INTERNATIONAL JOURNAL OF CLIMATOLOGY
Int. J. Climatol. (2012)
Published online in Wiley Online Library
(wileyonlinelibrary.com) DOI: 10.1002/joc.3521

Canadian RCM projected changes to short- and long-term drought characteristics over the Canadian Prairies

Debasish PaiMazumder,[a]* Laxmi Sushama,[a] René Laprise,[a] M. Naveed Khaliq[b] and Dave Sauchyn[c]

[a] *Centre ESCER (Étude et Simulation du Climat à l'Échelle Régionale), Université du Québec à Montréal, Montréal, Québec, Canada*
[b] *Global Institute for Water Security, School of Environment and Sustainability, University of Saskatchewan, Saskatoon, Saskatchewan, Canada*
[c] *Prairie Adaptation Research Collaborative, University of Regina Regina, Saskatchewan, Canada*

ABSTRACT: The Canadian Prairies have experienced severe and extended droughts that have had significant impacts on agriculture, energy and other socio-economic sectors; it is therefore desirable to assess future changes to drought characteristics in this drought prone region, in the context of a changing climate. This study addresses validation and projected changes to short- and long-term drought characteristics, i.e. severity, frequency and duration, over the Canadian Prairies, using an ensemble of ten Canadian RCM (CRCM) simulations, of which five correspond to the current 1971–2000 period and the other five are the matching simulations for the future 2041–2070 period. These five pairs of current and future CRCM simulations were driven by five different members of a Canadian Global Climate Model ensemble. Validation of CRCM simulated precipitation suggests that the model reproduces the observed precipitation distribution for all seasons, except summer, across a large portion of the Canadian Prairies. However, 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 associated with longer events, possibly due to the overestimation of summer precipitation by the model. Analysis of projected changes to precipitation and drought characteristics between the 1971–2000 and 2041–2070 periods suggests a decrease in mean precipitation in summer and an increase for the other seasons, while the severity, frequency and maximum duration of both short- and long-term droughts are projected to increase over the southern Prairies, with the largest projected changes associated with longer drought events. Classification of the watersheds spanning the southern Prairies based on changes to both severity and frequency further reveal the vulnerability of this region in a changing climate. Copyright © 2012 Royal Meteorological Society

KEY WORDS Canadian Prairies; climate change; drought frequency; drought severity; precipitation deficit; regional climate

Received 28 February 2011; Revised 9 April 2012; Accepted 1 May 2012

1. Introduction

Several extensive and persistent droughts have affected the Canadian Prairies, most notably in the 1910s, 1930s, 1960s and 1980s (Nkemdirm and Weber, 1999; Chipanshi *et al.*, 2006), with the most severe, single year drought occurring in 1961 (Maybank *et al.*, 1995). The multi-year drought conditions of 1999–2002 were the most severe in 100 years with below normal precipitation for eight consecutive seasons from September 2000 to August 2002 (Bonsal and Wheaton, 2005; Bonsal and Regier, 2007). According to third assessment report of the Intergovernmental Panel on Climate Change (IPCC, 2001), the Canadian Prairies will possibly face a further increase in drought frequency in future climate, which would have significant impacts on a wide range of sectors including agriculture, forestry, industry, ecosystem and health; it is therefore desirable to perform thorough assessments of future changes to various drought characteristics to enable improved adaptation strategies for the region.

The primary tools used to study anticipated climate change are Coupled Global Climate Models (CGCMs) and Regional Climate Models (RCMs) integrated from the recent past to some time in the future with a prescribed, time-evolving emission scenario for anthropogenic greenhouse gases and aerosols (GHGA) (IPCC, 2007). At this point, RCMs offer higher spatial resolution than GCMs, allowing for greater topographic complexity and finer scale atmospheric dynamics to be simulated, and thereby representing a more adequate tool for generating climate change information required for many impact and adaptation studies. GCM projections were used by Bonsal and Regier (2006) to assess future changes to drought characteristics in Canada for the period 2041–2070; their study suggests an increase in the frequency and severity of droughts in southern Canada. More recently, Sushama *et al.* (2010) projected changes to dry spell characteristics over Canada using the Canadian RCM (CRCM); their results suggest increases in the number of dry days and 10- and 30 year return levels of maximum dry spell

* Correspondence to: D. PaiMazumder, National Center for Atmospheric Research Earth System Laboratory, 3090 Center Green Drive, Boulder, CO 80301, USA. E-mail: debasish@ucar.edu

duration for the Canadian Prairies, particularly the southern parts of the region, for 2041–2070 and 2071–2100 future periods.

Several indices have been developed to study the frequency, severity and persistence of droughts (Palmer, 1965; van Rooy, 1965; Bhalme and Mooley, 1980; McKee *et al.*, 1993; Meyer *et al.*, 1993; Phillips and McGregor, 1998), with the majority being based on meteorological and hydrological parameters, i.e. precipitation, evapotranspiration, temperature, soil moisture, runoff, etc. However, except for precipitation, long-term values of other hydroclimatic parameters are not available for the Canadian Prairies (Bonsal and Regier, 2007); therefore indices solely based on precipitation are commonly used to assess drought characteristics in this region, such as the Standardized Precipitation Index (SPI), originally defined in McKee *et al.* (1993). The SPI was used by Quiring and Papakryiakou (2003) and Bonsal and Regier (2007) to study drought characteristics over Canadian Prairies. Over Europe, however, many RCM-based studies focusing on future changes to drought characteristics have used other indices based on cumulative monthly precipitation anomalies (Fowler and Kilsby, 2002; Blenkinshop and Fowler, 2007a, 2007b). These studies have investigated the frequency and severity of short-term droughts of 3–6 months duration, and long-term droughts of at least 6 and 10 months duration. The above cumulative monthly precipitation anomalies-based drought indices and events have been the most commonly used approaches due to their simplicity, small data requirements and easy interpretation (Phillips and McGregor, 1998; Fowler and Kilsby, 2002; Blenkinshop and Fowler, 2007a, 2007b). We therefore in this study analyse cumulative monthly precipitation anomaly-based drought indices and events derived from the CRCM simulated precipitation series for the current (1971–2000) and future (2041–2070) periods to assess projected changes to the severity, frequency and duration of short- and long-term droughts, over the Canadian Prairies.

The paper is organised as follows. Section 2 describes the CRCM and its simulations and observation dataset. A detailed methodology for the estimation of precipitation-based drought indices and drought events is described in Section 3. In Section 4, suitability of various precipitation-based drought events for the Canadian Prairies, validation of CRCM simulated short- and long-term drought characteristics and their projected changes are presented. Discussion and conclusions of the study are given in section 5.

2. Model and data

2.1. Model description

The precipitation outputs used in this study to define droughts are generated by the fourth generation of the CRCM (Music and Caya, 2007), which is the current operational version. The CRCM is a fully elastic non-hydrostatic 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; Caya and Laprise, 1999). The model's horizontal grid is uniform in polar stereographic projection with 45 km horizontal resolution and uses 15 min time step. The model uses Gal-Chen scaled height terrain-following vertical coordinates (Gal-Chen and Somerville, 1975) with 29 levels in the vertical and the top of the domain is located at 29 km altitude.

Spectral nudging technique was implemented to large-scale winds within the regional domain for all CRCM simulations used in this study in order to achieve a better representation of large-scale flow of the driving data (Frigon *et al.*, 2010). The spectral nudging technique applied for CRCM, developed by Riette and Caya (2002), uses the spectral decomposition from Denis *et al.* (2002). The spectral nudging applied is considered relatively weak, where horizontal winds with wavelengths greater than 1400 km are nudged with varying intensity at the vertical, starting just above 500 hPa and reaching a characteristic relaxation time of 10 h at the model top (near 10 hPa).

The CRCM's lateral boundary conditions are provided through one-way nesting method over a regional domain inspired by Davies (1976) and redefined by Yakimiw and Robert (1990). Therefore, the CRCM receives atmospheric nesting information from its driving data, but does not influence the driving data in return. The CRCM is driven by time-dependent vertical profiles from the driving data's wind, air temperature, humidity and pressure imposed at the lateral boundaries exactly, as interpolated onto the CRCM's atmospheric levels. The simulated horizontal winds are relaxed toward values of the driving data over the sponge zone. In addition, spectral large-scale nudging is also imposed to force coherence of the CRCM large-scale winds with the driving data (Biner *et al.*, 2000).

The CRCM generally uses most of the sub-grid scale physical parameterization packages of the Coupled General Circulation Model (CGCM3.1; Flato and Boer, 2001), except for moist convection. 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 and 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 and Fritsch (1990) and Bechtold *et al.* (2001).

2.2. Simulations

An ensemble of ten 30 year simulations are analysed in this paper, of which five correspond to current 1971–2000 period and the other five are the matching simulations for the future 2041–2070 period; these five pairs of current and future CRCM simulations were driven by five different members of a CGCM3.1 initial condition ensemble. RCM simulations in general are associated with several uncertainties including structural uncertainties associated with regional model formulation, uncertainties associated with the lateral boundary conditions from the driving GCM, emission scenarios, as well as the RCM's own internal variability (de-Elia *et al*., 2008). The ensemble of CRCM used in this study would be helpful in addressing the combined uncertainty associated with the natural variability of the driving GCM and the internal variability of CRCM. The future simulations are affected by changes in GHGA, following IPCC's (2001) Special Report on Emissions Scenarios (SRES) A2 scenario. Though in this study we focus only on the Canadian Prairies, the model simulations were performed over a 200 × 192 point grid covering the whole of North America (see inset in Figure 1). Figure 1 shows the study region, and the spatial distribution of major/minor watersheds within the region; the names of the various watersheds are provided in Table I. There are 47 watersheds and some of these extend into the United States, e.g. Red River and Winnipeg River. In the rest of the paper, results will only be displayed for the subset of the domain corresponding to the 47 Prairie watersheds.

