Clim Dyn (2013) 41:501–516
DOI 10.1007/s00382-012-1422-0

An assessment of Canadian prairie drought: past, present, and future

Barrie R. Bonsal · Rabah Aider · Philippe Gachon · Suzan Lapp

Received: 10 April 2012 / Accepted: 9 June 2012 / Published online: 28 June 2012

Abstract Within Canada, the Canadian Prairies are particularly drought-prone mainly due to their location in the lee of the western cordillera and distance from large moisture sources. Although previous studies examined the occurrence of Canadian Prairie droughts during instrumental, pre-instrumental and to a lesser extent, future periods, none have specifically focused on all time three scales. Using two different drought indicators, namely the Palmer Drought Severity Index (PDSI) and Standardized Precipitation Index (SPI), this investigation assesses the variability of summer drought duration and intensity over a core region of the Prairies during (a) the pre-instrumental record extending back several centuries (inferred from tree rings), (b) the instrumental record (1901–2005), and (c) the twenty-first century using statistically downscaled climate variables from several Atmosphere–Ocean Global climate models with multiple emission scenarios. Results reveal that observed twentieth century droughts were relatively mild when compared to pre-settlement on the Prairies, but these periods are likely to return (and even worsen) in the future due to the anticipated warming during the course of the twenty-first century. However, future drought projections are distinctly different between the two indices. All PDSI-related model runs show greater drought frequency and severity mainly due to increasing temperatures. Conversely, the precipitation-based SPI indicates no significant changes to future summer drought frequency although there tends to be a higher persistence of multi-year droughts in central and southern portions of Canadian Prairies. These findings therefore stress the importance of considering anticipated warming trends when assessing future regional-scale drought, especially given the uncertainties and lack of consistency in future precipitation signals among climate models. This study can be considered an initial step toward quantifying and understanding Canadian Prairie drought occurrence and severity over several centuries as determined from paleo, instrumental, and climate model data sources.

Keywords Droughts · Canadian Prairies · Paleo-climate · Climate change · Downscaling · Atmosphere–Ocean Global climate models

B. R. Bonsal (✉)
Environment Canada, 11 Innovation Boulevard,
Saskatoon, SK S7N 3H5, Canada
e-mail: barrie.bonsal@ec.gc.ca

R. Aider · P. Gachon
Environment Canada, Adaptation and Impacts
Research Section, Montreal, QC, Canada

R. Aider · P. Gachon
ESCER (Étude et Simulation du Climat à l'Échelle Régionale)
Centre, University of Québec at Montréal, Montréal,
QC, Canada

S. Lapp
Prairie Adaptation Research Collaborative,
University of Regina, Regina, SK, Canada

1 Introduction

Prolonged, large-area drought events are among Canada's costliest natural disasters, having major impacts on sectors such as agriculture, forestry, industry, recreation, human health and society, and aquatic ecosystems (e.g. Bonsal et al. 2011a). Although many areas of Canada periodically experience drought, the agricultural regions of the Canadian Prairies are more drought-prone due to their location in the lee of the western cordillera, their distance from large water bodies, and high precipitation variability. In any year, there is usually some region within the Prairies that has a precipitation deficit, but it is the larger area droughts that have the greatest impacts (e.g. Bonsal and Regier 2007). Moreover, severe Prairie droughts have been documented throughout the instrumental and pre-instrumental record, and are certain to continue in the future.

The general consensus among researchers is that increases in air temperature will be accompanied by enhanced continental interior drying and associated risk of droughts (e.g. Meehl and Stocker 2007). Even though the observed twentieth century warming has been associated with increases in very dry areas on a global basis (Dai et al. 2004), trend investigations on a more regional basis have shown mixed results. For example, although mean annual temperature during the last century has increased by 1.6 °C over the southern Canadian Prairies (e.g. Sauchyn and Kulshreshtha 2008), assessments of Prairie droughts using a variety of indicators suggest periodic occurrences with no clear trend. In particular, large-area, multi-year dry episodes were identified during the 1910s, 1930s, 1980s, and from 1999 to 2005 (Quiring and Papakyriakou 2005; Chipanshi et al. 2006; Bonsal and Regier 2007; Stewart et al. 2011). These findings are consistent with observed Canadian Prairie precipitation that has been variable with decadal-scale fluctuations dominating the instrumental record (Bonsal et al. 2011b). Note that Prairie droughts have also been reconstructed back several centuries using dendro-chronological techniques. Results tended to show that the twentieth century lacked the prolonged droughts of the eighteenth and nineteenth centuries when decadal-scale droughts consistently occurred (e.g. Sauchyn and Skinner 2001).

Atmosphere–Ocean Global climate models (AOGCMs) used in the most recent Intergovernmental Panel on Climate Change assessment project a greater risk of drought due to increased temperature and potential evapotranspiration not being balanced by projected changes to precipitation (e.g. Dai 2011). However, there are considerable spatial variations in these projections mainly due to the regional uncertainty regarding future precipitation in these large-scale climate models (particularly, during the summer season). Regional-scale factors contributing to this uncertainty include for example, the water content of the soil, spring snowmelt run-off, vegetation, and soil type, which are key regional sources of moisture. This moisture can play a vital role in modulating summer convective precipitation, especially via moisture recycling (see for example, Schär et al. 1999). Only a few studies have examined future drought occurrence over the Canadian Prairie region. Sushama et al. (2010) analyzed future dry spell characteristics over Canada using a single simulation from the Canadian Regional Climate Model. Results indicated that by the end of this century, the southern Prairies will experience an increase in the number of dry days and dry spell durations during the critical April to September period. A preliminary, first-order assessment of future (2041–2070) annual-scale Canadian droughts by Bonsal and Regier (2006) showed small positive changes in the Standardized Precipitation Index (SPI) over the southern Prairies for the majority of AOGCM climate-change scenarios, reflecting the projected increase in annual precipitation over most of this region. The Palmer Drought Severity Index (PDSI), however, revealed dramatic increases to the potential for future droughts particularly, in the warm-dry scenario. These differences were attributed to the inclusion of temperature in the PDSI calculation.

Although studies have been carried out regarding the occurrence of Canadian Prairie droughts during instrumental, pre-instrumental, and to a lesser extent, future periods, none have specifically examined variability in their frequency over all three time scales. The main objective of this investigation is to assess the variability of drought duration and intensity over a core region of the Canadian Prairies during (a) the recent paleo-record extending back several centuries (as inferred from tree rings), (b) the instrumental record of 1901–2005, and (c) the twenty-first century as projected by three AOGCMs with different emission scenarios. This temporal comparison study is carried out using two different meteorological drought indices, namely the PDSI to assess longer-scale drought from a water balance perspective, and the SPI to assess summer precipitation drought. Data and methods are described in Sect. 2, while Sect. 3 assesses drought characteristics during the aforementioned three periods both individually and collectively. Conclusions are provided in Sect. 4.

2 Data, methods, and validation

2.1 Drought indices

Several indices specific to certain types of drought have been devised to quantify drought severity. Meteorological indices range from those that consider only precipitation, to more complex methods that incorporate a water balance approach using precipitation, potential evapotranspiration, antecedent soil moisture, and runoff. Agricultural drought indices relate directly to soil moisture availability, while hydrologic indicators generally use groundwater levels, runoff, snow pack, and soil moisture as input. The vast majority of drought analyses in Canada, however, have utilized meteorological indices since the temperature and precipitation input variables are readily available for longer periods and larger areas (e.g. Bonsal et al. 2011a).

