Vol. 58: 209–220, 2014
doi: 10.3354/cr01196

CLIMATE RESEARCH
Clim Res

Published January 7

Uncertainties in long-term drought characteristics over the Canadian Prairie provinces, as simulated by the Canadian RCM

Debasish PaiMazumder*, James M. Done

National Center for Atmospheric Research Earth System Laboratory, 3090 Centre Green Drive, Boulder, Colorado 80301, USA

ABSTRACT: Projected changes to the severity, frequency and duration of long-term droughts for 47 watersheds in the Canadian Prairie provinces, as well as uncertainties associated with the lateral boundary forcing data and choice of drought index are explored using an ensemble of Canadian Regional Climate Model (CRCM) simulations for current (1971–2000) and future (2041–2070) climates. Drought characteristics are defined using 2 drought indices: the precipitation anomaly based Drought Severity Index (DSI) and the more complex Palmer Drought Severity Index (PDSI). Forty-seven watersheds were subjectively classified as northern (15) and southern (32) watersheds to examine regional differences. Comparison of CRCM simulated drought characteristics with those observed suggests that the model has difficulties in reproducing observed severity, frequency and duration of drought events, particularly those based on PDSI. Projections show a decrease in severity, frequency and duration of long-term droughts for the majority of the northern watersheds, and an increase for the southern watersheds for DSI-based drought, while the majority of the 47 watersheds experience increasingly severe and prolonged droughts according to PDSI-based assessment. Uncertainties associated with the choice of drought index are larger for the northern watersheds compared to the southern watersheds. For DSI-based drought uncertainties associated with the CRCM, driving data are larger for southern watersheds only, whereas for PDSI-based drought the uncertainties are large for most watersheds. In general, uncertainty associated with the choice of drought index is as important as uncertainty in the CRCM simulated data. Nevertheless, a trivariate classification based on changes to various drought characteristics derived from the ensemble mean of CRCM simulations shows worsening DSI-based drought for southern watersheds and worsening PDSI-based drought for the entire Praries, thus posing challenges for regional water resource management.

KEY WORDS: Uncertainty · Climate change · Drought index · Regional climate modelling · Canadian Prairie provinces

1. INTRODUCTION

Drought is a recurrent event in the Canadian Prairie provinces of Alberta, Saskatchewan and Manitoba, causing extreme strain on water resources, agriculture, forestry, ecosystem and human health. In the context of a changing climate, this drought-prone region of Canada will be subjected to more intense droughts in the future, according to the Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC 2007), and in agreement with 2 recent studies — a global study by Dai (2011) and a regional study by Sushama et al. (2010). Dai (2011) analysed projected future drought using 22 coupled climate model projections reported in IPCC AR4, and their results suggest continued drying over southern Canada in the 21st century. Based on the analysis of the Canadian Regional Climate

*Corresponding author: debasish@ucar.edu

Model (CRCM) projections, Sushama et al. (2010) suggest increases in the number of dry days, and 10 and 30 yr return levels of maximum dry spell durations for southern parts of the Canadian Prairie provinces during the 2041–2070 and 2071–2100 future time windows.

Presently, compared to Global Climate Models (GCMs), Regional Climate Models (RCMs) are more suitable to study regional scale changes because of their finer resolution, allowing for greater topographic complexity and finer-scale atmospheric dynamics to be simulated. For detailed description of potential advantage and disadvantage of RCMs, refer to Laprise et al. (2008) and Rummukainen (2010). Many recent studies evaluated the relative skill of RCMs and their driving fields (e.g. Bärring & Laprise 2005, Rockel et al. 2010, Di Luca et al. 2012). Di Luca et al. (2012) introduced the concept of potential added value (PAV) based on the magnitude of fine-scale variance to determine the regions and climate statistics for which RCMs produce more skilful results than GCMs. The highest PAV is found in summer due to the larger portion of precipitation being associated with small scale convective systems, and over complex topography that exerts strong control on climate statistics.

RCM simulations, however, are inevitably subject to uncertainties due to internal variability, sensitivity to nesting configuration, physics and dynamics of the model and errors in the lateral boundary forcing data used to drive the RCM (de Elia et al. 2008); and assessment of these uncertainties are important to policy-makers for planning long-term strategies. Sensitivity studies of CRCM simulated climate (de Elia et al. 2008) and climate change (de Elia & Côté 2010) over North America to initial condition, domain size, boundary information, nesting technique and CRCM version, found that the largest uncertainties were associated with the lateral forcing data and CRCM version. The smallest uncertainty was found to be associated with internal variability.

Several indices specific to certain types of drought have been developed to quantify the frequency, severity and persistence of droughts (Palmer 1965, McKee et al. 1993, Meyer et al. 1993, Phillips & McGregor 1998). Meteorological drought indices are expressed simply, in terms of precipitation (e.g. Standardised Precipitation Index, Drought Severity Index, DSI; Bryant et al. 1992) or in terms of more complex surface water balance which incorporates precipitation, potential evapotranspiration, soil moisture and runoff (e.g. Palmer Drought Severity Index, PDSI; originally developed by Palmer 1965). Agricultural drought indices depend on soil moisture availability (e.g. Agrohydropotential, Dry Day Sequences, Crop Moisture Index and Moisture Availability Index) and hydrologic indices are estimated using ground water level, runoff, snow pack and soil moisture (e.g. Surface Water Supply Index, Reclamation Drought Index).

In terms of meteorological drought indices, both PDSI and DSI have been used to assess historical droughts and their future changes over the United States and Europe (e.g. Dai et al. 2004, Phillips & McGregor 1998, Fowler & Kilsby 2002, Wells et al. 2004, van der Schrier et al. 2006, Blenkinsop & Fowler 2007a,b, Burke & Brown 2008, Dai 2011) and no single drought index is universally applicable or universally superior. The selection of drought indices for a specific area is therefore often guided by the quantity and quality of the climate data available, and the ability of the indices to describe the temporal and spatial characteristics of historical droughts in that area. Except for precipitation and temperature, long-term values of other hydroclimate parameters are not readily available for the Canadian Prairie provinces (e.g. Bonsal et al. 2011). Quite recently, Bonsal et al. (2013) used PDSI to quantify and understand the Canadian Prairies' past, present and future drought. Therefore, this study utilizes 2 different meteorological drought indices, PDSI and DSI, to extract drought events and their characteristics from the CRCM simulated data.

In an earlier study (PaiMazumder et al. 2013), validation of CRCM simulated DSI-based short- and long-term drought characteristics and their projected changes were addressed. That study revealed increasing long-term drought characteristics over the southern Canadian Prairie provinces. The study included a very limited analysis of uncertainties associated with projected changes. In the present study, sensitivities of projected changes in long-term drought characteristics to both the lateral boundary forcing data and choice of drought index are explored. Though RCMs are associated with many sources of uncertainty, we focus here on exploring uncertainty due to lateral boundary conditions and drought definition. Both DSI and PDSI are explored due to the availability of regional input data. Specifically, projected changes to the severity, frequency and duration of long-term droughts lasting at least 12 months are explored, for 47 watersheds in Alberta, Saskatchewan and Manitoba, using an ensemble of CRCM simulations for current (1971–2000) and future (2041–2070) climates.

