercomparison project 6. *Geoscientific Model Development*, *15*(7), 2973–3020. https://doi.org/10.5194/gmd-15-2973-2022

Droogers, P., & Allen, R. G. (2002). Estimating reference evapotranspiration under inaccurate data conditions. *Irrigation and drainage systems*, *16*, 33–45. https://doi.org/10.1023/A:1015508322413

Dunne, J. P., Horowitz, L. W., Adcroft, A. J., Ginoux, P., Held, I. M., John, J. G., Krasting, J. P., Malyshev, S., Naik, V., Paulot, F., Shevliakova, E., Stock, C. A., Zadeh, N., Balaji, V., Blanton, C., Dunne, K. A., Dupuis, C., Durachta, J., Dussin, R., … Zhao, M. (2020). The gfdl earth system model version 4.1 (GFDL-ESM 4.1): Overall coupled model description and simulation characteristics. *Journal of Advances in Modeling Earth Systems*, *12*(11), e2019MS002015. https://doi.org/10.1029/2019MS002015

Environment and Climate Change Canada. (2023). *Canadian climate data and scenarios*. https://climate-scenarios.canada.ca

Eyring, V., Bony, S., Meehl, G. A., Senior, C. A., Stevens, B., Stouffer, R. J., & Taylor, K. E. (2016). Overview of the coupled model intercomparison project phase 6 (CMIP6) experimental design and organization. *Geoscientific Model Development*, *9*(5), 1937–1958. https://doi.org/10.5194/gmd-9-1937-2016

Ficklin, D. L., & Novick, K. A. (2017). Historic and projected changes in vapor pressure deficit suggest a continental-scale drying of the United States atmosphere. *Journal of Geophysical Research: Atmospheres*, *122*(4), 2061–2079. https://doi.org/10.1002/2016JD025855

Haddeland, I., Heinke, J., Voß, F., Eisner, S., Chen, C., Hagemann, S., & Ludwig, F. (2012). Effects of climate model radiation, humidity and wind estimates on hydrological simulations. *Hydrology and Earth System Sciences*, *16*(2), 305–318. https://doi.org/10.5194/hess-16-305-2012

Hajima, T., Watanabe, M., Yamamoto, A., Tatebe, H., Noguchi, M. A., Abe, M., Ohgaito, R., Ito, A., Yamazaki, D., Okajima, H., Ito, A., Takata, K., Ogochi, K., Watanabe, S., & Kawamiya, M. (2020). Development of the MIROC-ES2L Earth system model and the evaluation of biogeochemical processes and feedbacks. *Geoscientific Model Development*, *13*(5), 2197–2244. https://doi.org/10.5194/gmd-13-2197-2020

Hargreaves, G. H., & Samani, Z. A. (1985). Reference crop evapotranspiration from temperature. *Applied Engineering in Agriculture*, *1*(2), 96–99. https://doi.org/10.13031/2013.26773

Hasiotis, S. T., Kraus, M. J., & Demko, T. M. (2007). Climatic controls on continental trace fossils. In *Trace fossils* (pp. 172–195). Elsevier. https://doi.org/10.1016/B978-044452949-7/50137-6.

Hogg, E. H., & Hurdle, P. A. (1995). The aspen parkland in western Canada: A dry-climate analogue for the future boreal forest? *Water, Air, and Soil Pollution*, *82*(1-2), 391–400. https://doi.org/10.1007/BF01182849

Jensen, M. E., Burman, R. D., & Allen, R. G. (1990). *Evapotranspiration and irrigation water requirements*. https://doi.org/10.1061/9780784414057.

Katerji, N., & Rana, G. (2011). Crop reference evapotranspiration: A discussion of the concept, analysis of the process and validation. *Water Resources Management*, *25*(6), 1581–1600. https://doi.org/10.1007/s11269-010-9762-1

Kingston, D. G., Todd, M. C., Taylor, R. G., Thompson, J. R., & Arnell, N. W. (2009). Uncertainty in the estimation of potential evapotranspiration under climate change. *Geophysical Research Letters*, *36*(20), https://doi.org/10.1029/2009GL040267

Lai, C., Chen, X., Zhong, R., & Wang, Z. (2022). Implication of climate variable selections on the uncertainty of reference crop evapotranspiration projections propagated from climate variables projections under climate change. *Agricultural Water Management*, *259*, 107273. https://doi.org/10.1016/j.agwat.2021.107273

Lee, J.-Y., Marotzke, J., Bala, G., Cao, L., Corti, S., Dunne, J. P., Engelbrecht, F., Fischer, E., Fyfe, J. C., & Jones, C. (2021). *Future global climate: Scenario-based projections and near-term information*. IPCC.