Table 1 Moisture classifications based on the PDSI and SPI

Classification	PDSI	SPI
Drought		
Exceptional	≤−5.0	≤−2.5
Extreme	>−5.0 to −4.0	>−2.5 to −2.0
Severe	>−4.0 to −3.0	>−2.0 to −1.5
Moderate	>−3.0 to −2.0	>−1.5 to −1.0
Mild	>−2.0 to −1.0	>−1.0 to −0.5
Near normal	>−1.0 to 1.0	>−0.5 to 0.5
Wet		
Mild	1.0 to <2.0	0.5 to <1.0
Moderate	2.0 to <3.0	1.0 to <1.5
Severe	3.0 to <4.0	1.5 to <2.0
Extreme	4.0 to <5.0	2.0 to <2.5
Exceptional	≥5.0	≥2.5

Given these data limitations, this study utilizes two different meteorological indices to analyze historical and future Prairie droughts. The first is the self-calibrated PDSI that incorporates precipitation and temperature in its calculation. The index determines the physical severity of drought and is generally considered useful for longer-term agricultural and hydrologic applications. Values are determined on a monthly basis with negative quantities indicating a shortage of water (Palmer 1965) (Table 1). Note that the calculated PDSI value is comprised of only one-third of the current month's precipitation deficit and almost nine-tenths of the previous month's PDSI (Guttman 1998). Therefore, the PDSI for a given month contains a long-term memory of previous moisture conditions. The second is the SPI (McKee et al. 1993), which has been recently recommended by the World Meteorological Organization to characterize meteorological droughts around the world. This index differs from PDSI in that it is based solely on precipitation, can be computed over any duration, and does not contain a memory of previous moisture. The SPI interprets observed precipitation as a standardized departure with respect to a precipitation probability distribution and is dimensionless (see Table 1). The calibration period used for the computation of these indices is 1961–2003 (to coincide with the availability of daily temperature and precipitation data; see Sect. 2.3). Both the PDSI and SPI have been extensively used for drought analyses both over North America, and globally.

For all analyses, PDSI and SPI are determined for the summer (June–August) period since this is when the Prairies receive the majority of their annual precipitation (e.g. Dey 1982) and as a result, severe droughts have the greatest impact on water-related sectors. Given the nature of the two indices, summer PDSI are representative of

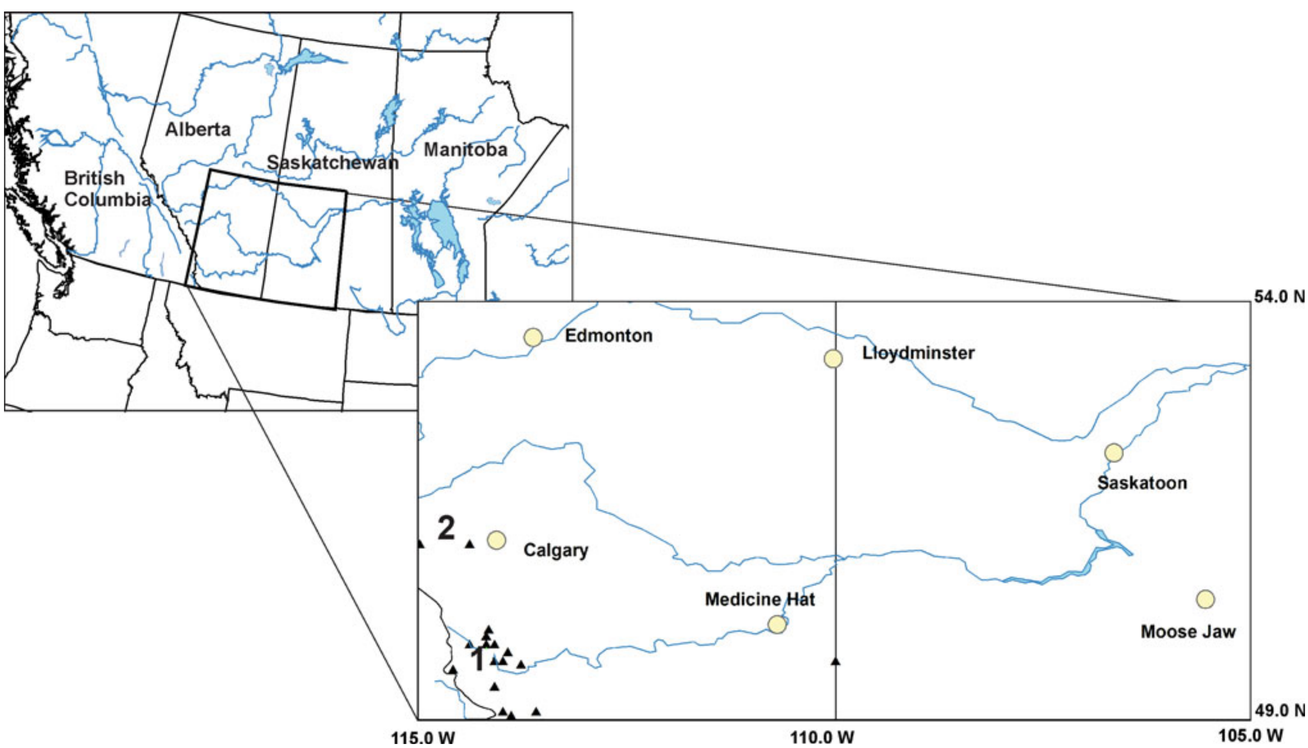

Fig. 1 Study area for this investigation. Original tree-ring sites are shown by *black triangles*. Numbers correspond to the two site chronologies used for the reconstructions (see text for details). #1: Oldman River, Species: *Pinus flexilis*, 49.8°N, 114.2°W, Elevation: 1447 m. #2: Wildcat Hills, Species: *Pseudotsuga menziesii*, 51.3°N 114.7°W, Elevation: 1,351 m

more prolonged droughts that take into account antecedent conditions and are impacted by temperature. Conversely, the 3-month SPI ending in August is a direct measure of summer drought based only on precipitation. Hence, by using these two indices, this study will improve current knowledge regarding the paleo, instrumental, and future variability in Canadian Prairie drought occurrence and severity from both a single variable, short-term memory index (SPI) and a multiple variable, long-term memory index (PDSI) over the same summer period. Note that the main purpose of the study is not the comparison of these indices, but rather a drought assessment over the three aforementioned time scales using precipitation alone and precipitation combined with temperature information.

2.2 Study area

Although instrumental and projected future temperature and precipitation values (required for drought index calculations) are available for the entire Canadian Prairies, reconstruction of the paleo-drought record is spatially limited to the region correlated with the current tree-ring network (see Fig. 1). Based on this network, a core drought area of southern Alberta and south-western Saskatchewan (49°N–54°N, 115°W–105°W; Fig. 1) is chosen for study. This closely corresponds to the main area that was affected during several identified Prairie droughts, including that of 1999–2005 (e.g. Bonsal et al. 2011b).

2.3 Instrumental record

Due to the inconsistency of climate station data within the study area (both spatially and temporally), this analysis utilizes available gridded temperature and precipitation for the instrumental record. The primary dataset comprises of monthly values from 1901 to 2005 and is described in McKenney et al. (2006). The data are at a 10 km resolution and were generated using thin-plate smoothing splines as implemented by ANUSPLIN (Hutchinson 2004). Input data include all available climate stations from the Environment Canada archives. Summer PDSI and SPI values for each of the 105 years are calculated at the original 10 km resolution and then spatially aggregated to a 50 km grid (to reduce the amount of data and correspond with the future drought procedures described in Sect. 2.5). The indices are then areally-averaged over the study area in Fig. 1. Recently, Hutchinson et al. (2009) developed a Canada-wide 10 km gridded dataset for daily precipitation and temperature for the period 1961–2003. These data are used in the downscaling and calibration procedures (Sect. 2.5). The preceding datasets are referred to as monthly ANUSPLIN (1901–2005) and daily ANUSPLIN (1961–2003), respectively.