2. MODEL AND SIMULATIONS

2.1. Model description

The simulated precipitation used in this study to derive drought indices is generated by the current-operational fourth generation of the CRCM. The CRCM is a fully elastic, limited-area, nested model. It uses a semi-implicit and semi-Lagrangian numerical scheme to solve the basic non-hydrostatic Euler equations (Caya 1996, Laprise et al. 1998). The model's horizontal grid is uniform in polar stereographic projection with 45 km horizontal grid spacing and 15 min time step. The model uses Gal-Chen scaled-height terrain-following vertical coordinates (Gal-Chen & Somerville 1975) with 29 levels in the vertical, and the top of the domain is located at 29 km altitude. The CRCM generally uses most of the sub-grid scale physical parameterization packages of CGCM3.1 (Flato & Boer 2001), with the exception of the moist convection parameterization. Cloud cover is parameterized in terms of local relative humidity assuming maximum (random) overlap, depending on presence (or absence) of clouds in adjacent layers as in CGCM3.1; precipitation is parameterized in terms of a simple super saturation based condensation scheme as in CGCM3.1 (Laprise et al. 2003). Mesoscale convection follows the parameterization scheme of Kain & Fritsch (1990) and Bechtold et al. (2001).

2.2. Simulations

An ensemble of ten 30 year simulations are analysed, of which 5 correspond to the current period (1971–2000) and 5 correspond to the future period (2041–2070). Time slices of 30 yr are suitable to explore statistics of long-term droughts and minimize the potential impact of decadal variability. They are sufficiently far apart to capture a climate change signal, yet within the period of the global model simulations. The 5 CRCM pairs dynamically downscale 5 members of an initial condition ensemble of CGCM3.1 simulations that follow the 20C3M scenario (IPCC 2001) for the current period, and Special Report on Emissions Scenarios A2 scenario (IPCC 2001) for the future period. CRCM simulations are performed over a 200 × 192 point grid domain covering North America (see inset of Fig. 1). Analysis focuses on the subset of the domain corresponding to 47 watersheds that span the Canadian Prairie provinces (Fig. 1, Table 1).

Our focus is not in determining predictive skill at the regional scale, but rather on understanding the uncertainty of the future change associated with both the lateral boundary forcing data and choice of drought index for defining drought. One advantage of focusing on the future change is the removal of model bias, assuming stationary bias. Using 2 versions of the CRCM that exhibited different current climate bias, Sushama et al. (2006) found that their projected changes in monthly and annual climatology of various surface fields are at least consistent in the direction of change, but vary in magnitude. Many other studies have shown that the CRCM can reasonably simulate the seasonal mean large-scale circulation and temporal variability (e.g. Laprise et al. 1998, 2003). Therefore, we consider the CRCM to be an adequate tool for climate change studies.

3. METHODOLOGY

We assessed drought using both DSI and PDSI. PDSI assesses the cumulative departure in surface water balance from a long-term average. A given value of PDSI is a combination of the current condition and previous PDSI values (Guttman 1998). Therefore, the PDSI for a given month reflects a long-term memory of previous moisture conditions. Full details of the PDSI calculation can be found at the National Agricultural Decision Support System web site. The self-calibrated PDSI developed by Wells et al. (2004) is used here instead of the original definition by Palmer (1965). The self-calibrated PDSI replaces empirically derived parameters used in the PDSI calculation, with values based upon historical climate data of the location such as (1) duration factors, (2) climate characteristics, (3) water balance coefficient and (4) the Thornthwaite heat index and exponent used in calculating evapotranspiration. The algorithm developed by Wells (2004) is used for PDSI computations (available at http://greenleaf.unl.edu/downloads). Time series of monthly precipitation and monthly-mean temperature were obtained from the Climate Research Unit (CRU) gridded dataset (CRU TS 3.1; Mitchell et al. 2004) and CRCM current and future period simulations. Water field capacity was obtained from a global digital format dataset of water holding capacity (Webb et al. 1993).

Positive PDSI indicates wetter conditions, while negative PDSI indicates shortage of water resulting in drier conditions or drought. For categorizing droughts, the negative PDSI range is arbitrarily split into 6 non-overlapping parts that represent near normal (1 > PDSI > –1), mild (–1 > PDSI > –2), moderate