Lee, W.-L., Wang, Y.-C., Shiu, C.-J., Tsai, I.-c., Tu, C.-Y., Lan, Y.-Y., Chen, J.-P., Pan, H.-L., & Hsu, H.-H. (2020). Taiwan earth system model version 1: Description and evaluation of mean state. *Geoscientific Model Development*, *13*(9), 3887–3904. https://doi.org/10.5194/gmd-13-3887-2020

Li, L., Yu, Y., Tang, Y., Lin, P., Xie, J., Song, M., Dong, L., Zhou, T., Liu, L., Wang, L., Pu, Y., Chen, X., Chen, L., Xie, Z., Liu, H., Zhang, L., Huang, X., Feng, T., Zheng, W., … Wei, J. (2020). The flexible global ocean-atmosphere-land system model grid-point version 3 (FGOALS-g3): Description and evaluation. *Journal of Advances in Modeling Earth Systems*, *12*(9), e2019MS002012. https://doi.org/10.1029/2019MS002012

Liljedahl, A. K., Hinzman, L. D., Harazono, Y., Zona, D., Tweedie, C. E., Hollister, R. D., Engstrom, R., & Oechel, W. C. (2011). Nonlinear controls on evapotranspiration in arctic coastal wetlands. *Biogeosciences (online)*, *8*(11), 3375–3389. https://doi.org/10.5194/bg-8-3375-2011

Lloyd-Hughes, B. (2014). The impracticality of a universal drought definition. *Theoretical and Applied Climatology*, *117*(3-4), 607–611. https://doi.org/10.1007/s00704-013-1025-7

Lofgren, B. M., Hunter, T. S., & Wilbarger, J. (2011). Effects of using air temperature as a proxy for potential evapotranspiration in climate change scenarios of Great Lakes basin hydrology. *Journal of Great Lakes Research*, *37*(4), 744–752. https://doi.org/10.1016/j.jglr.2011.09.006

Lovato, T., Peano, D., Butenschön, M., Materia, S., Iovino, D., Scoccimarro, E., Fogli, P. G., Cherchi, A., Bellucci, A., Gualdi, S., Masina, S., & Navarra, A. (2022). CMIP6 simulations with the CMCC Earth system model (CMCC-ESM2). *Journal of Advances in Modeling Earth Systems*, *14*(3), e2021MS002814. https://doi.org/10.1029/2021MS002814

Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S. L., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., & Gomis, M. I. (2021). Climate change 2021: The physical science basis. *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, *2*.

Masud, M. B., Khaliq, M. N., & Wheater, H. S. (2017). Future changes to drought characteristics over the Canadian Prairie Provinces based on NARCCAP multi-RCM ensemble. *Climate Dynamics*, *48*(7), 2685–2705. https://doi.org/10.1007/s00382-016-3232-2

Mauritsen, T., Bader, J., Becker, T., Behrens, J., Bittner, M., Brokopf, R., Brovkin, V., Claussen, M., Crueger, T., Esch, M., Fast, I., Fiedler, S., Fläschner, D., Gayler, V., Giorgetta, M., Goll, D. S., Haak, H., Hagemann, S., Hedemann, C., … Roeckner, E. (2019). Developments in the MPI-M earth system model version 1.2 (MPI-ESM1. 2) and its response to increasing CO2. *Journal of Advances in Modeling Earth Systems*, *11*(4), 998–1038. https://doi.org/10.1029/2018MS001400

McAfee, S. A. (2013). Methodological differences in projected potential evapotranspiration. *Climatic Change*, *120*(4), 915–930. https://doi.org/10.1007/s10584-013-0864-7