2.4 Pre-instrumental record

Areally-averaged summer PDSI and SPI are reconstructed for the Prairie study area using a network of tree-rings from sites in south-western Alberta (Fig. 1). The tree-ring cores, gathered by the University of Regina Tree-Ring Laboratory, comprise of moisture-sensitive chronologies located in dry sites (south-and west-facing slopes, sandy soils, and ridge crests). Each core is detrended with the program ARSTAN and then standardized using a 100-year cubic spline (50 % cutoff) to maintain low frequency variability and to remove the age-related growth and other long-term variability not associated with climate (see Cook 1985). The overall site chronology is obtained by averaging all standardized cores for the site in question. Chronologies were maintained if the Subsample Signal Strength (SSS) (a function of inter-tree correlation and sample size; Briffa and Jones 1990) was $\geq$0.85 (Cook and Kairiukstis 1990).

The PDSI and SPI reconstruction firstly incorporates a Principal Component Analysis (PCA) procedure, similar to St. George et al. (2009) for their Canadian Prairie paleoclimate analysis. The PCA is carried out on the 23 site chronologies that are significantly correlated ($p < 0.05$) with areally-averaged summer PDSI and SPI over the period 1901–2005; with the first Principle Component (PC1) explaining 41 % of the variance. A reduced network is then determined by individually excluding the shortest

Table 2 Calibration and verification statistics for the tree-ring reconstructions of summer PDSI and SPI over the periods 1901–1960 and 1961–2005

	Summer PDSI		Summer SPI	
	Calibration/verification	Calibration/verification	Calibration/verification	Calibration/verification
Period	1901–1960/1961–2005	1961–2005/1901–1960	1901–1960/1961–2005	1961–2005/1901–1960
R_a^2	31.8 %	24.8 %	35.0 %	19.2 %
RE	0.34	0.18	0.21	0.06
Sign test (±)	32/12	47/13	24/20*	44/16

* Signifies values not significant at the 0.05 significance level

Table 3 AOGCM runs used in this investigation

AOGCMs	Available emission scenarios	References
Canadian Global Climate Model (CGCM2)	A2	Flato and Boer (2001)
Canadian Global Climate Model (CGCM3)	A2, A1B	Kim et al. (2002, 2003)
Hadley Centre (HadCM3)	A2, B2	Gordon et al. (2000), Pope et al. (2000)

Table 4 Skill scores between ASD downscaled and daily ANUSPLIN summer temperature and precipitation over the Prairie study area for the calibration (1961–1982) and validation (1983–2003) periods

	Calibration 1961–1982		Validation 1983–2003	
	Precipitation	Temperature	Precipitation	Temperature
r	0.58	0.94	0.60	0.95
MAE	19.2 mm/month	0.36 °C	20 mm/month	0.41 °C
RMSE	24.4 mm/month	0.45 °C	25.8 mm/month	0.5 °C
RRMSE	0.82 STD	0.34 STD	0.84 STD	0.33 STD

Skill scores include Pearson correlation coefficient (r), Mean Absolute Error (MAE), Root Mean Square Error (RMSE) and Relative RMSE (RRMSE). STD corresponds to standard deviation

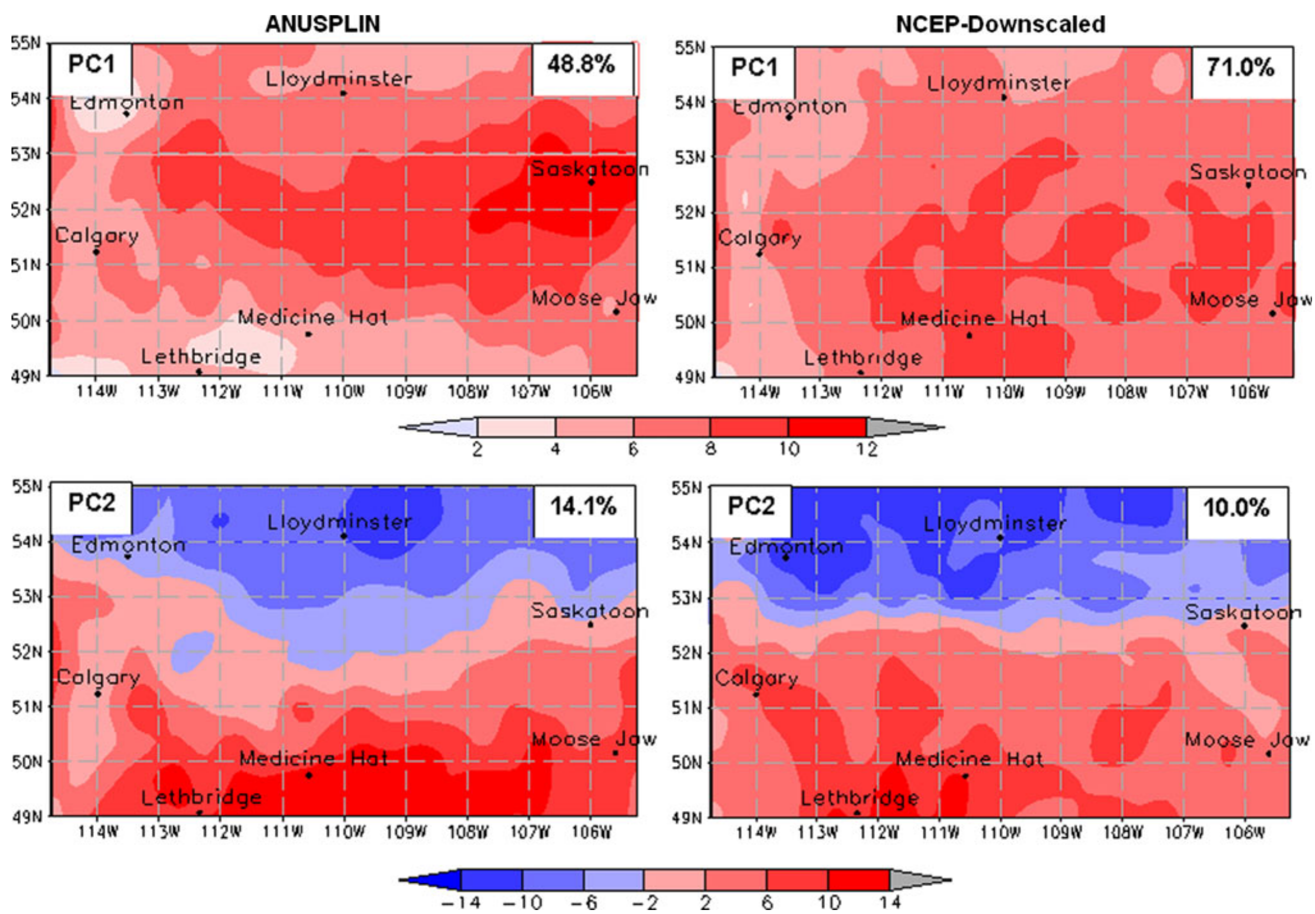

Fig. 2 First two PCs of summer PDSI derived from daily ANUSPLIN (*left panels*) and NCEP/NCAR-downscaled values (*right panels*) over the period 1961–2003. The % variance explained by each PC is also provided. Values refer to the relative amplitude of each pattern and are non-dimensional