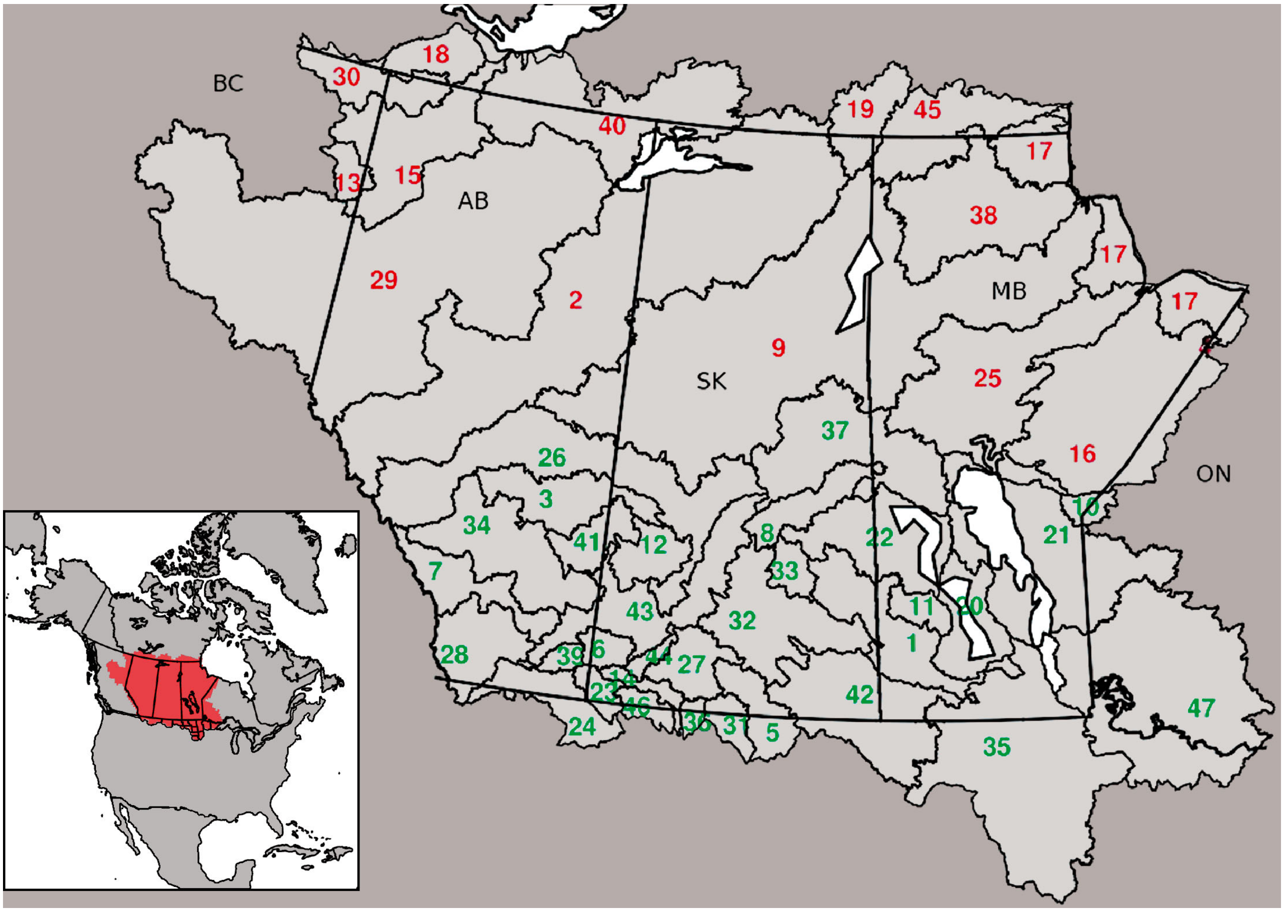

Fig. 1. Study area showing the location of the 47 watersheds contained mainly in the Canadian prairie provinces of Alberta, Saskatchewan and Manitoba. The names of the watersheds corresponding to the identification numbers (1–47) can be found in Table 1. Green and red colours are used to distinguish 32 southern and 15 northern watersheds, respectively. Inset: Canadian Regional Climate Model (CRCM) experimental domain (red: study area)

Table 1. Identification numbers (ID) and names of 47 watersheds, located in the Canadian Prairie provinces of Alberta, Saskatchewan and Manitoba. Spatial distribution of the watersheds is shown in Fig. 1

ID	Watershed name	ID	Watershed name	ID	Watershed name
1	Assiniboine River	17	Hudson Bay	33	Quill Lakes
2	Athabasca River	18	Kakisa River	34	Red Deer River
3	Battle River	19	Kazan River	35	Red River
4	Beaver Stone River	20	Lake Manitoba	36	Rock Creek
5	Big Muddy Creek	21	Lake Winnipeg	37	Saskatchewan River
6	Bigstick Lake	22	Lake Winnipegosis	38	Seal River
7	Bow River	23	Lodge-Battle Creeks	39	Seven Persons Creek
8	Carrot River	24	Milk River	40	Slave River
9	Churchill River	25	Nelson River	41	Sounding Creek
10	Cobham River	26	North Saskatchewan River	42	Souris River
11	Dauphin Lake	27	Old Wives Lake	43	South Saskatchewan River
12	Eagle Creek	28	Oldman River	44	Swift Current Creek
13	Fontas River	29	Peace River	45	Thlewiaza River
14	Frenchman River	30	Petitot River	46	Whitewater Creek
15	Hay River	31	Poplar River	47	Winnipeg River
16	Hayes River	32	Qu'Appelle River		

(–2 > PDSI > –3), severe (–3 > PDSI > –4), extreme (–4 > PDSI > –5) and exceptional (PDSI < –5) drought categories. The PDSI is strongly correlated with precipitation-based indices on 12 mo timescales (Bordi & Sutrea 2001, Lloyd-Hughes & Saunders 2002, Redmond 2002, Dubrovsky et al. 2009).

DSI is based on the accumulated precipitation deficit concept of Bryant et al. (1992), further elaborated in the work of Phillips & McGregor (1998) and Blenkinsop & Fowler (2007a,b). As mentioned earlier, our focus in this study was on long-term droughts lasting at least 12 mo. Accordingly, the DSI uses a 12 mo initiation and termination rule. The calculation of DSI is based on cumulative monthly-precipitation anomalies with respect to the 1971–2000 simulated reference climatology. A drought event is triggered whenever the total precipitation received in the preceding 12 mo is less than the mean climatology; DSI is then initialized to precipitation anomaly x_t in month, t with respect to the 1971–2000 reference climatology, if the following month is characterized by a precipitation deficit. The DSI for the following months is computed by adding respective monthly anomalies to the previous month's DSI. However, if (for any month) total precipitation received in the preceding 12 mo is above the mean climatology, drought termination occurs and DSI is assigned a zero value. The computed DSI is then expressed as a percentage of the annual mean precipitation. Due to its simplicity of calculation, small data requirements and easy interpretation, DSI is one of the most popular precipitation-based drought indices (Phillips & McGregor 1998, Blenkinsop & Fowler 2007a,b).

In this study, drought severity is defined as the absolute maximum precipitation deficit for DSI, whereas for PDSI drought severity is defined as the modulus of PDSI values for a continuous period in which PDSI is always below –1. Drought duration is defined as the number of months elapsed between drought initiation and termination. Fig. 2 demonstrates the temporal structure of the monthly-time series of DSI and PDSI, derived from the CRU TS 3.1 for the southern Saskatchewan River watershed for 1902–2009. DSI and PDSI reveal similar general patterns, and both capture well the multi-year droughts of the 1910s, 1930s, 1960s and 1999–2002. DSI and PDSI capture, respectively, 16 and 12 multi-annual droughts over the southern Saskatchewan River watershed for 1902–2009 with relatively high correlation (R ~0.60) between them. On average, the correlation between DSI and PDSI is 0.565 for the Canadian Prairie provinces, with the highest correlation (0.819) for Lake Winnipegosis and lowest correlation (0.460) for Thlewiaza River. The spatial distribution of severity of DSI and PDSI-based events, derived from the CRU dataset for the multi-year droughts (i.e. 1910s, 1930s and 1999–2002 drought events) are shown in Fig. 3. The spatial distributions of drought-affected areas for both indices are in good agreement with other observation-based assessments (i.e. Nkemdirim & Weber 1999, Chipanshi et al. 2006, Bonsal & Regier 2006); the most severe drought occurred over western Alberta, southern Saskatchewan and southeastern Manitoba in the 1910s; over southern and central Alberta and Saskatchewan and eastern and southeastern Manitoba in the 1930s; and over southwestern and southeastern Alberta, and southwestern Saskatchewan during 1999–2002.

This analysis suggests that both indices are suitable for studying drought over the Canadian Prairie provinces. Although both DSI and PDSI show similar multi-year drought patterns, there are notable differences in individual drought characteristics (i.e. severity and duration) due to differences in the underlying computational procedures and differences in variables used to determine these 2 indices. Using both DSI and PDSI, drought severity and frequency are calculated for the ensemble of CRCM 30 year current and future period simulations for the 47 watersheds. Drought severity represents the average severity of all drought events lasting ≥12 mo, and drought duration represents average duration associated with such events. The drought frequency represents the number of occurrences of all drought events lasting ≥12 mo over the selected 30 yr time slice.