2.3. Observations

The Climate Research Unit (CRU) dataset (CRU TS 2.1; Mitchell *et al*., 2004), which consists of gridded global land surface observations of monthly precipitation at 0.5° × 0.5° resolution, is used in this study to validate model simulated precipitation and drought characteristics because of its high-spatial resolution. The intercomparison of CRU data, WM global precipitation dataset (Willmott and Matsuura, 2001), available at 0.5° × 0.5°, and the Global Precipitation Climatology Centre Dataset (GPCC; Rudolf *et al*., 1994), available on a 1° × 1° grid, shows substantial numerical differences with largest absolute differences in the wet Tropics and largest relative

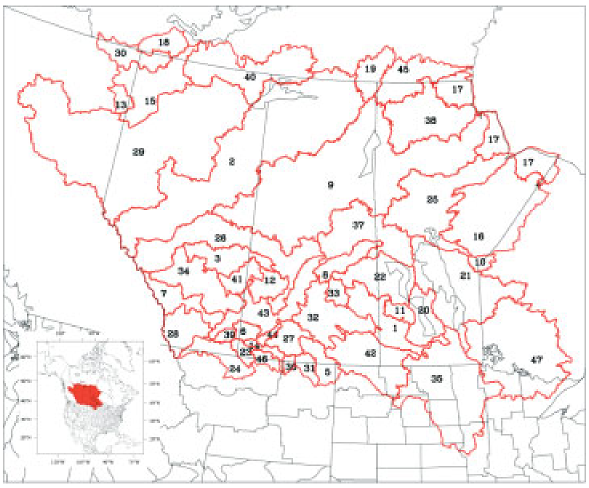

Figure 1. The study area with its 47 watersheds. The names of the watersheds corresponding to the identification numbers (1–47) are given in Table I. The CRCM experimental domain is shown in the inset.

difference in the dry regions. Despite these differences, the overall precipitation pattern in CRU data is fairly similar to that of WM and GPCC global precipitation dataset (Fekete and Vörömarty, 2004). The correlation between CRU and GPCC (WM) annual precipitation is about 0.92 (0.98) globally and 0.76 (0.83) for Canadian Prairies. The differences between the CRU and GPCC (WM) annual precipitation generally lie within ±0.06 (±0.05) mm d^{-1} range for the Canadian Prairies. As the precipitation patterns for the three observed datasets for the Canadian Prairies are fairly similar, we have decided to use only CRU as the observed dataset in this study. The CRU data is interpolated via inverse distance weighting (IDW) method to the CRCM grid prior to comparisons and computation of drought characteristics.

3. Methodology

In this study, three drought severity indices, DSI3, DSI6 and DSI10 based on the accumulated monthly precipitation deficit concept of Bryant *et al*. (1992) are applied to the Canadian Prairies. The DSI3 index uses a 3 month initiation and termination rule, after Bryant *et al*. (1992, 1994). The calculation of DSI3 is briefly explained below. Similarly, the DSI6 (DSI10) uses a six-monthly (ten-monthly) rule, after Marsh *et al*. (1994) and further elaborated in the work of Phillips and McGregor (1998) and Blenkinsop and Fowler (2007a, 2007b).

The calculations of DSIs are based on monthly precipitation anomalies with respect to the 1971–2000 reference climatology. If x_t represents precipitation anomaly in month t, then DSI3 is triggered at month t whenever the mean three-monthly precipitation in the preceding three months (i.e. $t-1, t-2$, and $t-3$) is less than the mean three-monthly climatologic precipitation for the same months for the reference 1971–2000 period and the month t is associated with a precipitation deficit (i.e. $x_t < 0$); DSI3 is then initialised to x_t. The DSI3s for the following months are computed by adding respective monthly anomalies to previous month's DSI3. However, if for any month, the mean three-monthly precipitation received in the preceding three months is above the mean three-monthly climatologic precipitation, drought termination occurs and DSI3 is assigned a zero value. The computed DSI3s are then expressed as a percentage of the annual mean precipitation. The DSI6 and DSI10 are calculated in a similar manner except that six- and ten-monthly periods are used in the calculations. The DSI6 and DSI10 are indicative of more severe drought than DSI3 because longer lasting precipitation deficits will be required over the preceding two or three seasons to initiate such severe droughts for a particular season.

The short- and long-term drought events DRO3, DRO6 and DRO10, defined as droughts lasting between 3 to 6 months, and at least 6 and 10 months, respectively, are based on DSI3, DSI6 and DSI10, with accumulated deficits exceeding 10% of mean annual precipitation. The DRO3 events are likely to influence surface

Table I. Identification numbers (IDs) and names of 47 watersheds, located in the Canadian Prairies. Their distribution is shown in Figure 1.

ID	Watershed	ID	Watershed	ID	Watershed
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		

water resources and represent only weak drought conditions, while the DRO6 and DRO10 events are likely to affect groundwater resources and hence represent strong drought conditions. Additional details and discussion about these indicators of drought conditions can also be found in Fowler and Kilsby (2002, 2004) and Blenkinsop and Fowler (2007a, 2007b). Every occurrence of DRO3, DRO6 and DRO10 event is associated with a maximum precipitation deficit and duration, defined as the time (in months) between drought initiation and termination. In this study, severity is defined as the average of absolute maximum precipitation deficits for each category of DRO events, while frequency is taken as the number of occurrences over a given period of time. The DSIs and DROs are computed for the observed data using monthly precipitation anomalies with respect to the 1971–2000 observed climatology and for five current and five future CRCM simulations using monthly precipitation anomalies with respect to the CRCM climatology for the 1971–2000 period. It must be noted that all figures presented in this article correspond to ensemble means, unless indicated otherwise.

4. Results

4.1. Evaluation of current climate simulation (1971–2000)

4.1.1. Precipitation

As the drought indices considered in this study are based on precipitation, we start by validating model-simulated precipitation. The errors in the CRCM simulated precipitation over the region corresponding to the 47 watersheds are assessed first by comparing simulated average seasonal precipitation with gridded seasonal climatology of precipitation from CRU for the period 1971–2000. Figure 2 reveals that the model captures the observed distribution of winter (DJF), spring (MAM) and fall (SON) precipitation across a large portion of the Canadian Prairies, with errors within the ± 40% range, with the exception of south-western Alberta where the model overestimates precipitation by up to 50% in winter (DJF) along the eastern slopes of the Rocky Mountains (Figure 2(a), (b)). The large errors over south-western Alberta can be explained by the underestimation of the orographic effect in the model, yielding an underestimation of precipitation in the high-elevated region and a corresponding overestimation in the downwind region. Summer precipitation is overestimated across a substantial part of the Canadian Prairies (on average up to 60%), except western central Alberta where there is a slight underestimation (Figure 2(e), (f)); summer errors reach up to 100% over much of Alberta and Saskatchewan. Since summer precipitation is mostly convective, it is believed that the summer precipitation error is mostly associated with the inadequacies of the convective parameterizations in the model (Caya and Biner, 2004; Plummer *et al.*, 2006).

In addition to the seasonal averages, simulated and observed interannual precipitation variability is compared. Interannual standard deviation of seasonal precipitation is normalized by corresponding seasonal average to compute coefficient of variation. The observed precipitation coefficient of variation varies between 0.15 and 0.53 throughout the year, with largest coefficient of variation over south-western Prairies in winter (DJF) (Figure 3(a)) and southern Prairies in fall (SON) (Figure 3(g)), while the CRCM simulated coefficient of variation varies between 0.06 and 0.20 with the highest coefficient of variation over Saskatchewan and Manitoba in spring (MAM) (Figure 3(d)) and southern Saskatchewan in fall (SON) (Figure 3(h)). Overall, the model generally underestimates observed interannual variability, with relatively better agreement in spring. In winter (DJF) and fall (SON), the model underestimates the observed coefficient of variation by up to 75% over southern and central