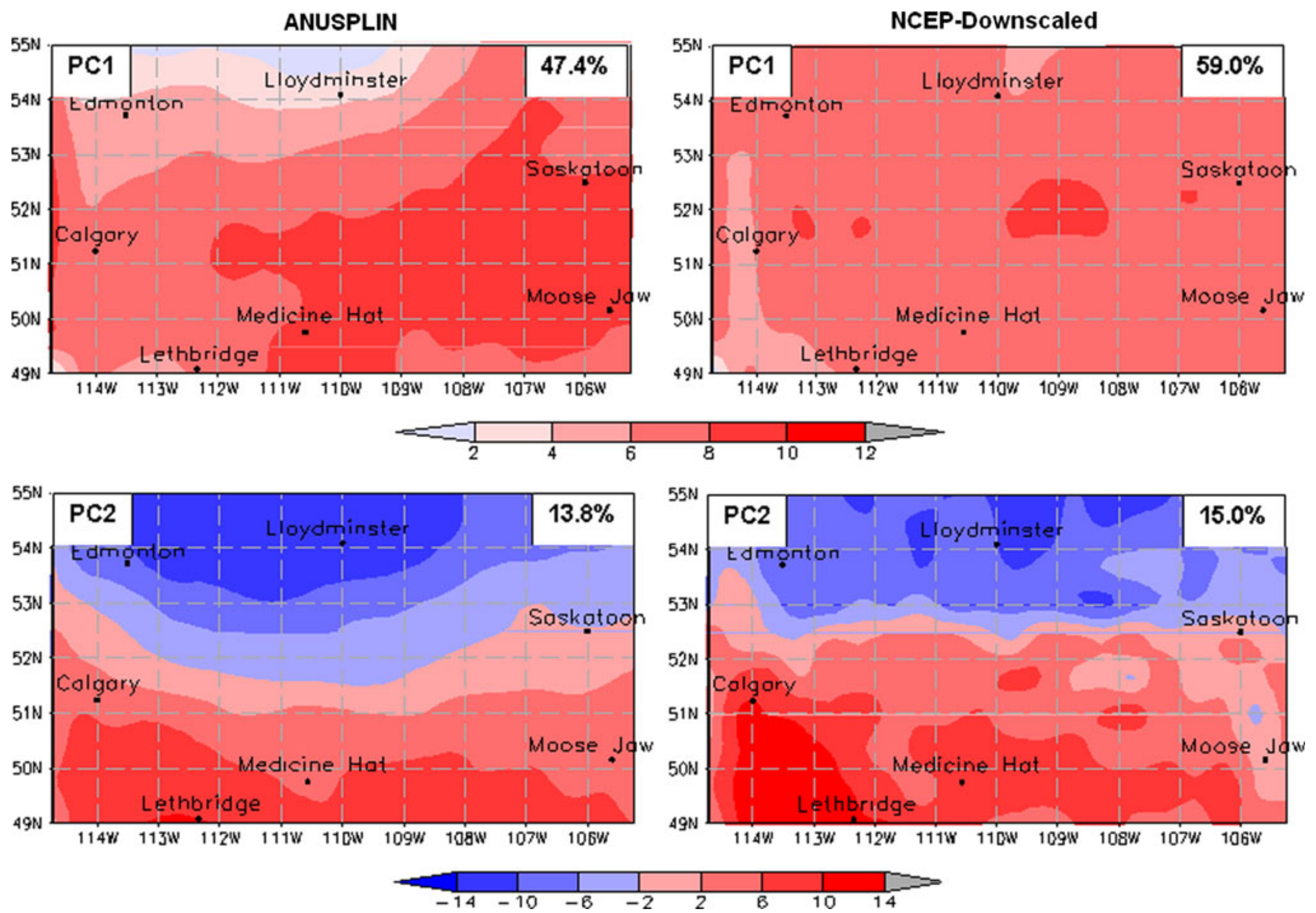

Fig. 3 Same as Fig. 2 but for summer SPI

chronologies and carrying out another PCA. The process continued until the correlation between the newly calculated PC1 and the original PC1 (from all 23 sites) dropped below 0.90. This results in a record extension back to 1365 using two site chronologies (Fig. 1), with PC1 explaining 74 % of the variance (known as the standard chronology time series). This standard series is pre-whitened in MATLAB® (Meko 2011) to obtain a residual chronology series. Summer PDSI and SPI are then reconstructed (through linear regression models) using the standard and residual chronologies, respectively.

To ensure stability of the linear regression models, calibration and verification statistics are performed on two intervals within the observational period (1901–1960 and 1961–2005). Each interval is used to build a model, and then verified over the other period. Statistics include explained variance (adjusted) (R_a^2), the reduction of error (RE) statistic, that measures common variance between actual and estimated series with positive values being indicative of a transfer model with predictive skill, and the sign test, which tabulates the direction of change in ring widths and climate from 1 year to the next as either an increase or a decrease (Cook and Kairiukstis 1990). Table 2 shows that for the most part, the models perform well over both periods. The PDSI reconstruction is more robust than SPI with the early model explaining 31.8 and 35.0 % and the latter model 24.8 and 19.2 % of the summer PDSI and SPI total variance, respectively. All RE values are positive (higher for PDSI), and with the exception of the 1961–2005 summer SPI, all sign test values are significant at the 0.05 level. The better PDSI results may be reflective of tree growth being influenced by winter/spring moisture (that is captured by the PDSI since it contains a memory of previous conditions), while the SPI specifically represents summer precipitation. To maximize the instrumental record variability, the regression model is then calibrated using the full 1901–2005 period and cross validated with the "leave-1-out" approach. The final PDSI reconstruction explains 32 % ($r = 0.57$) and the SPI 25 % ($r = 0.50$) of the total variance (see Sect. 3.2; Fig. 6).

2.5 Future projections

Changes to the temporal and spatial characteristics of future (2011–2100) PDSI and SPI are assessed using statistically downscaled daily temperature and precipitation