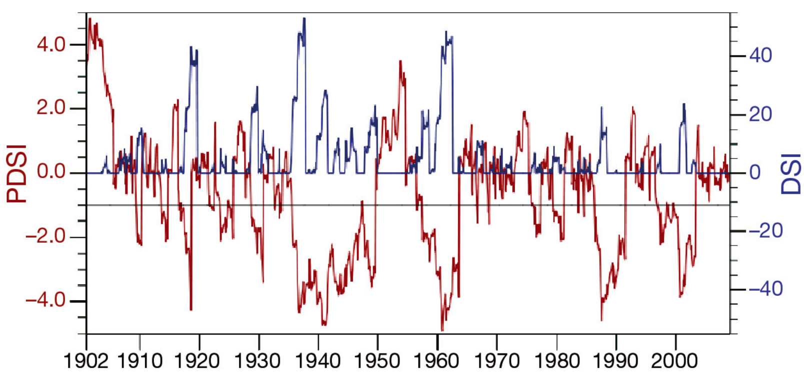

Fig. 2. Comparison of monthly Drought Severity Index, DSI (blue, right y-axis) and Palmer Drought Severity Index, PDSI (brown, left y-axis) values derived from observed data for the southern Saskatchewan River watershed for 1902–2009. Grey line: PDSI = –1

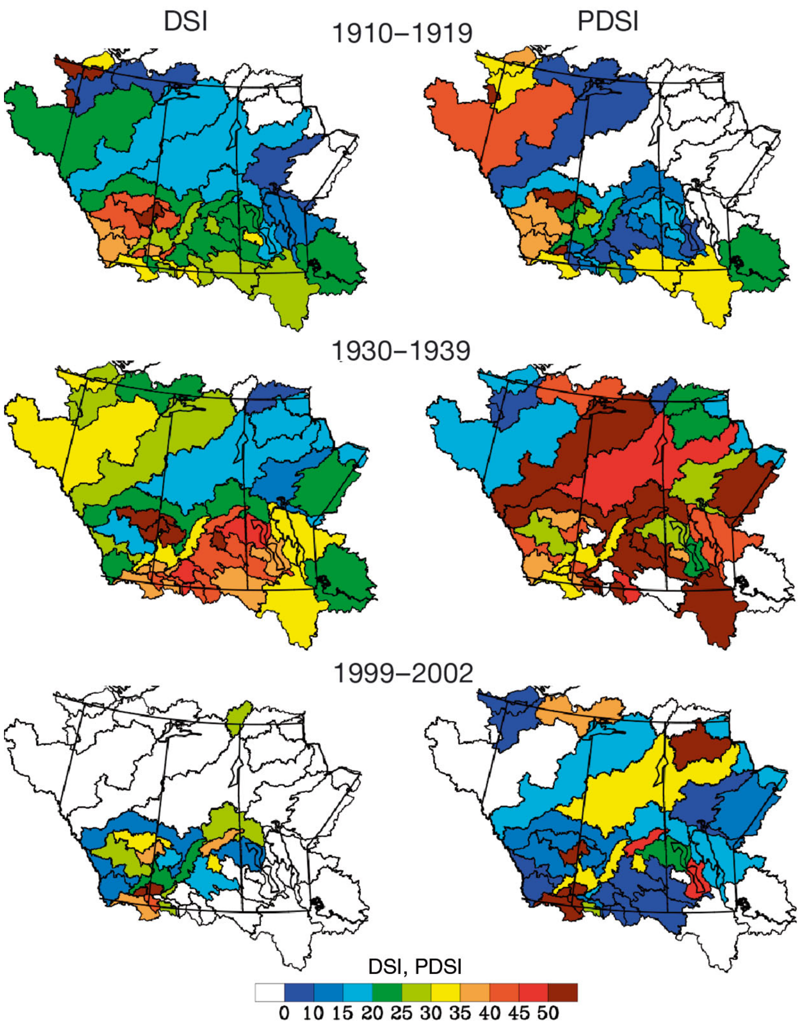

Fig. 3. Drought severity index (DSI; left) and Palmer drought severity index (PDSI; right) derived from Climate Research Unit (CRU) data for the 1910–1919, 1930–1939 and 1999–2002 historical drought years over the Canadian Prairie provinces

4. RESULTS

4.1. Current climate

Prior to presenting the uncertainty in projected changes to long-term drought characteristics, it is useful to provide an overall view of the CRCM performance in reproducing observed DSI- and PDSI-based drought characteristics in the current climate (1971–2000). The severity, frequency and duration of DSI- and PDSI- based droughts derived from the CRU gridded data for the period 1971–2000 and the differences between the ensemble means of CRCM-simulated and CRU-based drought characteristics are shown in Fig. 4. CRCM underestimates DSI-based severity of droughts over Alberta, southern Saskatchewan and southeastern Manitoba and overestimates elsewhere, and it overestimates PDSI-based severity of drought over the majority of the watersheds (Fig. 4a–d). The performance of CRCM drought frequency is mixed, with slight underestimation in the western and eastern regions and overestimation elsewhere for DSI-based drought, and slightly underestimation over the southern regions and overestimation elsewhere for PDSI-based drought (Fig. 4e–h). In general, the CRCM-derived PDSI-based average drought durations are overestimated over a substantial part of the Canadian Prairie provinces. The model underestimates the DSI-based average drought durations over a greater part of Alberta, while it is overestimated for parts of Manitoba (Fig. 4i–l).

4.2. Future changes

Projected changes to severity, frequency and duration of long-term droughts for the future (2041–2070) period and associated uncertainties, i.e. uncertainty associated with the choice of the drought index and those associated with the CRCM driving data, are discussed below. For the convenience of presentation, the 47 watersheds are classified into southern or northern watersheds based on their relative location as shown in Fig. 1; this classification leads to 15 northern watersheds and 32 southern watersheds.