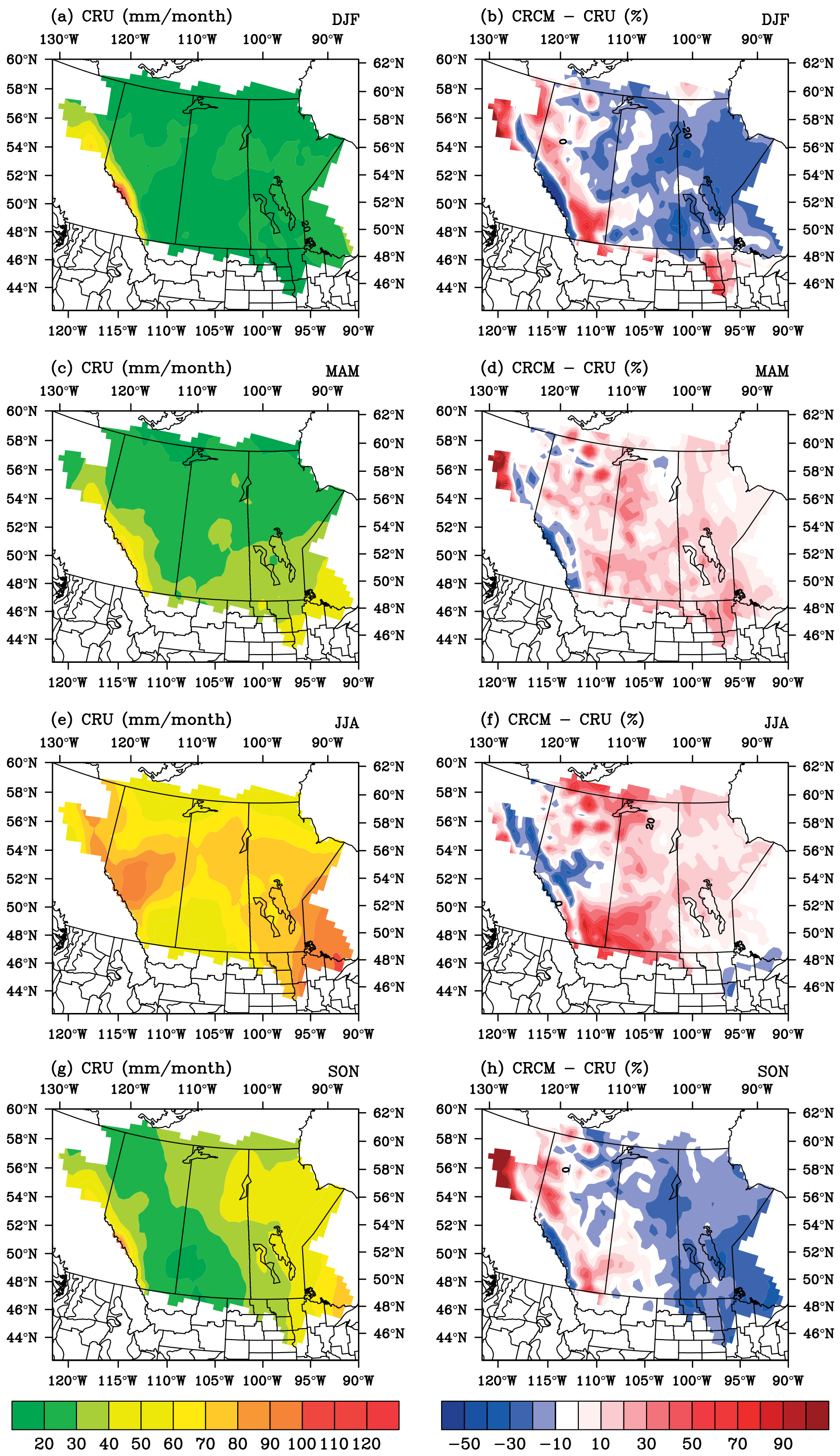

Figure 2. The 30 year observed mean seasonal precipitation (in mm month^{-1}), computed from the CRU gridded precipitation for the period 1971–2000, for the winter (DJF), spring (MAM), summer (JJA) and fall (SON) seasons is shown in panels (a), (c), (e) and (g), respectively. The panels (b), (d), (f) and (h) show the difference (in %) between the CRCM simulated and observed values for winter, spring, summer and fall seasons, respectively.

Alberta and Saskatchewan and the eastern slopes of the Rocky Mountains. The evaluation of interannual variability for summer (JJA) is influenced by the precipitation errors for this season with highest underestimation of observed variability over northern and north-western Alberta (Figures 2(e), (f), and 3(e), (f)).

4.1.2. *Drought characteristics*

Before comparing the model simulated characteristics of DRO events with those derived from CRU data, the usefulness of the DRO events as indicators of drought conditions for the Canadian Prairies is investigated.

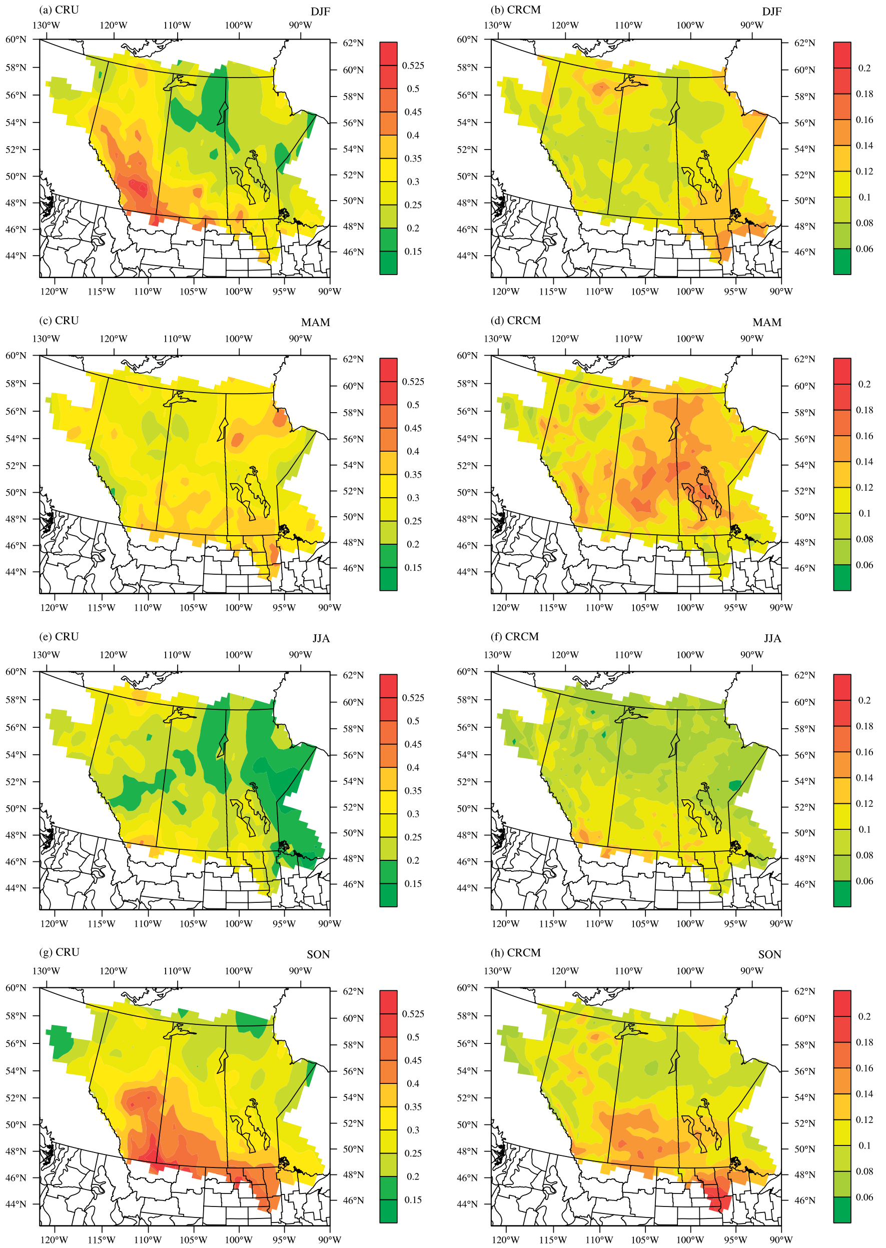

Figure 3. The 30 year observed mean interannual coefficient of variation of seasonal precipitation (in mm month^{-1}), computed from the CRU gridded precipitation for the period 1971–2000, for the winter (DJF), spring (MAM), summer (JJA) and fall (SON) seasons is shown in panels (a), (c), (e) and (g), respectively. The panels (b), (d), (f) and (h) show CRCM simulated values for winter, spring, summer and fall seasons, respectively.

Severity of DRO events, derived from the CRU dataset, for the 1910s, 1930s, 1980, 1984, 1989 and 1999–2002 drought events are shown in Figure 4. Note that for multi-year droughts, i.e. 1910s, 1930s and 1999–2002 periods, DRO10 events are considered, while in the case of single year droughts, i.e. 1980, 1984 and 1989, DRO3 events are considered. The spatial distribution of drought affected areas in Figure 4 is in good agreement with the findings of Nkemdirim and Weber (1999), Chipanshi *et al*. (2006), Bonsal and Regier (2007); the most severe drought occurred generally over western Alberta, Saskatchewan and south-eastern Manitoba in the 1910s (Figure 4(a)), over southern and central Alberta and Saskatchewan and eastern and south-eastern Manitoba in the 1930s (Figure 4(c)), over northern and southern Saskatchewan in 1980 (Figure 4(b)), over the southern Prairies in 1984 (Figure 4(d)), over northern Alberta, south-eastern Saskatchewan and central and southern Manitoba in 1989 (Figure 4(f)) and over south-western and south-eastern Alberta, south-western Saskatchewan during the period 1999–2002 (Figure 4(e)). The above confirms the suitability of DROs for studying droughts over the Canadian Prairies.