McKenney, D. W., Hutchinson, M. F., Papadopol, P., Lawrence, K., Pedlar, J., Campbell, K., Milewska, E., Hopkinson, R. F., Price, D., & Owen, T. (2011). Customized spatial climate models for North America. *Bulletin of the American Meteorological Society*, *92*(12), 1611–1622. https://doi.org/10.1175/2011BAMS3132.1

McKenney, M. S., & Rosenberg, N. J. (1993). Sensitivity of some potential evapotranspiration estimation methods to climate change. *Agricultural and Forest Meteorology*, *64*(1–2), 81–110. https://doi.org/10.1016/0168-1923(93)90095-Y

McMahon, T. A., Peel, M. C., Lowe, L., Srikanthan, R., & McVicar, T. R. (2013). Estimating actual, potential, reference crop and pan evaporation using standard meteorological data: A pragmatic synthesis. *Hydrology and Earth System Sciences*, *17*(4), 1331–1363. https://doi.org/10.5194/hess-17-1331-2013

Meinshausen, M., Nicholls, Z. R., Lewis, J., Gidden, M. J., Vogel, E., Freund, M., Beyerle, U., Gessner, C., Nauels, A., Bauer, N., Canadell, J. G., Daniel, J. S., John, A., Krummel, P. B., Luderer, G., Meinshausen, N., Montzka, S. A., Rayner, P. J., Reimann, S., … Wang, R. H. J. (2020). The shared socio-economic pathway (SSP) greenhouse gas concentrations and their extensions to 2500. *Geoscientific Model Development*, *13*(8), 3571–3605. https://doi.org/10.5194/gmd-13-3571-2020

Mizuta, R., Yoshimura, H., Murakami, H., Matsueda, M., Endo, H., Ose, T., Kamiguchi, K., Hosaka, M., Sugi, M., & Yukimoto, S. (2012). Climate simulations using MRI-AGCM3. 2 with 20-km grid. ☒☒☒☒. ☒ *2* ☒, *90*, 233–258. https://doi.org/10.2151/jmsj.2012-A12

Müller, W. A., Jungclaus, J. H., Mauritsen, T., Baehr, J., Bittner, M., Budich, R., Bunzel, F., Esch, M., Ghosh, R., Haak, H., Ilyina, T., Kleine, T., Kornblueh, L., Li, H., Modali, K., Notz, D., Pohlmann, H., Roeckner, E., Stemmler, I., … Marotzke, J. (2018). A higher-resolution version of the max planck institute earth system model (MPI-ESM1. 2-HR). *Journal of Advances in Modeling Earth Systems*, *10*(7), 1383–1413. https://doi.org/10.1029/2017MS001217

PaiMazumder, D., Sushama, L., Laprise, R., Khaliq, M. N., & Sauchyn, D. (2013). Canadian RCM projected changes to short-and long-term drought characteristics over the Canadian Prairies. *International Journal of Climatology*, *33*(6), 1409–1423. https://doi.org/10.1002/joc.3521

Pak, G., Noh, Y., Lee, M.-I., Yeh, S.-W., Kim, D., Kim, S.-Y., Lee, J.-L., Lee, H. J., Hyun, S.-H., Lee, K.-Y., Lee, J.-H., Park, Y.-G., Jin, H., Park, H., & Kim, Y. H. (2021). Korea institute of ocean science and technology earth system model and its simulation characteristics. *Ocean Science Journal*, *56*(1), 18–45. https://doi.org/10.1007/s12601-021-00001-7

Palmer, W. C. (1965). *Meteorological drought (Vol. 30)*. US Department of Commerce.

Paredes, P., & Pereira, L. S. (2019). Computing FAO56 reference grass evapotranspiration PM-ETo from temperature with focus on solar radiation. *Agricultural Water Management*, *215*, 86–102. https://doi.org/10.1016/j.agwat.2018.12.014

Pereira, L. S., Allen, R. G., Smith, M., & Raes, D. (2015). Crop evapotranspiration estimation with FAO56: Past and future. *Agricultural Water Management*, *147*, 4–20. https://doi.org/10.1016/j.agwat.2014.07.031

Pimentel, R., Arheimer, B., Crochemore, L., Andersson, J. C. M., Pechlivanidis, I. G., & Gustafsson, D. (2023). Which potential evapotranspiration formula to use in hydrological modelling world-wide? *Water Resources Research*, e2022WR033447. https://doi.org/10.1029/2022WR033447