4.2.1. Uncertainty due to choice of drought index

Projected changes to DSI- and PDSI-based long-term drought characteristics (severity, frequency and duration) are shown in Fig. 5. The sign of the ensemble mean climate change in drought severity appears to be robust to drought indices for only 47% of the southern watersheds (with both drought indices suggesting an increase), and 33% of the northern watersheds (with both drought indices suggesting a

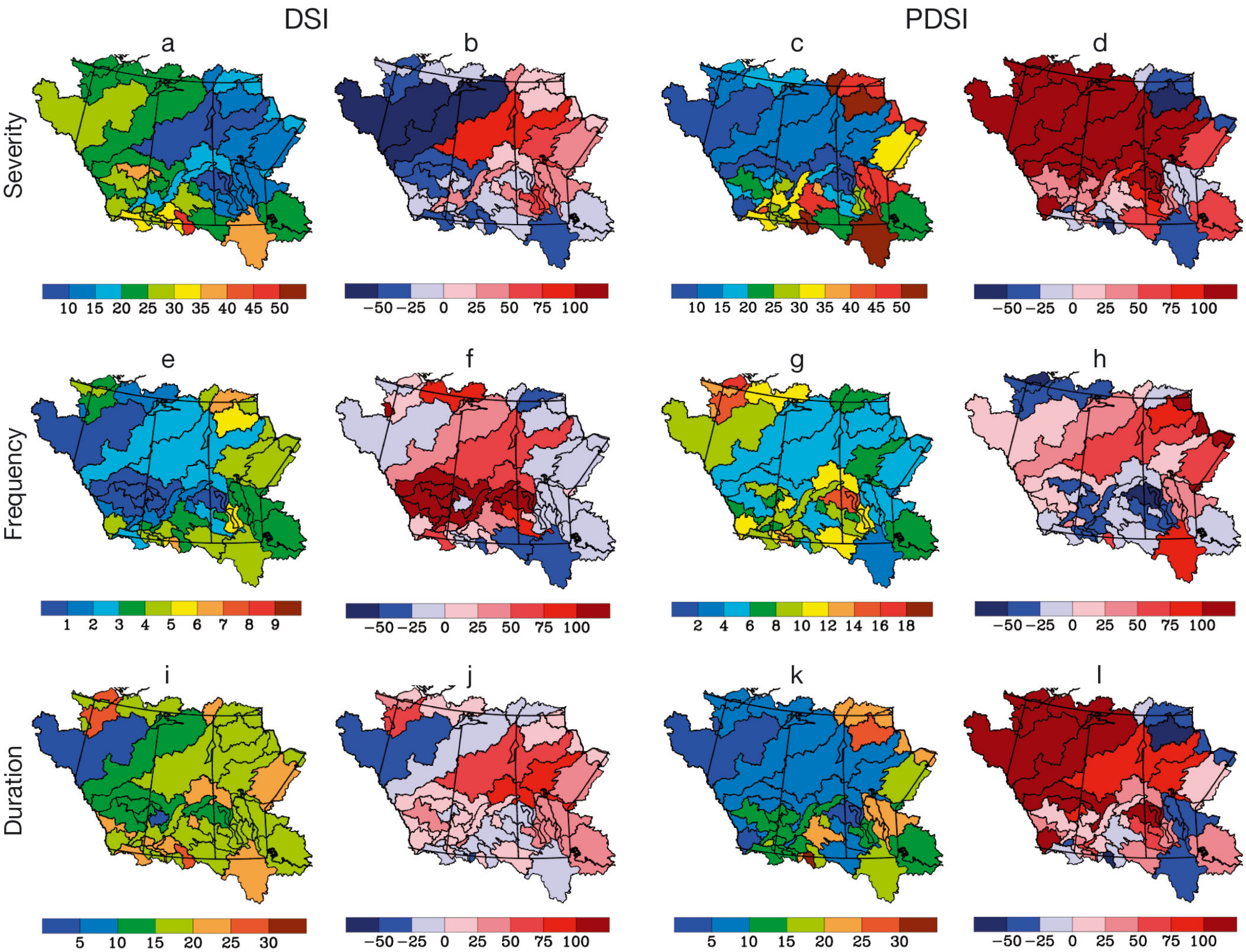

Fig. 4. Panels (a), (c), (e), (g), (i) and (k) show the severity, frequency and duration (in months) of droughts according to the drought severity index (DSI) and Palmer drought severity index (PDSI) for the 47 watersheds, derived from Climate Research Unit (CRU) data for the period 1971–2000. (b), (f) and (j) show the differences (in %) between the Canadian Regional Climate Model (CRCM) simulated and CRU based severity, frequency and duration of droughts for the case of DSI, and in (d), (h) and (l) for the case of PDSI

decrease) (Fig. 5a). The sign of the climate change disagrees between DSI and PDSI for 38 % of the southern watersheds and 67 % of the northern watersheds. The future increase in drought severity for the southern watersheds is related mostly to the projected decrease in summer precipitation over the region (PaiMazumder et al. 2013).

Northern watersheds show a future decrease in drought frequency for DSI-based droughts, yet 66 % of these watersheds show more frequent PDSI-based droughts. The sign of the climate change in drought frequency for both DSI and PDSI agrees for 59 % of southern watersheds (22 % are associated with projected increase and 37 % are associated with projected decrease in frequency), while the 2 indices disagree over 41 % of the remaining southern watersheds (Fig. 5b).

Sixty-six percent of the northern watersheds show an increase in PDSI-based drought duration, whereas for DSI-based drought duration, 60 % of northern watersheds show a decrease in drought duration. The 2 indices disagree over 33 % of the northern watersheds. For southern watersheds, both drought indices suggest an increase in drought duration for 69 % watersheds, and disagree in sign for 28 % of watersheds.

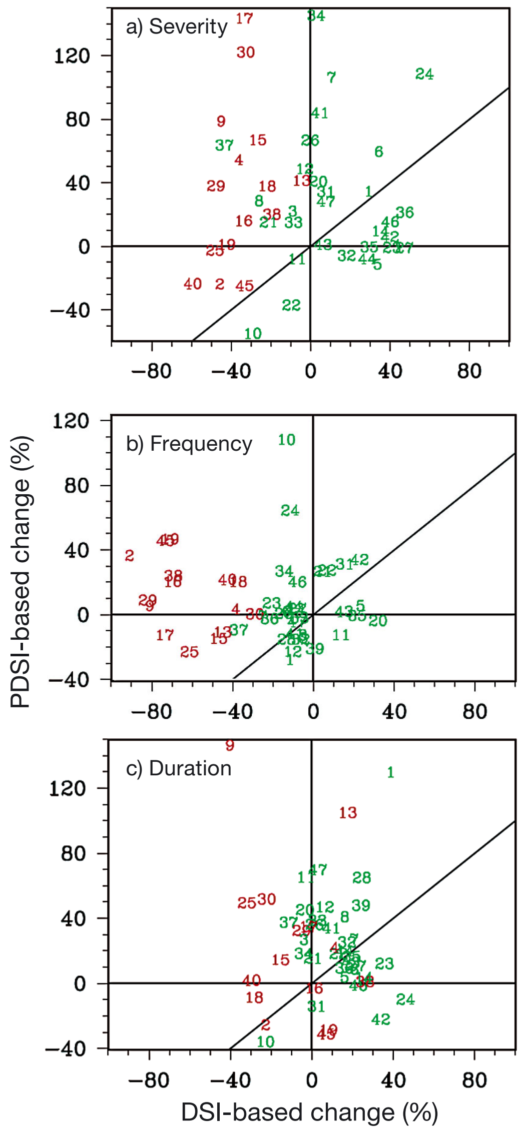

Fig. 5. Projected changes to (a) severity, (b) frequency and (c) duration of droughts according to the Palmer drought severity index (PDSI) and the drought severity index (DSI), derived from the ensemble mean of 5 pairs of Canadian Regional Climate Model (CRCM) simulations. Green and red colours are used to distinguish 32 southern and 15 northern watersheds, respectively. Numbers correspond to the watershed IDs given in Table 1

In general, projections of drought characteristics are distinctly different between the 2 indices. According to DSI-based analysis of droughts, most of the 32 southern watersheds show more severe and prolonged droughts in future climate. According to PDSI-based analysis of droughts, most watersheds show more severe, frequent and prolonged droughts in future climate. The magnitude of projected increase in drought characteristics is generally higher for PDSI than DSI, and appears to be due to increasing temperature in future climate. This observation is consistent with the findings of Bonsal et al. (2013).