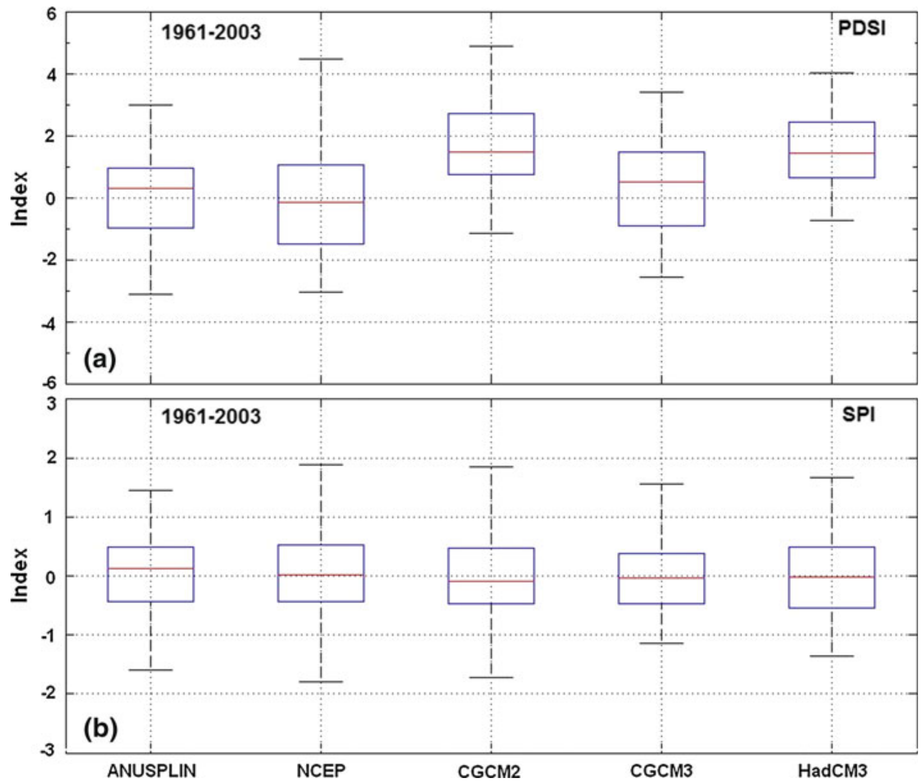

Fig. 4 Box and whisker plots of areally-averaged summer **a** PDSI and **b** SPI values over the Canadian Prairie study area using daily ANUSPLIN, and downscaled values from NCEP/NCAR, CGCM2, CGCM3, and HadCM3 predictors for the period 1961–2003. Median values are represented by *red lines* with the bottom and top of *each box* signifying the inter-quartile range. *Whiskers* indicate the minimum and maximum data values

over the Prairie study area from three AOGCMs with different emission scenarios (Nakicenovic et al. 2000) for a total of five scenarios (Table 3). Most analyses focus on average changes over the 2020s (2011–2040), 2050s (2041–2070), and 2080s (2071–2100). The downscaling is carried out via the Automated Statistical Downscaling method (ASD; Hessami et al. 2008) using predictors from the AOGCM simulations (for current baseline and future climates) and the National Centres for Environmental Prediction/National Centre for Atmospheric Research (NCEP/NCAR; Kistler et al. 2001) reanalyses (for calibration and validation). The most common predictors for precipitation and temperature downscaling are geopotential height, meridional wind components, 1,000, 850, and 500-hPa wind speed and direction, 500-hPa vorticity and divergence, and 850-hPa specific humidity. These variables represent both dynamic and thermodynamic processes, and have been regularly used in the statistical downscaling of precipitation and temperature over regions of northern and eastern Canada (e.g. Gachon and Dibike 2007; Jeong et al. 2012).

To calibrate and validate the ASD procedure, downscaled daily precipitation and mean temperature (using NCEP/NCAR predictors) are compared to the daily ANUSPLIN values from 1961 to 2003. The period 1961–1982 is used for calibration, and the remaining years (1983–2003) for validation (Table 4). Each skill score is based on areally-averaged summer values over the study area that are generated from 200 downscaling simulations for each climate variable. Table 4 shows r values of 0.58 (0.60) and 0.94 (0.95) for downscaled precipitation and temperature, respectively, over the calibration (validation) period. This confirms the more stochastic nature of precipitation and thus, a greater skill in downscaling temperature. Nonetheless, the correlations for both variables are high and more importantly, almost identical between calibration and validation. Other skill scores show similar findings between the two periods. Note that a spatial assessment of observed versus downscaled temperature and precipitation over the study region reveals a homogeneous and strong correlation ($r > 0.9$) for temperature. Precipitation has a west to east gradient in r values ranging from near 0.7 in the west to 0.4 in the east (not shown).

The ability of the ASD procedure to reproduce the observed spatial characteristics of PDSI and SPI over the Prairie region (at the aforementioned 50 km grid) is assessed by conducting a PCA on these indices derived from both the daily ANUSPLIN and NCEP/NCAR-downscaled values over the period 1961–2003. Figures 2 and 3 show the first two PCs for PDSI and SPI, respectively. Although local differences are apparent, the overall patterns of variability for both indices and PCs are remarkably well reproduced across the study area. The correlation between the associated time series of these PCs is also significant; 0.65 (PDSI) and 0.71 (SPI) for PC1; 0.41 (PDSI) and 0.62 (SPI) for PC2. The preceding confirms the

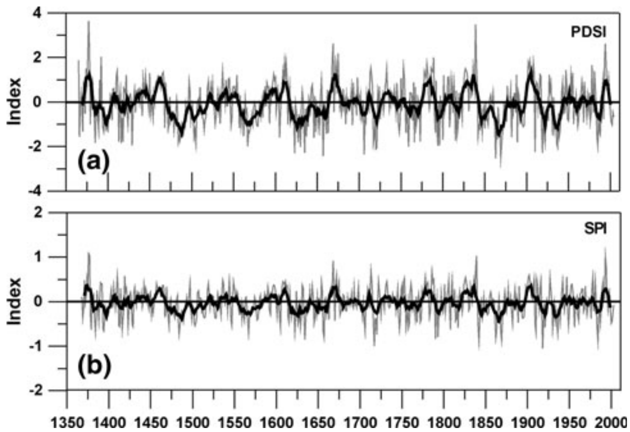

Fig. 5 Reconstructed areally-averaged summer **a** PDSI and **b** SPI values over the Canadian Prairie study area for the period 1365–2005. The *thick black lines* represent the 9-year running means

ASD's ability to reproduce the observed temporal and spatial variability in drought indices across the region.

An assessment of downscaled drought indices using the AOGCMs in Table 3 is also carried out (1961–2003). Figure 4a, b show box and whisker plots of areally-averaged summer PDSI and SPI derived from the three AOGCMs compared to those from the NCEP/NCAR predictors and daily ANUSPLIN. For SPI, all downscaling results reproduce the daily ANUSPLIN values quite well, with only a slight underestimation in the observed variability using CGCM3 predictors. PDSI has more differences, with an overestimation of positive indices for CGCM2 and HadCM3, while CGCM3 has the closest correspondence to the observed values.

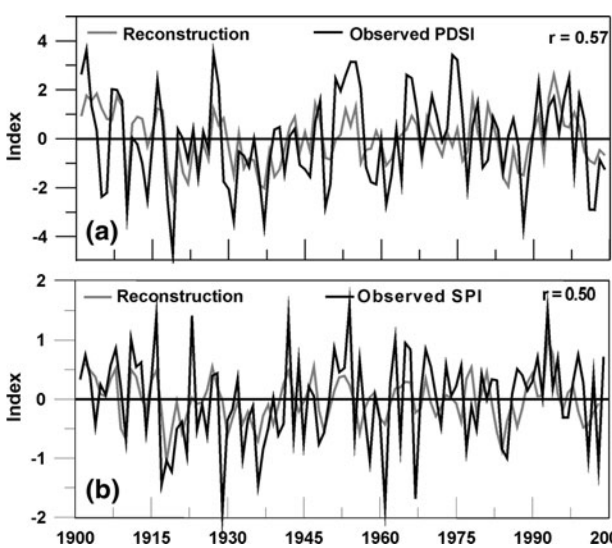

Fig. 6 Observed areally-averaged summer **a** PDSI and **b** SPI values over the Canadian Prairie study area for the period 1901–2005 (based on monthly ANUSPLIN). Reconstructed values are provided for comparison

3 Results

3.1 Drought reconstructions

Figure 5a, b provide tree-ring reconstructed summer PDSI and SPI over the Prairie region from 1365 to 2005. The indices display considerable inter-annual variability and prolonged decadal-scale drought and pluvial periods, with the PDSI reconstruction tending to capture a broader range of year-to-year variability. This likely reinforces the importance of temperature and antecedent moisture conditions in tree growth (that are captured in the PDSI). Both reconstructed series reveal significant drought events during the late 1300s, 1480–1500, 1550–1575, 1620–1655, the 1720s, and mid to late 1800s. It is also noteworthy that for the most part, these pre-instrumental droughts have been longer in duration and intensity than those during the 1930s or the severe early twenty-first century event. Additional analyses on pre-instrumental drought are provided in Sect. 3.4.