We now compare the CRCM simulated short- and long-term drought characteristics (i.e. severity and frequency of DROs) with those derived from the CRU dataset for the current climate (1971–2000) in Figures 5 and 6. The model has difficulties in reproducing the

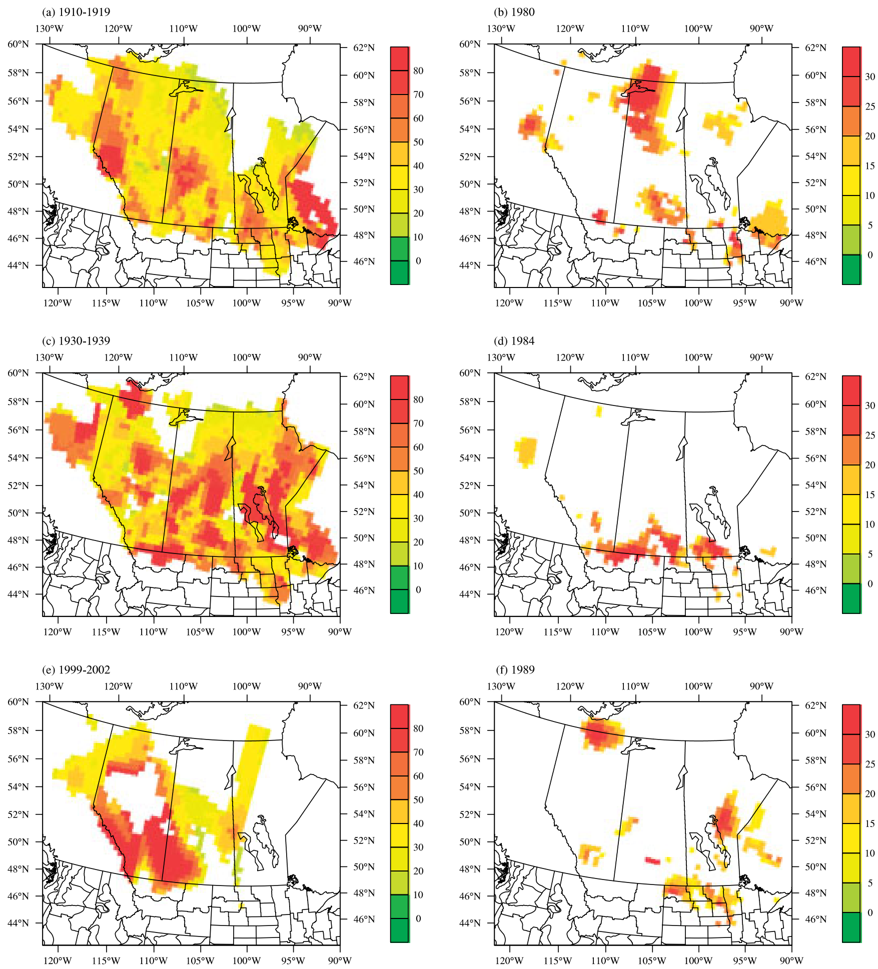

Figure 4. The severity of DRO events determined from the CRU gridded precipitation for (a) 1910–1919, (c) 1930–1939, (b) 1980, (d) 1984, (f) 1989 and (e) 1999–2002 historical drought years over the Canadian Prairies. Note that DRO10 is used for (a), (c) and (e) and DRO3 is used for (b), (d), and (f).

observed severity of long-term droughts, i.e. DRO6 and DRO10 events, over northern Alberta and Manitoba, central Alberta and the southern Prairies (Figure 5(c)–(f)). However, the model captures the severity of the shorter droughts (i.e. DRO3 events) (Figure 5(a), (b)). Severity of DRO6 events is consistently underestimated for a substantial part of the Canadian Prairies and the same conclusion holds for DRO10 events. In general, the model has difficulties in reproducing severities of drought events over the north western and southern Prairies, while it reasonably reproduces severities elsewhere (Figure 5).

The model also has some difficulties in reproducing the observed patterns of frequency of occurrence of DRO3, DRO6 and DRO10 events, especially over regions that experience highest and lowest frequencies of drought events (Figure 6). It underestimates the occurrences of 3- to 6 month long droughts by up to eight events over southern Alberta and Saskatchewan, northern and north-western Alberta and north-eastern Manitoba and overestimates by up to three events over the southern Manitoba (Figure 6(a), (b)). For droughts lasting at least 6 months, the model produces negative biases over southern Prairies, south-western Alberta and northern Alberta and Manitoba (Figure 6(c), (d)). The model also underestimates the frequency of DRO10 events by up to five events over south-western and northern Alberta and overestimates by up to three events over north-eastern Saskatchewan and south-western Manitoba (Figure 6(e), (f)). However, the underestimations of drought occurrence are largest for DRO6 events and are believed to be related to the excessive CRCM summer precipitation, which reduces DSI6 values based on 6 month initiation and termination rules and thus reduces the frequency of occurrence of DRO6 events. Similarly, the overestimations of drought occurrence of DRO10 events are believed to be due to the underestimation of fall and winter precipitation.

The model underestimates the maximum duration of DRO6 and DRO10 events over a greater part of Alberta and Manitoba as shown in Figure 7, while it is overestimated over parts of Saskatchewan.

4.2. Future projections

4.2.1. Precipitation

Projected changes to average seasonal precipitation in the future 2041–2070 period with respect to the current 1971–2000 period are shown in Figure 8. The model

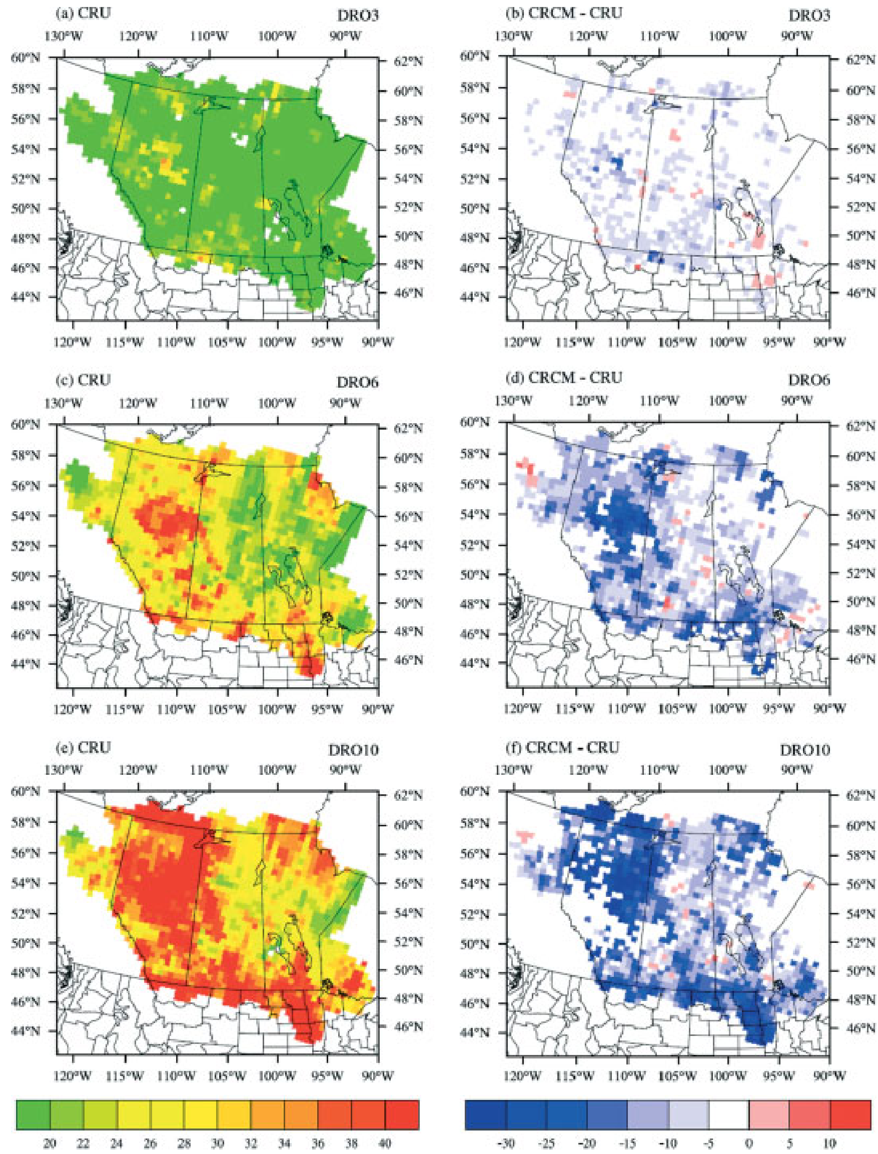

Figure 5. The severity of DRO3, DRO6 and DRO10 events determined from the CRU gridded precipitation for the period 1971–2000 are shown in panels (a), (c) and (e), respectively, while the differences between the CRCM simulated and CRU derived severities are shown in panels (b), (d) and (f).

projects widespread precipitation increases across the Canadian Prairies for all seasons except summer (JJA). In winter (DJF), large relative increases in precipitation (up to 50%) are projected for northern and north-eastern Manitoba, and a secondary increase in precipitation is projected to occur along the eastern slopes of the Rocky Mountains (Figure 8(a), (b)). In spring (MAM), the model projects up to a 30% increase in precipitation over the eastern Prairies (Manitoba) (Figure 8(c), (d)). The projected change for the summer (JJA) season is more mixed, with the largest relative decrease (up to 10%) in precipitation over the western and southern Prairies (Figure 8(e), (f)). The maxima in the summer (JJA) precipitation are likely to decrease from the current climate to future climate over the Rocky Mountains in western Alberta. For fall (SON), the model projects increased precipitation along the eastern slopes of the Rocky Mountains (Figure 8(g), (h)).

4.2.2. *Drought characteristics*

Future changes in the characteristics of drought events for the period 2041–2070 exhibit an increase in the severity of short and long drought events across the southern parts of the Canadian Prairies and along the eastern slopes of the Rocky Mountains (Figure 9). However, increases in the severity of longer drought events (i.e. DRO10s and DRO6s) are larger in comparison to shorter drought events (i.e. DRO3s). Thus, in general, future projections of DRO3 type drought events exhibit the smallest change in severity across the Canadian Prairies.