Reid, K. A., Reid, D. G., & Brown, C. D. (2022). Patterns of vegetation change in Yukon: Recent findings and future research in dynamic subarctic ecosystems. *Environmental Reviews*, *30*(3), 380–401. https://doi.org/10.1139/er-2021-0110

Saenz, G. A., & Huang, H.-P. (2015). Trends in downward solar radiation at the surface over North America from climate model projections and implications for solar energy. *Advances in Meteorology*, *2015*, 1–7. https://doi.org/10.1155/2015/483679

Saint-Martin, D., Geoffroy, O., Voldoire, A., Cattiaux, J., Brient, F., Chauvin, F., Chevallier, M., Colin, J., Decharme, B., Delire, C., Douville, H., Guérémy, J-F, Joetzjer, E., Ribes, A., Roehrig, R., Terray, L., & Valcke, S. (2021). Tracking changes in climate sensitivity in CNRM climate models. *Journal of Advances in Modeling Earth Systems*, *13*(6), e2020MS002190. https://doi.org/10.1029/2020MS002190

Santiago, B., & Vicente-Serrano, S. (2023). *R package: Calculation of the standardized precipitation-evapotranspiration index*. https://spei.csic.es

Séférian, R., Nabat, P., Michou, M., Saint-Martin, D., Voldoire, A., Colin, J., Decharme, B., Delire, C., Berthet, S., Chevallier, M., Sénési, S., Franchisteguy, L., Vial, J., Mallet, M., Joetzjer, E., Geoffroy, O., Guérémy, J., Moine, M., Msadek, R., … Madec, G. (2019). Evaluation of CNRM earth system model, CNRM-ESM2-1: Role of Earth system processes in present-day and future climate. *Journal of Advances in Modeling Earth Systems*, *11*(12), 4182–4227. https://doi.org/10.1029/2019MS001791

Seland, Ø, Bentsen, M., Olivìè, D. J. L., Toniazzo, T., Gjermundsen, A., Graff, L. S., Debernard, J. B., Gupta, A. K., He, Y.-C., Kirkevåg, A., Schwinger, J., Tjiputra, J., Aas, K. S., Bethke, I., Fan, Y., Griesfeller, J., Grini, A., Guo, C., Ilicak, M., … Schulz, M. (2020). Overview of the Norwegian Earth System Model (NorESM2) and key climate response of CMIP6 DECK, historical, and scenario simulations. *Geoscientific Model Development*, *13*(12), 6165–6200. https://doi.org/10.5194/gmd-13-6165-2020

Seneviratne, S. I., Zhang, X., Adnan, M., Badi, W., Dereczynski, C., Di Luca, A., Vicente-Serrano, S. M., Wehner, M., & Zhou, B. (2021). *11 Chapter 11: weather and climate extreme events in a changing climate*.

Sentelhas, P. C., Gillespie, T. J., & Santos, E. A. (2010). Evaluation of FAO Penman–Monteith and alternative methods for estimating reference evapotranspiration with missing data in Southern Ontario, Canada. *Agricultural Water Management*, *97*(5), 635–644. https://doi.org/10.1016/j.agwat.2009.12.001

Shaw, S. B., & Riha, S. J. (2011). Assessing temperature-based PET equations under a changing climate in temperate, deciduous forests. *Hydrological Processes*, *25*(9), 1466–1478. https://doi.org/10.1002/hyp.7913

Sheffield, J., Wood, E. F., & Roderick, M. L. (2012). Little change in global drought over the past 60 years. *Nature*, *491*(7424), 435–438. https://doi.org/10.1038/nature11575

Sobie, S. R., Ouali, D., Curry, C. L., & Zwiers, F. W. (2023). Multivariate canadian downscaled climate scenarios for CMIP6 (CanDCS-M6). *Manuscript Submitted*.

Stagge, J. H., Tallaksen, L. M., Xu, C. Y., & Van Lanen, H. A. (2014). Standardized precipitation-evapotranspiration index (SPEI): Sensitivity to potential evapotranspiration model and parameters. *Hydrology in a Changing World*, *363*, 367–373. https://doi.org/10.1002/joc.3887

Stocker, T. F., Qin, D., Plattner, G. K., Tignor, M., Allen, S. K., Boschung, J., Nauels, A., Xia, Y., Bex, V., & Midgley, P. M. (2013). Contribution of working group I to the fifth assessment report of the intergovernmental panel on climate change. *Climate Change*, *5*, 1–1552.