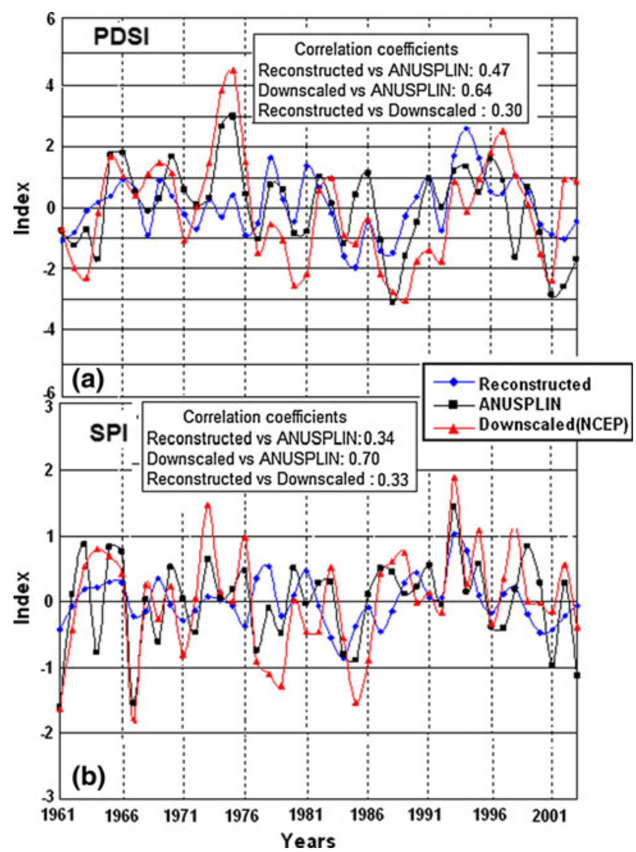

Fig. 7 Areally-averaged summer **a** PDSI and **b** SPI values over the Canadian Prairie study area for the period 1961–2003 based on tree-ring reconstructions, observed daily ANUSPLIN, and downscaled NCEP/NCAR predictors. Pearson correlations between the various series are provided with all values significant at the 0.05 significance level

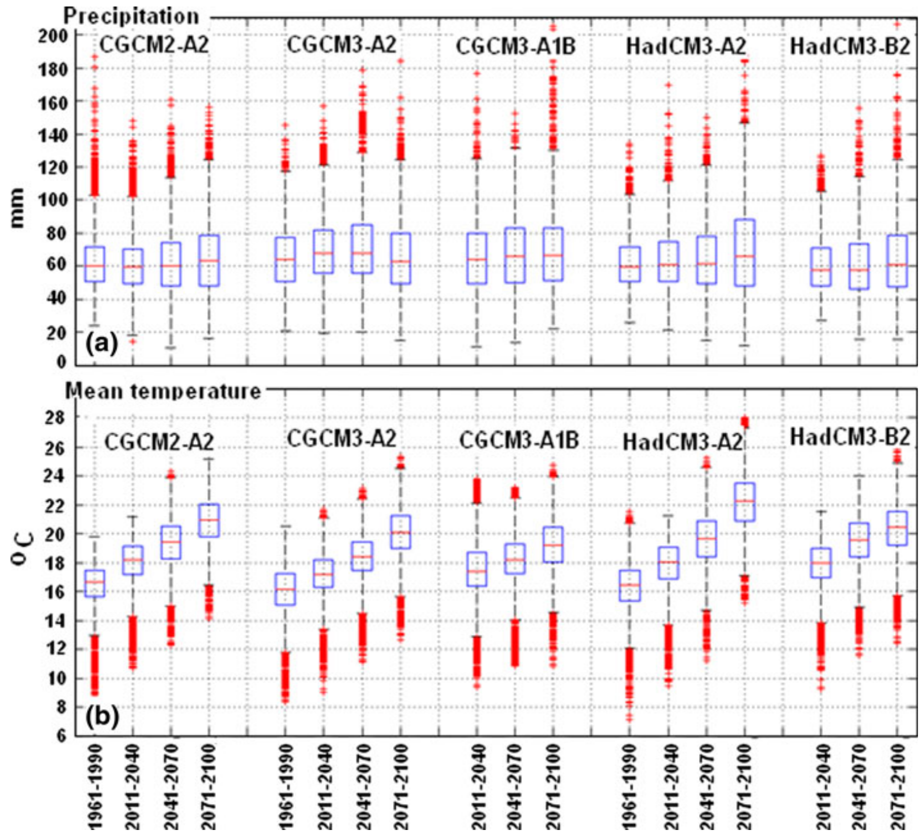

Fig. 8 Box and whisker plots of areally-averaged summer **a** precipitation and **b** mean temperature downscaled from the AOGCM runs in Table 3. Values for the baseline period (1961–1990) and three future time slices (2011–2040, 2041–2070, and 2071–2100) are provided. Median values are represented by *red lines* with the bottom and top of each *box* signifying the inter-quartile range (IQR). *Whiskers* indicate the 1.5 IQR data values and outliers are given by *red crosses*

3.2 Instrumental period

3.2.1 1901–2005

Observed summer PDSI and SPI (from monthly ANUSPLIN) for the period 1901–2005 are given in Fig. 6a, b. Corresponding values reconstructed from tree rings are provided for comparison. Both the PDSI and SPI observed series reflect major Prairie drought-like conditions that have been identified by several previous studies (e.g. Bonsal et al. 2011a, b) including 1918–1925, most of the 1930s, 1958–1962, 1983–1989, and 2000–2004. The tree-rings also identify these droughts and furthermore, they capture much of the observed inter-annual variability as evidenced by the significant r-values of 0.57 and 0.50 for PDSI and SPI, respectively. However, the reconstructed variability is lower; a result that is not unusual since climate reconstructions based on tree-ring data rarely capture more than 60 % of the variance observed in instrumental records (e.g. Sauchyn and Beaudoin 1998; Hughes 2002; Watson and Luckman 2005).

3.2.2 1961–2003

Comparisons of the individual drought indices are also examined from 1961 to 2003 when values for reconstructed, observed, and downscaled (using NCEP/NCAR predictors) are all available (Fig. 7a, b). Pearson correlation coefficients among the indices are also provided. The downscaled values reproduce the inter-annual variability of observed PDSI and SPI quite well as evidenced by the significant with r-values of 0.64 (PDSI) and 0.70 (SPI). Relationships between the tree-ring values and both the observed and downscaled values are weaker (0.47 and 0.30 for PDSI; 0.34 and 0.33 for SPI), and as alluded to previously, the reconstructed series have lower inter-annual variability. Nonetheless, in all cases, the tree-ring and downscaled series capture the persistent drought episodes of the 1980s and early 2000s and the major pluvial periods during the early 1970s and early 1990s. This suggests that the proxy and downscaled methods used to quantify droughts and particularly, extended dry periods are adequate for assessing and comparing drought variability in this region over the three identified periods.