For DRO3 type drought events, a large portion of southern Saskatchewan and Manitoba and eastern slopes of the Rocky Mountains is projected to experience more frequent droughts (Figure 10(a), (b)), while results suggest a decrease for the northern Prairies. The spatial patterns of projected changes associated with DRO6 events are similar to those of DRO3 events, however

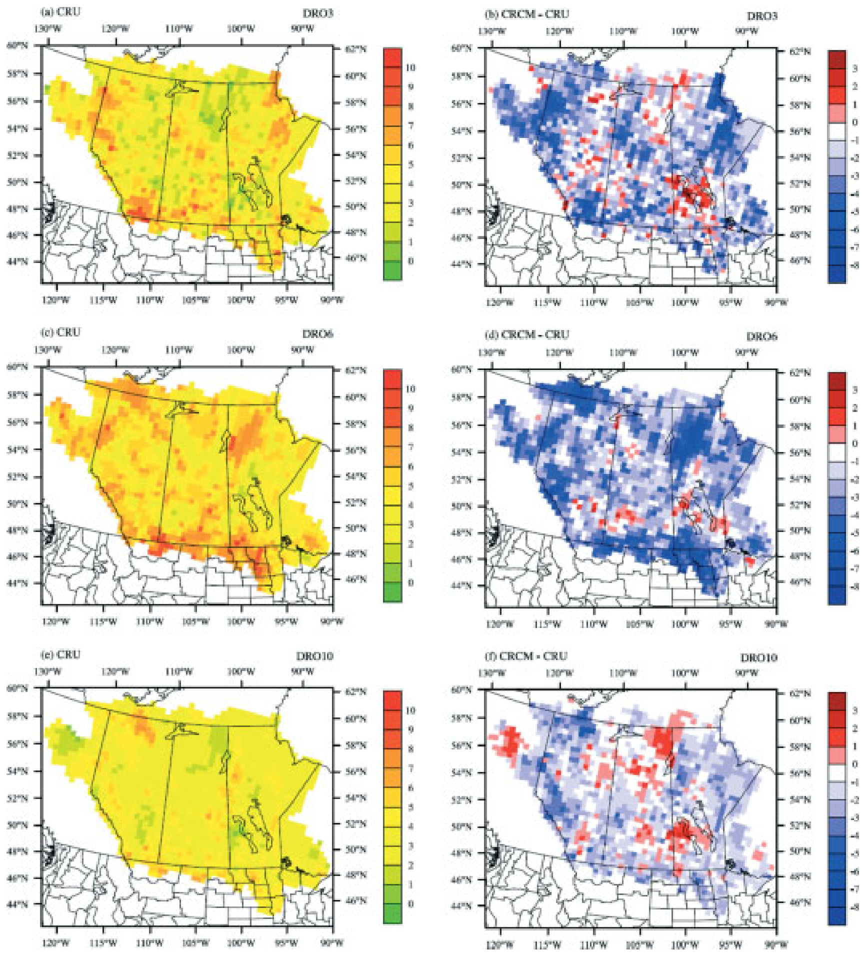

Figure 6. Same as in Figure 5, but for frequencies of DRO3, DRO6 and DRO10 events.

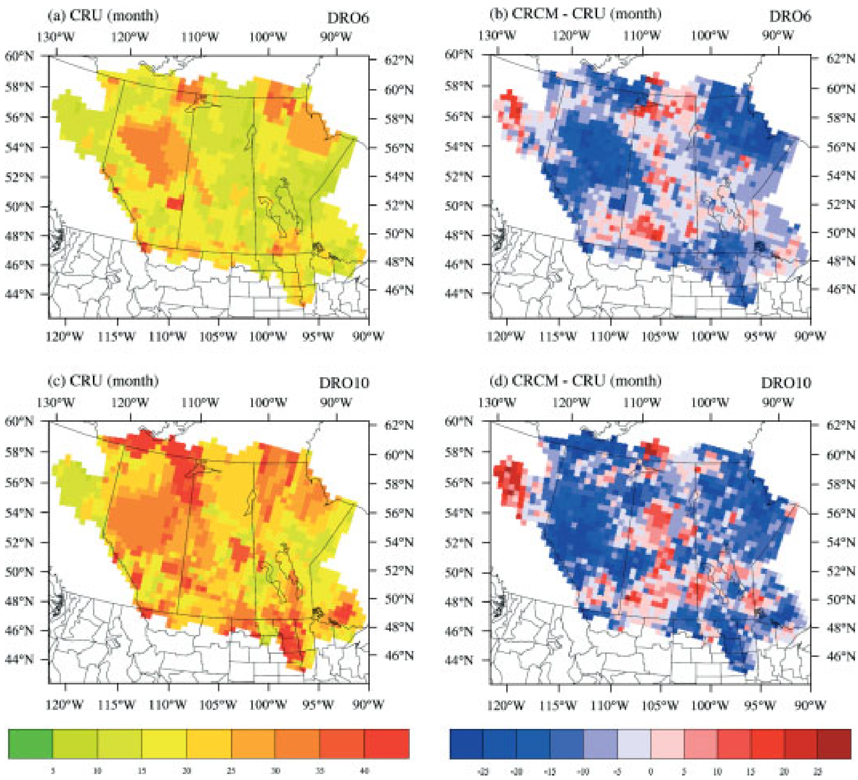

Figure 7. Same as in Figure 5, but for maximum duration (in months) of DRO6 and DRO10 events.

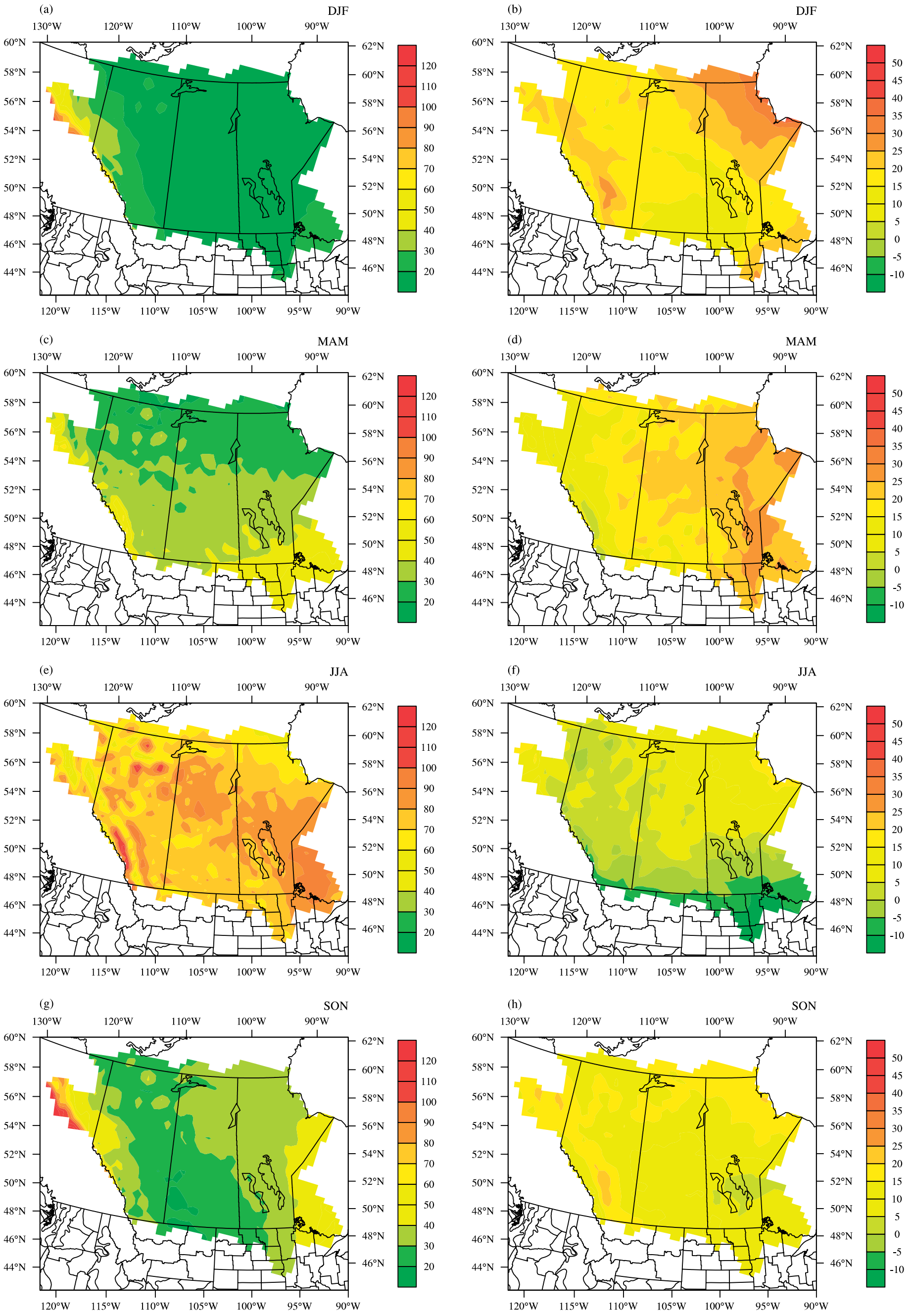

Figure 8. CRCM simulated average (a) winter (DJF), (c) spring (MAM), (e) summer (JJA) and (g) fall (SON) precipitation (in mm month^{-1}) for the current 1971–2000 period and projected changes (in %) for the future 2041–2070 period for the same four seasons are shown respectively in panels (b), (d), (f) and (h).

with generally larger magnitudes (Figure 10(c), (d)). The frequency of DRO10 type events is projected to increase by up to four events during 2041–2070 over southern Manitoba and Saskatchewan and eastern slopes of the Rocky Mountains (Figure 10(e), (f)). Similar to DRO6 events, the projected increases are generally larger in magnitude than those of shorter drought events resulting in more frequent and more severe longer drought events. The largest projected increase in the frequency of both short- and long-term drought events over southern Prairies is believed to be due to the projected decrease in summer precipitation (Figures 8(e), (f) and 10(e), (f)), while projected decreases in the drought events can be attributed to the large projected increases in winter (DJF), spring (MAM) and fall (SON) precipitation over northern, eastern and north-eastern Prairies which interrupt drought sequences.