Swart, N. C., Cole, J. N., Kharin, V. V., Lazare, M., Scinocca, J. F., Gillett, N. P., Anstey, J., Arora, V., Christian, J. R., Hanna, S., Jiao, Y., Lee, W. G., Majaess, F., Saenko, O. A., Seiler, C., Seinen, C., Shao, A., Sigmond, M., Solheim, L., … Winter, B. (2019). The Canadian earth system model version 5 (CanESM5. 0.3). *Geoscientific Model Development*, *12*(11), 4823–4873. https://doi.org/10.5194/gmd-12-4823-2019

Tam, B. Y., Cannon, A. J., & Bonsal, B. R. (2023). *Standardized precipitation evapotranspiration index (SPEI) for Canada: Assessment of probability distributions*. https://doi.org/10.1080/07011784.2023.2183143.

Tam, B. Y., Szeto, K., Bonsal, B., Flato, G., Cannon, A. J., & Rong, R. (2019). CMIP5 drought projections in Canada based on the Standardized Precipitation Evapotranspiration Index. *Canadian Water Resources Journal/Revue Canadienne Des Ressources Hydriques*, *44*(1), 90–107. https://doi.org/10.1080/07011784.2018.1537812

Tatebe, H., Ogura, T., Nitta, T., Komuro, Y., Ogochi, K., Takemura, T., Sudo, K., Sekiguchi, M., Abe, M., Saito, F., Chikira, M., Watanabe, S., Mori, M., Hirota, N., Kawatani, Y., Mochizuki, T., Yoshimura, K., Takata, K., O'ishi, R., … Kimoto, M. (2019). Description and basic evaluation of simulated mean state, internal variability, and climate sensitivity in MIROC6. *Geoscientific Model Development*, *12*(7), 2727–2765. https://doi.org/10.5194/gmd-12-2727-2019

Tian-Jun, Z., & Tao, H. (2013). Projected changes of palmer drought severity index under an RCP8. 5 scenario. *Atmospheric and Oceanic Science Letters*, *6*(5), 273–278. https://doi.org/10.3878/j.issn.1674-2834.13.0032

Tomas-Burguera, M., Vicente-Serrano, S. M., Beguería, S., Reig, F., & Latorre, B. (2019). Reference crop evapotranspiration database in Spain (1961–2014). *Earth System Science Data*, *11*(4), 1917–1930. https://doi.org/10.5194/essd-11-1917-2019

Van der Schrier, G., Jones, P. D., & Briffa, K. R. (2011). The sensitivity of the PDSI to the Thornthwaite and Penman-Monteith parameterizations for potential evapotranspiration. *Journal of Geophysical Research: Atmospheres*, *116*(D3). https://doi.org/10.1029/2010JD015001

Vicente-Serrano, S. M., Beguería, S., & López-Moreno, J. I. (2010). A multiscalar drought index sensitive to global warming: The standardized precipitation evapotranspiration index. *Journal of Climate*, *23*(7), 1696–1718. https://doi.org/10.1175/2009JCLI2909.1

Voldoire, A., Saint-Martin, D., Sénési, S., Decharme, B., Alias, A., Chevallier, M., Colin, J., Guérémy, J.-F., Michou, M., Moine, M.-P., Nabat, P., Roehrig, R., Salas y Mélia, D., Séférian, R., Valcke, S., Beau, I., Belamari, S., Berthet, S., Cassou, C., … Waldman, R. (2019). Evaluation of CMIP6 deck experiments with CNRM-CM6-1. *Journal of Advances in Modeling Earth Systems*, *11*(7), 2177–2213. https://doi.org/10.1029/2019MS001683

Volodin, E. M., Mortikov, E. V., Kostrykin, S. V., Galin, V. Y., Lykossov, V. N., Gritsun, A. S., Diansky, N. A., Gusev, A. V., & Iakovlev, N. G. (2017). Simulation of the present-day climate with the climate model INMCM5. *Climate Dynamics*, *49*(11–12), 3715–3734. https://doi.org/10.1007/s00382-017-3539-7