3.3 Projected future drought occurrence

3.3.1 Temporal changes

Initially, AOGCM projected changes to the input variables for drought index calculation (i.e. precipitation and mean temperature) are examined for the three future time slices (Fig. 8a, b). With respect to the baseline 1961-1990 period, the projected changes to summer precipitation from the five

AOGCM runs are relatively small, with a slight increase in median values toward the end of the century (with the exception of the 2080s from CGCM3-A2). There does, however, appear to be a more systematic increase in precipitation variability over time (as measured by both the Inter-Quartile Range (IQR) and high precipitation extremes), especially during the last three decades of the twenty-first century. Note that differences among the various emission scenarios are small, with greater variations occurring between different AOGCMs with the same scenario (e.g. CGCM2/CGCM3 and HadCM3-A2 runs). For temperature, progressive warming is projected by all runs with the highest increases associated with the A2 scenario. The range of warming varies between 1.0 and 1.5 °C for the 2020s, 2.1 and 3.2 °C for the 2050s, and 4.0 and 5.6 °C for the 2080s (with HadCM3-A2 having the highest increases). Most runs do not project any appreciable changes to summer temperature variability, except for HadCM3-A2, which shows a slight increase in IQR values during the 2080s.

The impact of these temperature and precipitation changes on future summer PDSI is given in Fig. 9a, which shows 2011–2100 time series of the ensemble mean values from the five downscaled AOGCM runs. The minimum and maximum AOGCM projections (for each individual summer in shaded grey) are also shown while observed PDSI from 1901 to 2005 is provided for context. The future mean value indicates the prevalence of more persistent negative PDSI particularly, following 2040 (with few positive values after this date), thus suggesting a permanent regime shift to a more arid climate. This clearly reflects the summer temperature increases in Fig. 8b, but due to the lag inherent in PDSI, is also likely impacted by projected future increases in winter/spring temperatures. Although there is considerable variability among the five future projections, a downward trend in PDSI is apparent. The ensemble mean future SPI series in Fig. 9b does not exhibit a dramatic change from twentieth century observations and no discernible trend towards negative values over the 2011–2100 period is evident. This finding is consistent with the summer precipitation projections from Fig. 8a.

3.3.2 Spatial changes

Insight into the areal extent of projected changes to PDSI and SPI are provided in Fig. 10a, b that show time series of the percentage of the study area encompassed by severe drought or worse (PDSI ≤ -3 and SPI ≤ -1.5, see Table 1) for both the instrumental (from monthly ANUSPLIN) and future (mean of the five AOGCM runs) periods. Dramatic

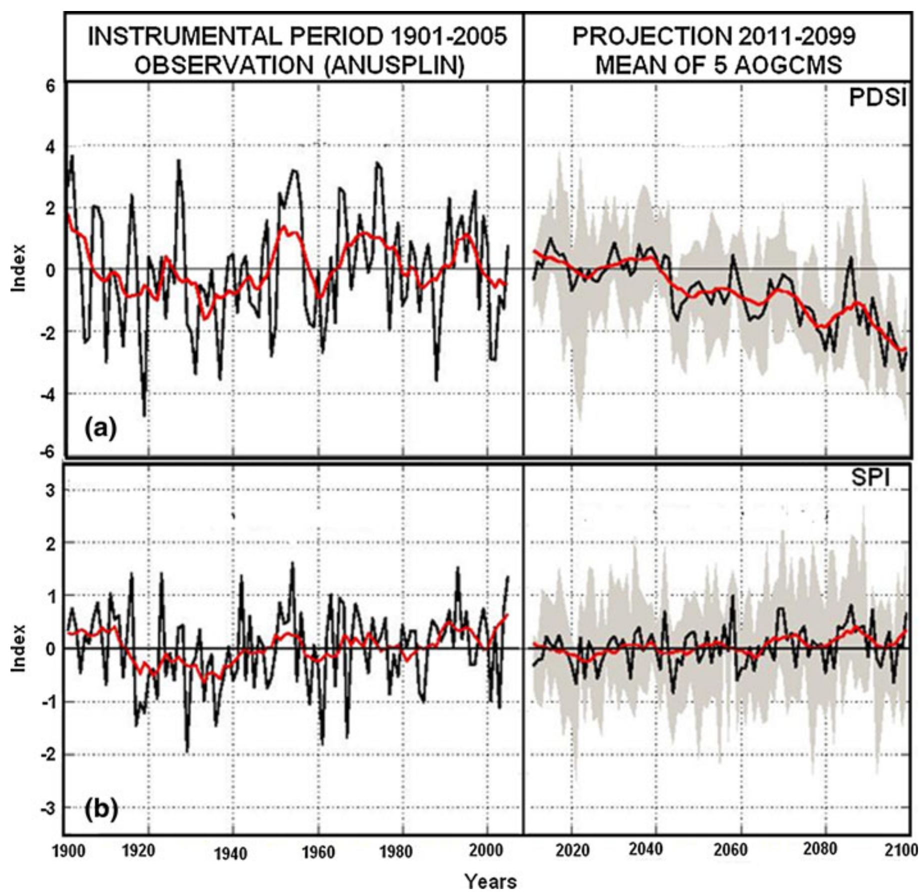

Fig. 9 Areally-averaged summer **a** PDSI and **b** SPI for both the 1901–2005 instrumental period (based on monthly ANUSPLIN) and the future 2011–2099 period (downscaled from the AOGCM runs in Table 3). For the future projection, the *black line* corresponds to the ensemble mean values from the five AOGCM runs while the *red lines* represent the 9-year running mean values. The minimum and maximum AOGCM projections (for each individual summer) are denoted in grey

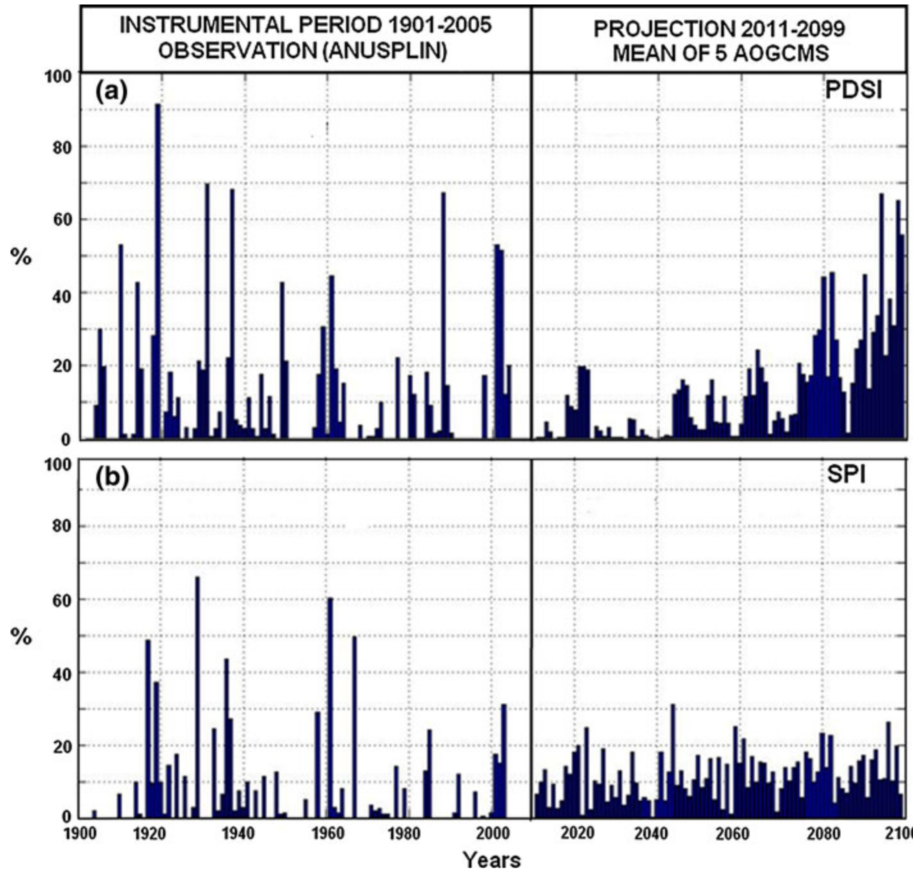

Fig. 10 Percentage of grid points over the Canadian Prairie study area encompassed by severe drought conditions or worse for **a** PDSI (≤−3) and **b** SPI (≤−1.5) during the 1901–2005 instrumental period (based on monthly ANUSPLIN) and the future 2011–2099 period (mean values of the five AOGCM runs)