The maximum duration of DRO6 events is projected to increase by up to 10 months over a few grid cells in the southern Prairies and along the eastern slopes of the Rocky Mountains and decrease by up to 10 months elsewhere (Figure 11(a), (b)). An increase (by more than 20 months) in the maximum duration of DRO10 type events is also projected across a larger proportion of grid

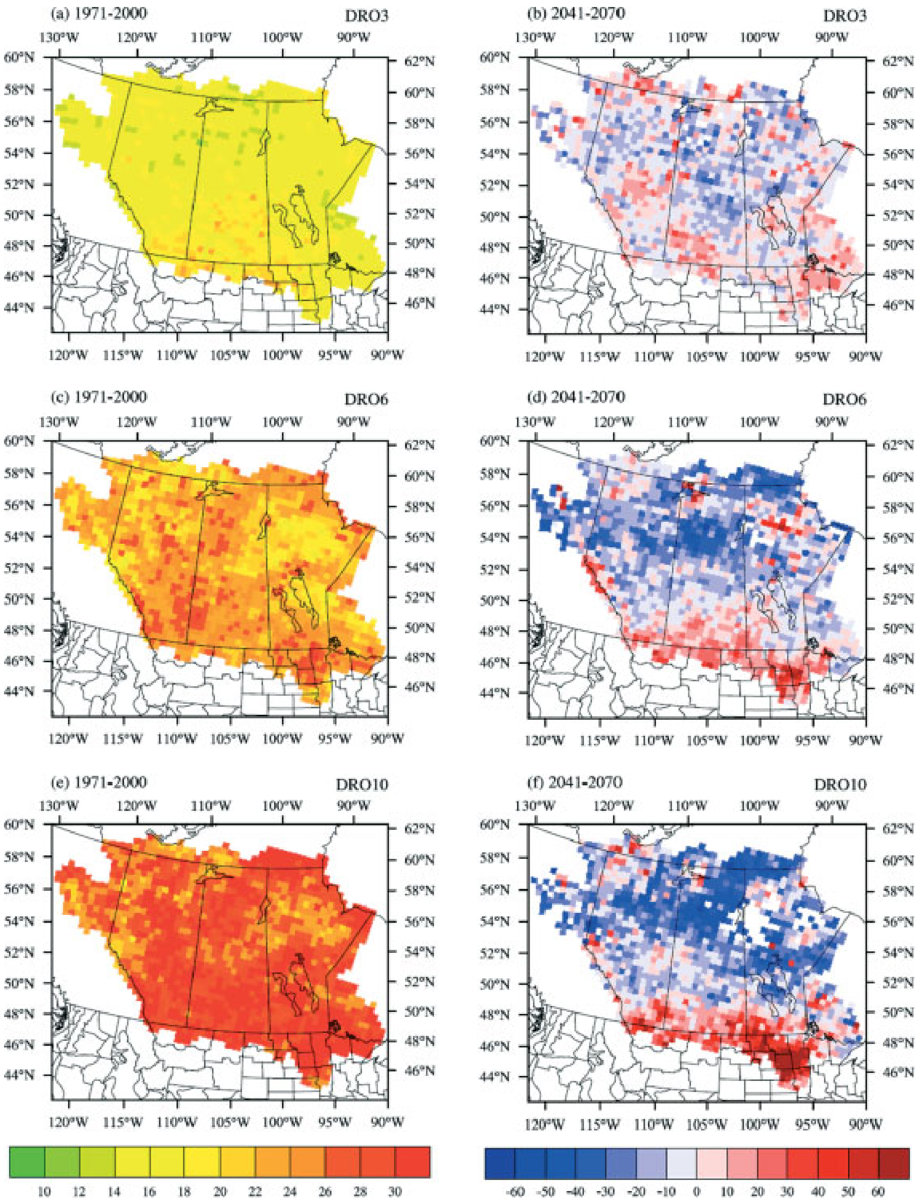

Figure 9. CRCM simulated severities of (a) DRO3, (c) DRO6 and (e) DRO10 events and their projected changes (in %), shown in panels (b), (d) and (f), for the 2041–2070 period with respect to the 1971–2000 period over the Canadian Prairies.

cells over the southern Prairies and along the eastern slopes of the Rocky Mountains (Figure 11(c), (d)). This study thus indicates that in the future, the severity, frequency and maximum duration of all drought events are likely to increase over southern Prairies, with the larger projected changes associated with longer drought events and hence, increased pressure on water resources, especially groundwater, due to decreases in recharge during cooler and wetter seasons.

4.2.3. *Uncertainty in drought characteristics at watershed scale*

The projected changes to both short- and long-term drought characteristics differ among simulation pairs due to the uncertainty introduced by the different CGCM3.1 members used to drive CRCM. To quantify uncertainty, the projected changes to the severity, frequency and maximum duration of DRO10 events, for the five simulation pairs, are discussed in this section. Results are very similar for DRO3 and DRO6 events and therefore they not discussed.

Figure 12(a)–(c) illustrates respectively projected changes to the severity, frequency and maximum duration of DRO10 events for the five simulation pairs, at watershed scale, for the 47 Prairie watersheds. Three out of the five pairs, i.e. Figure 12(a) (ii–iv), suggest increases in the severity of DRO10 events for the southern watersheds, while the remaining two pairs (Figure 12(a) (i, v)) suggest both increase/decrease in severity for the various southern watersheds. Similar behaviour is noticed for projected changes to the frequency and maximum duration of DRO10 events (Figure 12(b), (c)).

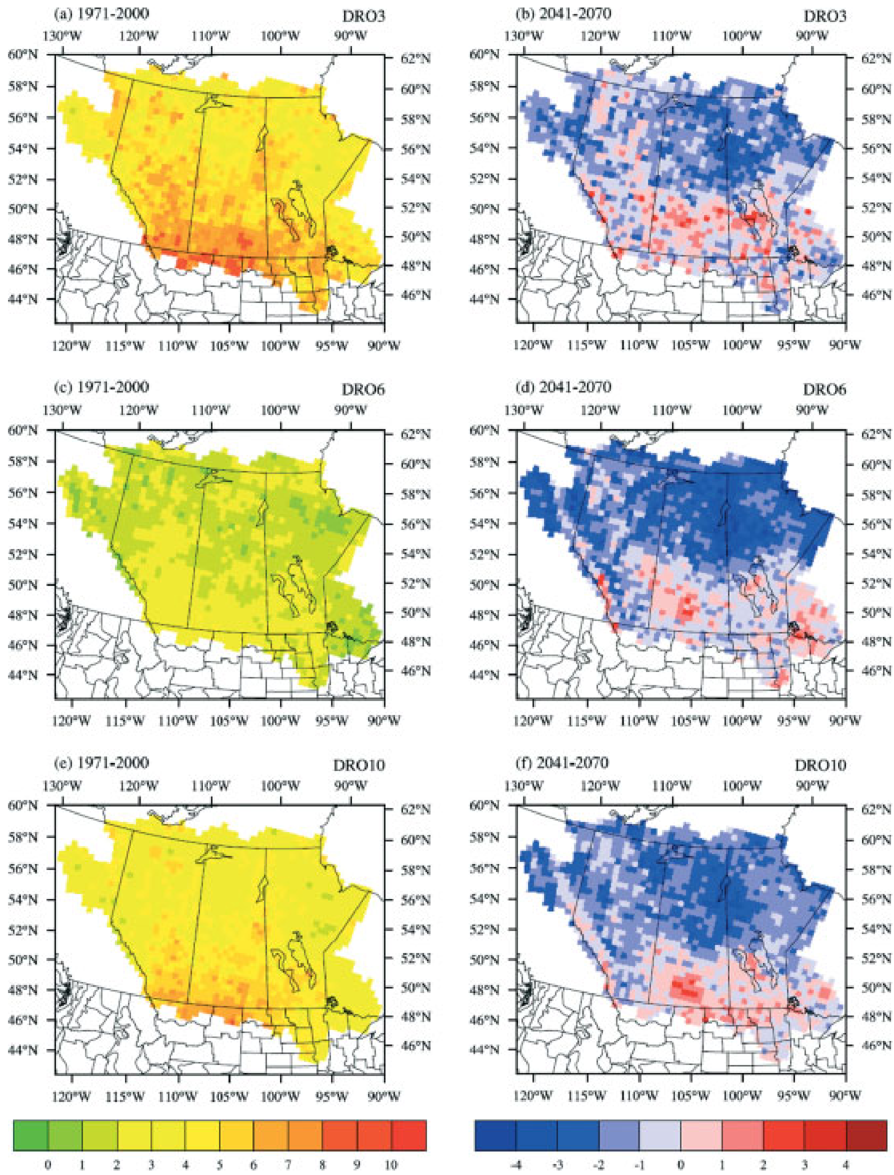

Figure 10. Same as in Figure 9, but for frequencies of DRO events.