Volodin, E. M., Mortikov, E. V., Kostrykin, S. V., Galin, V. Y., Lykossov, V. N., Gritsun, A. S., Diansky, N. A., Gusev, A. V., Iakovlev, N. G., Shestakova, A. A., & Emelina, S. V. (2018). Simulation of the modern climate using the INM-CM48 climate model. *Russian Journal of Numerical Analysis and Mathematical Modelling*, *33*(6), 367–374. https://doi.org/10.1515/rnam-2018-0032

Wang, Y., Hogg, E. H., Price, D. T., Edwards, J., & Williamson, T. (2014). Past and projected future changes in moisture conditions in the Canadian boreal forest. *The Forestry Chronicle*, *90*(5), 678–691. https://doi.org/10.5558/tfc2014-134

Werner, A. T., Schnorbus, M. A., Shrestha, R. R., Cannon, A. J., Zwiers, F. W., Dayon, G., & Anslow, F. (2019). A long-term, temporally consistent, gridded daily meteorological dataset for northwestern North America. *Scientific Data*, *6*(1), 1–16. https://doi.org/10.1038/sdata.2018.299

Wheaton, E., Kulshreshtha, S., Wittrock, V., Bonsal, B. R., Chipanshi, A., Grant, C., & Koshida, G. (2005). Canadian droughts of 2001 and 2002: Climatology, impacts, and adaptations. *Volumes I and II, Prepared for Agriculture and Agri-Food Canada, Saskatchewan Research Council, Saskatoon, SK*.

Wheaton, E., Kulshreshtha, S., Wittrock, V., & Koshida, G. (2008). Dry times: Hard lessons from the Canadian drought of 2001 and 2002. *The Canadian Geographer/Le Géographe Canadien*, *52*(2), 241–262. https://doi.org/10.1111/j.1541-0064.2008.00211.x

Wild, M., Folini, D., Henschel, F., Fischer, N., & Müller, B. (2015). Projections of long-term changes in solar radiation based on CMIP5 climate models and their influence on energy yields of photovoltaic systems. *Solar Energy*, *116*, 12–24. https://doi.org/10.1016/j.solener.2015.03.039

Wilhite, D., & Pulwarty, R. S. (2017). *Drought and water crises: Integrating science, management, and policy*. CRC Press.

Xiao, J., & Zhuang, Q. (2007). Drought effects on large fire activity in Canadian and Alaskan forests. *Environmental Research Letters*, *2*(4), 044003. https://doi.org/10.1088/1748-9326/2/4/044003

Yukimoto, S., Kawai, H., Koshiro, T., Oshima, N., Yoshida, K., Urakawa, S., Tsujino, H., Deushi, M., Tanaka, T., Hosaka, M., Yabu, S., Yoshimura, H., Shindo, E., Mizuta, R., Obata, A., Adachi, Y., & Ishii, M. (2019). The Meteorological Research Institute Earth System Model version 2.0, MRI-ESM2. 0: Description and basic evaluation of the physical component. *Journal of the Meteorological Society of Japan. Ser. II*, *97*(5), 931–965. https://doi.org/10.2151/jmsj.2019-051

Zhang, X., Vincent, L. A., Hogg, W. D., & Niitsoo, A. (2000). Temperature and precipitation trends in Canada during the 20th century. *Atmosphere-Ocean*, *38*(3), 395–429. https://doi.org/10.1080/07055900.2000.9649654

Zhou, Z., Zhang, L., Chen, J., She, D., Wang, G., Zhang, Q., Xia, J., & Zhang, Y. (2023). Projecting global drought risk under various SSP-RCP scenarios. *Earth's Future*, *11*(5), e2022EF003420. https://doi.org/10.1029/2022EF003420

Ziehn, T., Chamberlain, M. A., Law, R. M., Lenton, A., Bodman, R. W., Dix, M., Stevens, L., Wang, Y.-P., & Srbinovsky, J. (2020). The Australian earth system model: ACCESS-ESM1. 5. *Journal of Southern Hemisphere Earth Systems Science*, *70*(1), 193–214. https://doi.org/10.1071/ES19035