4.2.2. Uncertainty due to internal variability of the CGCM

The results presented above suggest important uncertainties associated with the choice of the drought index, and therefore, the results presented hereafter will consider the 2 methods separately (i.e. no combination of the 2 indices is attempted). The uncertainty due to the internal variability of the driving CGCM model is now explored. The uncertainty is estimated here using the spread of members within the CRCM ensemble, represented by the coefficient of variation (CV), defined as the ratio of the standard deviation to the ensemble-mean change.

Projected changes to the ensemble mean DSI- and PDSI-based severity, frequency and duration for the 47 watersheds are shown in Fig. 6, together with ensemble spread. There is a large uncertainty associated with the specific amplitude of the CRCM projected increase/decrease in severity of DSI-based drought over the southern region of the Prairie provinces. For PDSI, the spread amongst members is large over southwestern Saskatchewan, northern and eastern Manitoba and northern Alberta. The magnitude varies greatly between simulation pairs for both DSI- and PDSI-based droughts. For DSI-based droughts, a large spread amongst various members can be noted for changes to the frequency of droughts for all southern watersheds, while for PDSI, the spread is large over the majority of the 47 watersheds. As for drought duration, the spread is large mainly for portions of the southern, northeastern and western Prairie provinces for DSI; while for the PDSI, the spread is largest for southwestern Saskatchewan, northern and eastern Manitoba and northern Alberta — similar to severity. The uncertainties for severity and duration appear to be larger than those for frequency, particularly for the southern half of the study domain for DSI-based drought. The opposite is true for majority of the 47 watersheds for PDSI-based drought.

Despite these uncertainties, some form of synthesis of the CRCM projections is useful, and therefore Fig. 7 provides a trivariate classification of watersheds based on mean changes to severity, frequency and duration for both DSI- and PDSI-based droughts. While differences between drought characteristics based on the 2 drought indices are evident using the trivariate classification, particularly for northern

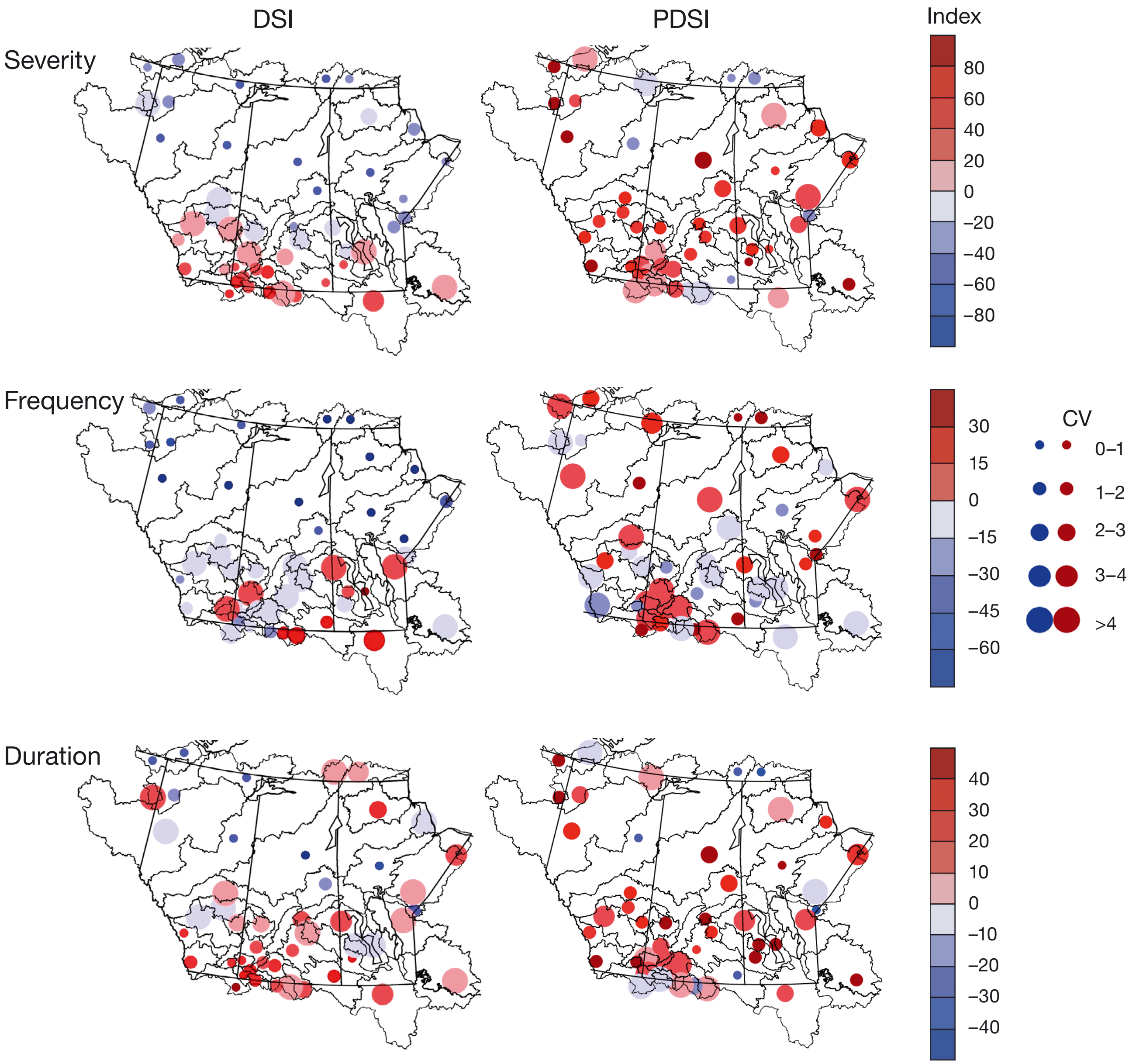

Fig. 6. Projected changes to the severity, frequency and duration of droughts according to the drought severity index (DSI) (left) and Palmer drought severity index (PDSI) (right), derived from the ensemble mean of 5 pairs of Canadian Regional Climate Model (CRCM) simulations. Increases in drought characteristics are shown in red and decreases in blue; circle size: spread (coefficient of variation) among the 5 pairs of CRCM simulations

watersheds, common patterns between DSI and PDSI emerge for the southern watersheds. The trivariate classification for DSI identifies some watersheds with projected increases in severity, duration and frequency along the southeastern region of the Prairie provinces; with PDSI, a similar pattern is shown over central and western areas, including southwestern Saskatchewan. The DSI-based classification also shows increases in 2 out of the 3 drought characteristics for the majority of the southern watersheds; and for the majority of the all 47 watersheds with PDSI.