Figure 12(d) classifies watersheds based on projected changes to severity and frequency of DRO10 events, for the five pairs of simulations. Once again, differences between the different pairs are evident in the subplots. The most vulnerable watersheds, i.e. those with projected increase in both severity and frequency of DRO10 events, clearly lie in the southern Prairies, as can be seen in Figure 12(d) (i–iv). Note that the spread of highly vulnerable watersheds is limited in the fifth pair of simulations shown in Figure 12(d) (v). However, in general, the ensemble mean, as already discussed, identifies the southern Prairies as a hot spot, with high likeliness of severe, more frequent drought events.

5. Discussion and conclusions

This study evaluated the drought characteristics of severity, frequency and maximum duration in the current climate (1971–2000) and projected changes for the future 2041–2070 period as simulated across the Canadian Prairies by the CRCM and SRES A2 scenario. The short- and long-term droughts are defined based on cumulative monthly precipitation anomalies.

Results suggest that the model consistently underestimates the severity and frequency of both short- and long-term drought events over the Canadian Prairies in current climate. The performance of the model is more mixed for long-term drought events, overestimating the observed maximum duration of these events over Saskatchewan and underestimating elsewhere. The CRCM biases in mean seasonal precipitation and the underestimation of interannual variability of seasonal precipitation probably influence the model performance in simulating drought events.

For future climate, the results of the study suggest an increase in severity of both short- and long-term droughts over a large portion of the southern Prairies and along the eastern slopes of the Rocky Mountains, with the

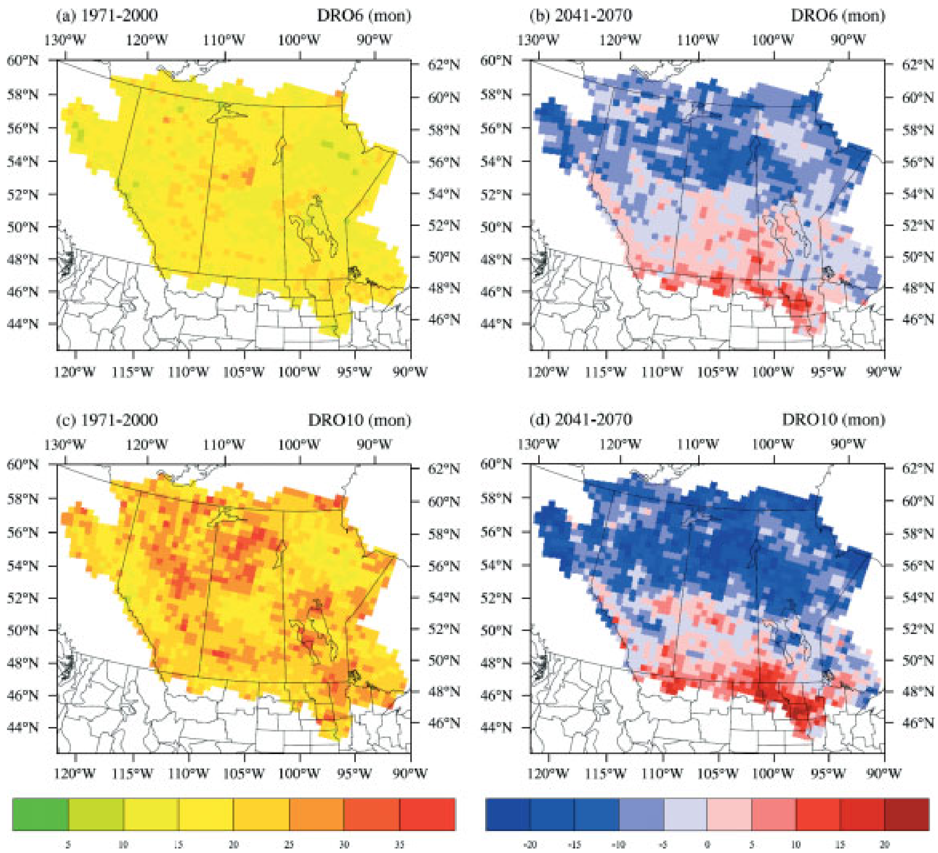

Figure 11. Same as in Figure 9, but for maximum duration (in months) of DRO6 and DRO10 events.

largest increase occurring with long-term events. Projected increases in shorter and longer drought frequency will affect the surface and groundwater resources over most of the southern Prairies, respectively. Maximum durations of long-term drought events are also projected to increase across a large portion of the southern Prairies with the largest increase associated with droughts lasting at least 10 months.

In general, this study indicates that the southern Canadian Prairies are projected to experience droughts of even greater severity and duration in the future than those of the 20th century, which could significantly impact environmental and socio-economic conditions in this region that contains more than 80% of Canada's cropland and rangeland (Chipanshi *et al*., 2006). Prolonged droughts are also likely to become a threat to conservation of biodiversity by damaging the domesticated forage plants for livestock, natural grasslands, savannas, many wetlands, tundra, and certain forb and shrub communities of the Canadian Prairies (Tilman and Haddi, 1992; Chipanshi *et al*., 2006). Consequently, more efficient adaptation strategies are essential to address the impact of these short- and long-term droughts in future.

The indices used in this study to determine severity, frequency and maximum duration of droughts have some limitations in spite of their usefulness. These indices capture only the effect of precipitation change on the occurrence and severity of droughts, but the severity also depends on other factors, such as evapotranspiration, soil moisture, temperature, etc., which were not taken into account. Therefore, in future, other drought indices will also be explored to study future changes in drought characteristics over the Canadian Prairies. In addition, multivariate copula-based approaches for modelling drought frequency, duration and severity will also be explored to characterize drought features in a multidimensional space. The results presented in this article are based on an ensemble of simulations from one model; in future, to further quantify the uncertainties, multi-model, multi-scenario simulations will need to be considered.

Acknowledgements

The authors would like to thank the Ouranos Climate Simulations Team for supplying the CRCM generated daily precipitation outputs used in this study. This research was carried out within the Canadian Regional Climate Modelling and Diagnostics (CRCMD) Network funded by the Canadian Foundation for Climate and Atmospheric Sciences (CFCAS), the Ouranos Consortium and the Pacific Climate Impacts Consortium (PCIC). Anonymous review comments are gratefully acknowledged.

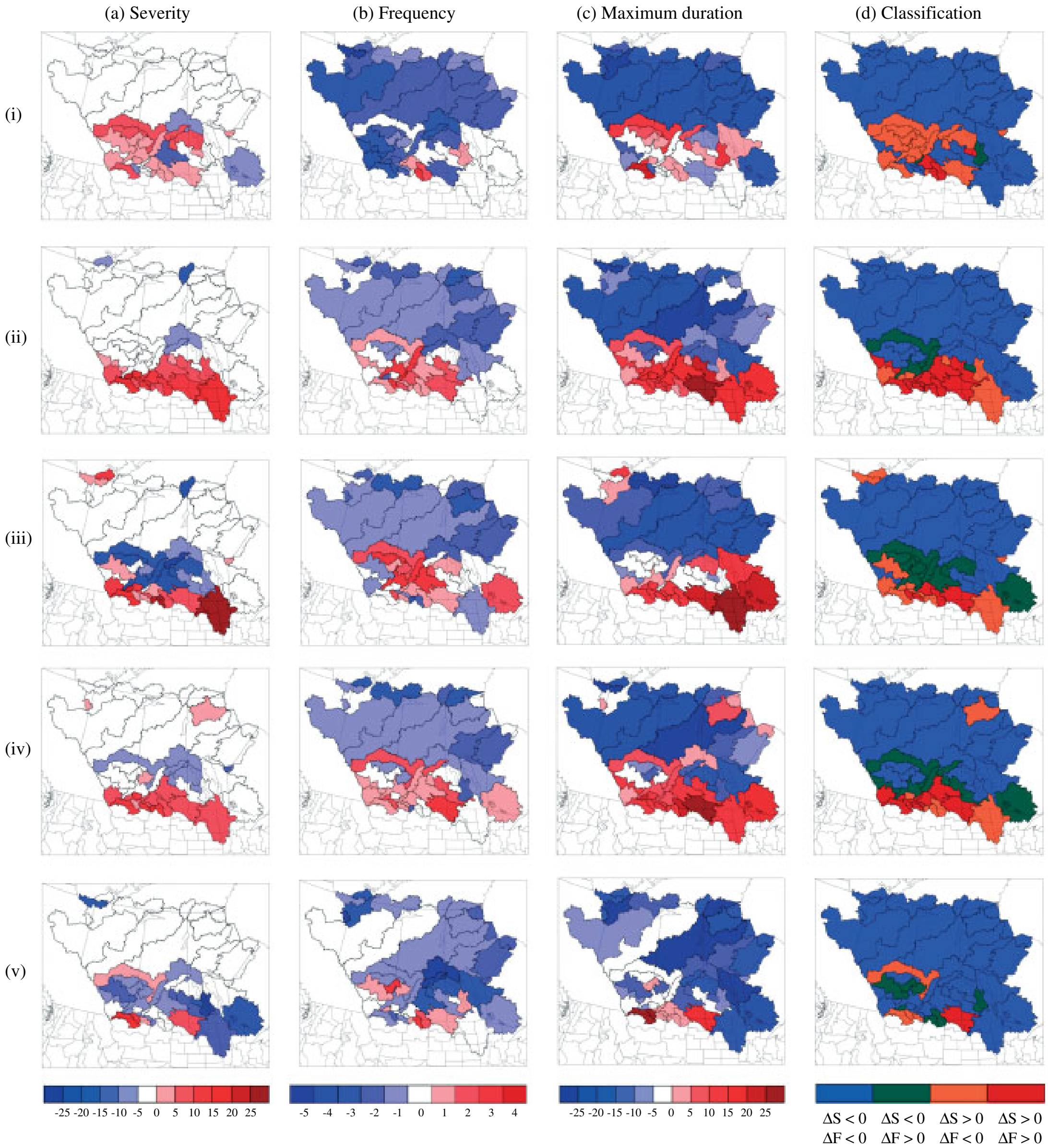

Figure 12. Projected changes to the (a) severity (in %), (b) frequency and (c) maximum duration (in months) of DRO10 events at the watershed scale, and (d) classification of watersheds based on projected changes to severity and frequency (respectively ΔS and ΔF) of DRO10 events for the 47 watersheds located in the Canadian Prairies, for the five pairs (i–v) of CRCM simulations.

References

Bechtold P, Bazile E, Guichard F, Mascart P, Richard E. 2001. A mass flux convection scheme for regional and global models. *Quarterly Journal of the Royal Meteorological Society* **127**: 869–886.

Bhalme HN, Mooley DA. 1980. Large-scale drought/floods and monsoon circulation. *Monthly Weather Review* **23**: 1100–1109.

Biner SD, Caya D, Laprise R, Spacek L. 2000. Nesting of RCMs by imposing large scales. In Research activities in Atmospheric and Ocean Modelling, WMO/TD – No. 987, Report No. 30: 7.3–7.4.

Blenkinshop S, Fowler HJ. 2007a. Changes in drought frequency, severity and duration for the British Isles projected by the PRUDENCE regional climate models. *Journal of Hydrology* **342**: 50–71.

Blenkinshop S, Fowler HJ. 2007b. Changes in European drought characteristics projected by the PRUDENCE regional climate models. *International Journal of Climatology* **27**: 1595–1610.

Bonsal B, Wheaton EE. 2005. Atmospheric circulation comparison between the 2001 and 2002 and the 1961 and 1988 Canadian Prairie droughts. *Atmosphere-Ocean* **43**: 163–172.

Bonsal BR, Regier M. 2006. The 2001and 2002 Canadian drought: historical context and potential future occurrence. Environmental Canada Water Science and Technology Directorate internal report No. AE1-TN-06-002, 58 pp.

Bonsal BR, Regier M. 2007. Historical comparison of the 2001/2002 drought in the Canadian Prairies. *Climate Research* **33**: 229–242.

Bryant SJ, Arnell NW, Law FM. 1992. The long-term context for the current hydrological droughts. In *IWEM Conference on the Management of Scarce Water Resources, London*.

Bryant SJ, Arnell NW, Law FM. 1994. The 1988–92 droughts in its historical perspective. *Journal of the Institution of Water and Environmental Management* **8**: 39–51.

Caya D. 1996. *Le modèle régional de climat de l'UQAM*. PhD thesis, Université du Québec à Montréal, Canada, 134 pp.

Caya D, Laprise R. 1999. A semi-implicit semi-Lagrangian regional climate model: the Canadian RCM. *Monthly Weather Review* **127**: 341–362.

Caya D, Biner S. 2004. Internal variability of RCM-simulations over an annual cycle. *Climate Dynamics* **22**: 33–46.

Chipanshi AC, Findlater KM, Hadwen T, O'Brien EG. 2006. Analysis of consecutive droughts on the Canadian Prairies. *Climate Research* **30**: 175–187.

Davies HC. 1976. A lateral boundary formulation for multi-level prediction models. *Quarterly Journal of the Royal Meteorological Society* **102**: 405–418.

de Elia R, Caya D, Cote H, Frigon A, Biner S, Giguere M, Paquin D, Harvey R, Plummer D. 2008. Evaluation of uncertainties in the CRCM-simulated North American climate. *Climate Dynamics*. **30**: 113–132.

Denis B, Côté J, Laprise R. 2002. Spectral decomposition of two-dimensional atmospheric fields on limited- area domains using discrete cosine transforms (DFT). *Monthly Weather Review*. **130**: 1812–1829.

Fekete BM, Vörömarty CJ. 2004. Uncertainties in precipitation and their impacts on runoff estimates. *Journal of Climate* **17**: 294–304.

Flato GM, Boer GJ. 2001. Warming asymmetry in climate change simulations. *Geophysical Research Letters* **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. *Journal of Hydrology* **262**: 177–192.

Fowler HJ, Kilsby CG. 2004. Future increase in UK water resource drought projected by a regional climate model. In *Proceedings BHS International conference on Hydrology: Science & Practice for the 21st Century*, London 1, 15–21.

Frigon A, Music B, Slivitzky M. 2010. Sensitivity of runoff and projected changes in runoff over Quebec to the update interval of lateral boundary conditions in the Canadian RCM. *Meteorologische Zeitschrift* **19**(4): 399–399.

Gal-Chen T, Somerville RC. 1975. On the use of a coordinate transformation for the solution of Navier-Stokes. *Journal Computation Physics* **17**: 209–228.

IPCC, 2001. In *Climate Change 2001. The Scientific Basis*, Houghton JT, Ding TY, Griggs DJ, Noguer M, van der Linder PJ, Dai X, Maskell K, Johnson CA (eds). Cambridge University Press: 881 pp.

IPCC, 2007. *Climate Change 2007: The Physical Science Basis – Summary for Policy Makers*. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC, Geneva, Switzerland, 18 pp.

Kain JS, Fritsch JM. 1990. A one-dimensional entraining/detraining plume model and application in convective parameterization. *Journal of Atmospheric Sciences* **47**: 2784–2802.

Laprise R, Caya D, Giguère M, Bergeron G, Côté H, Blanchet JP, Boer GJ, McFarlane NA. 1998. Climate of Western Canada under current and enhanced greenhouse gas concentration as simulated by the Canadian Regional Climate Model. *Atmosphere Ocean* **36**(2): 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 north-western North America. *Climate Dynamics* **21**: 405–421.

Marsh TJ, Monkhouse RA, Arnell NW, Lees ML, Reynard NS. 1994. The 1988–92 drought. *Institute of Hydrology and British Geological Survey*, Wallingford, pp 80.

Maybank J, Bonsal BR, Jones K, Lawford R, O'Brien EG, Ripley EA, Wheaton E. 1995. Drought as a natural disaster. *Atmosphere-Ocean* **33**: 195–222.

McKee TB, Doesken NJ, Kleist J, 1993. The relationship of drought frequency and duration to time scale. Preprints, 8th *Conference on Applied Climatology,* Anaheim, CA, American Meteorological Society, 179–184.

Meyer TB, Hubbard KG, Wilhite DA. 1993. The development of crop specific drought index for corn. Part I. Model development and validation. *Agronomy Journal* **85**: 388–395.

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 Working Paper 55, Tyndall Centre, UEA, Norwich, UK. http://www.tyndall.ac.uk/.

Music B, Caya D. 2007. Evaluation of the hydrological cycle over the Mississippi River Basin as simulated by the Canadian Regional Climate Model (CRCM). *Journal of Hydrometeorology* **8**(5): 969–988.

Nkemdirim L, Weber L. 1999. Comparison between the droughts of the 1930s and the 1980s in the southern Prairies of Canada. *Journal of Climate* **12**: 2434–2450.

Palmer WC. 1965. Meteorological drought. Research paper, US Weather Bureau, Washington, DC, 45, p 58.

Phillips ID, McGregor GR. 1998. The utility of a drought index for assessing the drought hazard in Devon and Cornwall, South West England. *Meteorological Applications* **5**: 359–372.

Plummer DA, Caya D, Frigon A, Côté H, Giguére M, Paquin D, Biner S. 2006. Climate and climate change over north America as simulated by the Canadian RCM. *Journal of Climate* **19**: 3112–3132.

Quiring SM, Papakryiakou TN. 2003. An evaluation of agricultural drought indices for the Canadian prairies. *Agricultural and Forest Meteorology* **118**: 49–62.

Riette S, Caya D. 2002. Sensitivity of short simulations to the various parameters in the new CRCM spectral nudging. In Ritchie H (ed). Research activities in Atmospheric and Oceanic Modeling, WMO/TD No. 1105, Report No. 32: 7.39–7.40.

Rudolf B, Hauschild H, Rueth W, Schneider U. 1994. Terrestrial precipitation analysis: operational method and required density of point measurements. In *Global Precipitation and Climate Change*, Desbois M, Desahmond F(eds). Springer-Verlag: Berlin, Heidelberg,173–186.

Sushama L, Khaliq MN, Laprise R. 2010. Dry spell characteristics over Canada in a changing climate as simulated by the Canadian RCM. *Global and Planetary Change* **74**: 1–14.

Statistics Canada. 2002. *Farm data for the 2001 Census of Agriculture*. Statistics Canada: Ottawa.

van Rooy MP. 1965. A rainfall anomaly index independent of time and space. *Notos* **14**: 43–48.

Von Storch H, Langenberg H, Feser F. 2000. A spectral nudging technique for dynamical downscaling purposes. *Monthly Weather Review* **128**: 3664–3673.

Willmott CJ, Matsuura K. 2001. Terrestrial air temperature and precipitation: Monthly and annual time series (1950–1999) Version 1.02, Available at http://climate.geog.udel.edu/climate.

Yakimiw E, Robert A. 1990. Validation experiments for a nested grid-point regional forecast model. *Atmosphere-Ocean* **28**: 466–472.