5. DISCUSSION AND CONCLUSIONS

In this study, uncertainty in projected changes to the severity, frequency and duration of long-term droughts over the Canadian Prairie provinces are studied at the watershed scale for the future (2041–2070) period relative to the current (1971–2000) period. Two drought indices, the DSI and PDSI, are used to define droughts, and a 5-member ensemble of CRCM simulations each for current and future climates is employed. The uncertainties in projected

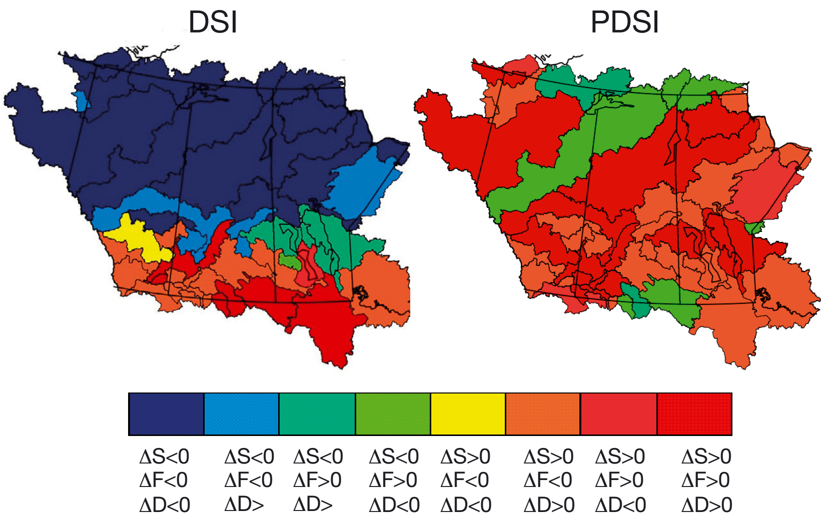

Fig. 7. Trivariate classification of watersheds based on projected changes to severity, frequency and duration (ΔS, ΔF and ΔD, respectively) of droughts according to the drought severity index (DSI; left) and Palmer drought severity index (PDSI; right) based droughts for the 47 watersheds located in the Canadian Prairie provinces

changes to drought characteristics, introduced by the CRCM driving data and the choice of drought index are highly variable within the studied region.

The projected changes to severity, frequency and duration for both DSI- and PDSI-based droughts reasonably agree in sign for the majority of the southern watersheds, with projected worsening drought, albeit with differences in magnitude. However, for the northern watersheds, the projected changes obtained for the DSI- and PDSI-based droughts do not agree in sign for many watersheds, with a decrease in DSI-based drought and increase in PDSI-based drought. The projected increase in drought in the future climate for the southern watersheds is related mostly to the projected reduction in summer precipitation over the region, while for northern watersheds, projected increase in precipitation is likely to reduce DSI-based drought as DSI is solely based on precipitation (PaiMazumder et al. 2013). Uncertainty associated with the CRCM driving data (i.e. the intermember spread of the ensemble) is generally larger for the southern watersheds compared to the northern watersheds. In general, we find that the uncertainty associated with the choice of drought index is as important as that associated with internal variability of the CRCM driving data.

Although not a main focus of this study, projections based on the PDSI show that twenty-first century droughts in the Canadian Prairie provinces will be more severe, longer and more frequent than those based on the DSI. These differences are directly attributable to the water balance approach and inherent lag effects associated with the PDSI compared to DSI, which does not incorporate potential effects of changes in temperature, and hence appears to be more conservative for assessing droughts in the context of climate change. These results are in agreement with Bonsal et al. (2013), who highlighted the importance of considering combined effects of both precipitation and evaporation changes when assessing changes to future regional-scale drought, especially given the uncertainties and lack of consistency in future precipitation signals. Dai (2011) also suggested that indices based solely on precipitation should not be used to assess drought characteristics in the context of climate change, and Trenberth (2011) showed that increasing temperature could lead to severe and prolonged droughts in the future. By using 2 drought indices with and without the inclusion of temperature, this study also reveals such noticeable differences in projected changes to the severity, frequency and duration of long-term droughts over the Prairie provinces due to atmospheric water supply (precipitation; controlled by atmospheric processes) and the cumulative effect of the imbalance between atmospheric water supply and demand (potential evapotranspiration; determined by near-surface temperature). Importantly, this study also showed that the differences are of similar magnitude to differences due to the internal variabilities of the global and regional models.

This study demonstrates that climate change is a major and complex challenge for water resource management in the Canadian Prairie provinces. Projection of long-term droughts, together with reliable assessment of uncertainties, is helpful for policymakers in formulating long-term strategies. This study employed 2 commonly used, credible drought indices (DSI and PDSI); however, Quiring (2009) suggested an objective location-specific method for defining operational drought thresholds, and it would be interesting to explore that in future similar studies. Although PDSI considers temperature, there are several limitations to this index, as it does not include the effect of geomorphology, soil type, snow cover and frozen ground. Therefore, it would also be interesting to explore drought indices that include the effect of geomorphology, soil and snow in future uncertainty assessment studies. The drawback of using only 5 members within CRCM ensemble is that the areas with large ensemble spread may not only characterize regions of variable skill in the model, but also regions that are sensitive to small configuration changes (de Elia et al. 2008). Therefore, in addition to multivariable-based drought indices, further detailed assessment of uncertainty, including multi-model and multi-scenario simulation approaches (e.g. Christensen et al. 2002) will need to be considered in future work. This would help improve quantification of uncertainties, which are important in planning adaptation strategies.

Acknowledgements. The authors thank the Ouranos Climate Simulations Team for supplying the CRCM-generated daily precipitation outputs used in this study, and D. Sauchyn for providing the boundaries of the watersheds. This research was funded by the Canadian Foundation for Climate and Atmospheric Sciences (CFCAS), the Ouranos Consortium and the Pacific Climate Impacts Consortium (PCIC) and partially funded by NSF EaSM grant 1048829. We thank Dr. N. Khaliq from the University of Saskatchewan, Dr. L. Sushama from Université du Québec à Montréal and 3 anonymous reviewers for their comments that helped us improve the overall quality of the analyses presented in this paper.

LITERATURE CITED

Bärring L, Laprise R (eds) (2005) High-resolution climate modelling: assessment, added value and applications. Extended abstracts of a WMO/WCRP-sponsored regional-scale climate modelling workshop, 29 March–2 April 2004. Lund University electronic reports in physical geography, Lund

Bechtold P, Bazile E, Guichard F, Mascart P, Richard E (2001) A mass flux convection scheme for regional and global models. QJR Meteorol Soc 127:869–886

Blenkinsop S, Fowler HJ (2007a) Changes in drought frequency, severity and duration for the British Isles projected by the PRUDENCE regional climate models. J Hydrol (Amst) 342:50–71

Blenkinsop S, Fowler HJ (2007b) Changes in European drought characteristics projected by the PRUDENCE regional climate models. Int J Climatol 27:1595–1610

Bonsal BR, Aider R, Gachon P, Lapp S (2013) An assessment of Canadian prairie drought: past, present, and future. Clim Dyn 41:501–516

Bordi I, Sutrea A (2001) Fifty years of precipitation: some spatially remote teleconnections. Water Resour Manag 15:247–280

Bryant SJ, Arnell NW, Law FW (1992) The long-term context for the current hydrological droughts. In: Proc IWEM Conf on the management of scarce water resources

Burke EJ, Brown SJ (2008) Evaluating uncertainties in the projection of future drought. J Hydrometeorol 9:291–299

Caya D (1996) Le modèle régional de climat de l'UQAM. PhD thesis, Université du Québec à Montréal

Chipanshi AC, Findlater KM, Hadwen T, O'Brien EG (2006) Analysis of consecutive droughts on the Canadian Prairies. Clim Res 30:175–187

Christensen JH, Carter TR, Giorgi F (2002) PRUDENCE employs new methods to assess European climate change. EOS:83–147

Dai A (2011) Drought under global warming: a review. Clim Change 2:45–65

Dai A, Trenberth KE, Qian T (2004) A global dataset of Palmer Drought Severity Index for 1870–2002: relationship with soil moisture and effects of surface warming. J Hydrometeorol 5:1117–1130

de Elia R, Caya D, Côté H, Frigon A and others (2008) Evaluation of uncertainties in the CRCM-simulated North American climate. Clim Dyn 30:113–132

Di Luca A, de Elia R, Laprise R (2012) Potential for added value in precipitation simulated by high-resolution nested Regional Climate Models and observations. Clim Dyn 38:1229–1247

Dubrovsky M, Svoboda MD, Trnka M, Hayes MJ, Wilhite DA, Zalud Z, Hlavinka P (2009) Application of relative drought indices in assessing climate-change impacts on drought conditions in Czechia. Theor Appl Climatol 96: 155–171

Flato GM, Boer GJ (2001) Warming asymmetry in climate change simulations. Geophys Res Lett 28:195–198

Fowler HJ, Kilsby CG (2002) A weather-type approach to analyzing water resource drought in the Yorkshire region from 1881 to 1998. J Hydrol (Amst) 262:177–192

Gal-Chen T, Somerville RC (1975) On the use of a coordinate transformation for the solution of Navier-Stockes. J Comput Phys 17:209–228

Guttman NB (1998) Comparing the Palmer Drought Index and the Standardized Precipitation Index. J Am Water Resour Assoc 34:113–121

IPCC (Intergovernmental Panel on Climate Change) (2001) Climate change 2001: the scientific basis. Contribution of Working Group I to the 3rd assessment report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge

IPCC (2007) Climate change 2007: the physical science basis. Contribution of Working Group I to the 4th assessment report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge

Kain JS, Fritsch JM (1990) A one-dimensional entraining/detraining plume model and application in convective parameterization. J Atmos Sci 47:2784–2802

Laprise R, Caya D, Giguère M, Bergeron G and others (1998) Climate of Western Canada under current and enhanced greenhouse gas concentration as simulated by the Canadian Regional Climate Model. Atmos-Ocean 36: 119–167

Laprise R, Caya D, Frigon A, Paquin D (2003) Current and perturbed climate as simulated by the second-generation Canadian Regional Climate Model (CRCM-II) over northwestern North America. Clim Dyn 21:405–421

Laprise R, de Elia R, Caya D, Biner S and others (2008) Challenging some tenets of regional climate modelling. Meteorol Atmos Phys 100:3–22

Lloyd-Hughes B, Saunders MA (2002) A drought climatology for Europe. Int J Climatol 22:1571–1592

McKee TB, Doesken NJ, Kleist J (1993) The relationship of drought frequency and duration to time scales. In: Proc 8th Conf on applied climatology. Anaheim, CA, p 179–184

Mitchell TD, Carter TR, Jones PD, Hulme M, New M (2004) A comprehensive set of high-resolution grids of monthly climate for Europe and the globe: the observed record (1901–2000) and 16 scenarios (2001–2100). Tyndall

Centre for Climate Change Research working paper No. 55, Tyndall Centre, Norwich. Available at www.tyndall.ac.uk/sites/default/files/wp55.pdf
Nkemdirim L, Weber L (1999) Comparison between the droughts of the 1930s and the 1980s in the southern Prairies of Canada. J Clim 12:2434–2450
PaiMazumder D, Sushama L, Laprise R, Khaliq MN, Sauchyn D (2013) Canadian RCM projected changes to short- and long-term drought characteristics over the Canadian Prairies. Int J Climatol 33:1409–1423
Palmer WC (1965) Meteorological drought. US Weather Bureau Research Paper No. 45. Washington, DC
Phillips ID, McGregor GR (1998) The utility of a drought index for assessing the drought hazard in Devon and Cornwall, South West England. Meteorol Appl 5: 359–372
Quiring SM (2009) Developing objective operational definition for monitoring drought. J Appl Meteorol Climatol 48: 1217–1229
Redmond KT (2002) The depiction of drought. Bull Am Meteorol Soc 83:1145–1147
Rockel B, Arritt R, Rummukainen M, Hense A (2010) The 2nd Lund regional-scale climate modelling workshop. Meteorol Z 19:223–224
Rummukainen M (2010) State-of-the-art with regional climate models. WIREs Clim Change 1:82–96
Sushama L, Laprise R, Caya D, Frigon A, Slivitzky M (2006) Canadian RCM projected climate-change signal and its sensitivity to model errors. Int J Climatol 26:2141–2159
Sushama L, Khaliq MN, Laprise R (2010) Dry spell characteristics over Canada in a changing climate as simulated by the Canadian RCM. Global Planet Change 74:1–14
Trenberth KE (2011) Water cycles and climate change. Section: Global change and climate. In: Freedman B (ed) Global environmental change. Springer, Heidelberg
van der Schrier G, Briffa KR, Jones PD, Osborn TJ (2006) Summer moisture variability across Europe. J Clim 19: 2818–2834
Webb RS, Rosenzweig CE, Levine ER (1993) Specifying land surface characteristics in general circulation models: soil profile data set and derived water-holding capacities. Global Biogeochem Cycles 7:97–108
Wells N, Goddard S, Hayes MJ (2004) A self-calibrating Palmer Drought Severity Index. J Clim 17:2335–2351

Editorial responsibility: Tim Sparks, Cambridge, UK

Submitted: March 21, 2013; Accepted: September 19, 2013
Proofs received from author(s): Dcember 16, 2013