changes are observed for PDSI, with a substantial increase in the frequency and areal extent of severe drought during the latter half of the twenty-first century. In fact, these later decades are consistently associated with severe drought encompassing a significant portion of the study area during every summer. The SPI (Fig. 10b), does not show a dramatic upward trend in the future, however, most twenty-first century summers are associated with severe drought conditions (for both occurrence and persistence over consecutive years) in some portion of the study area. This differs from the observational record where several years had 0 % of the study area in severe drought. Both Fig. 10a, b therefore suggest that severe droughts will be a more permanent feature in certain areas of the southwestern Prairies in terms of occurrence, duration/persistence and/or severity.

Figures 11 and 12 provide spatial changes to PDSI and SPI for the 2080s (relative to 1961–1990) for individual AOGCM runs over the Prairie study area. Consistent with Figs. 9 and 10, all PDSI projections reveal drier conditions over the entire study region. With the exception of CGCM3-A2, the most pronounced changes are found in southern and eastern areas, with values considerably lower than the 1961–1990 baseline period (−2 to −4). The SPI in Fig. 12 displays both negative and positive differences throughout the study area. All projections indicate wetter conditions in the northern Prairie region (52–54°N) with a gradual change to negative SPI values in central and southern portions. The driest area is projected to occur in the vicinity of Medicine Hat (except for CGCM3-A1B), which likely corresponds to the consistent region of latter twenty-first century drought indicated in Fig. 10b. Drier conditions are also evident in the east, but the pattern is not consistent for all AOGCM runs. As indicated previously, the strongest anomalies tend to be associated with the A2 scenario.

3.4 Entire series (1365–2100)

The preceding has outlined summer drought occurrence over the southwestern Canadian Prairies during pre-instrumental, instrumental, and projected future periods. Box and whisker plot inter-comparisons in drought variability among all three time frames are shown in Fig. 13a, b. Specifically, these include the 535 year pre-instrumental, the 105 year instrumental, and the three 30 year future time slices for each AOGCM run. As noted previously, the range of variability captured by the reconstruction for PDSI and SPI is lower than the instrumental record. Regarding future PDSI, there is a consistent decrease that translates

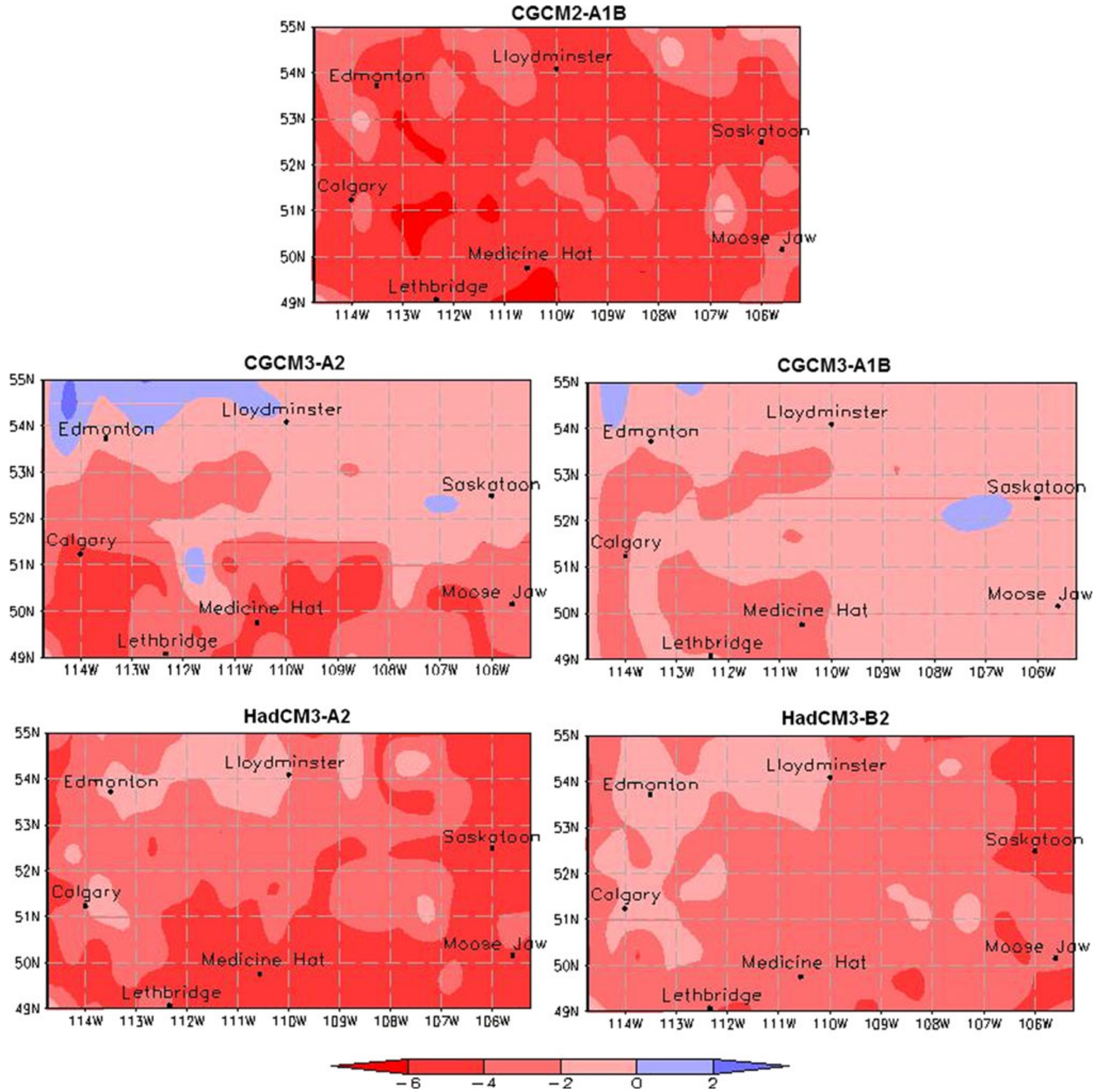

Fig. 11 Spatial changes in 2080s summer PDSI over the Canadian Prairie study area for each AOGCM run in Table 3. Values correspond to average differences between the 2071–2100 and 1961–1990 periods

into a higher probability of drought occurrence from all AOGCM runs, with little change in terms of variability. The CGCM2 and HadCM3 suggest a more rapid and intense decrease in PDSI with the time regardless of the emission scenario. For the SPI, changes in variability are more clearly evident, but there are considerable differences among the future time slices, and the various model runs. This is consistent with Fig. 8a where the analysis of precipitation changes indicated no consistency during future time slices or among model runs.

Given the reduced inter-annual variability inherent in drought index reconstructions, it is difficult to directly compare the full range of extremes in the pre-instrumental record to those for the instrumental and future periods. However, since the tree-rings were collected from moisture sensitive locations, drought index values below zero can be used to infer the duration and frequency of drought events. Table 5 shows drought duration characteristics associated with pre-instrumental, instrumental, and future periods over the study area. For this analysis, drought conditions

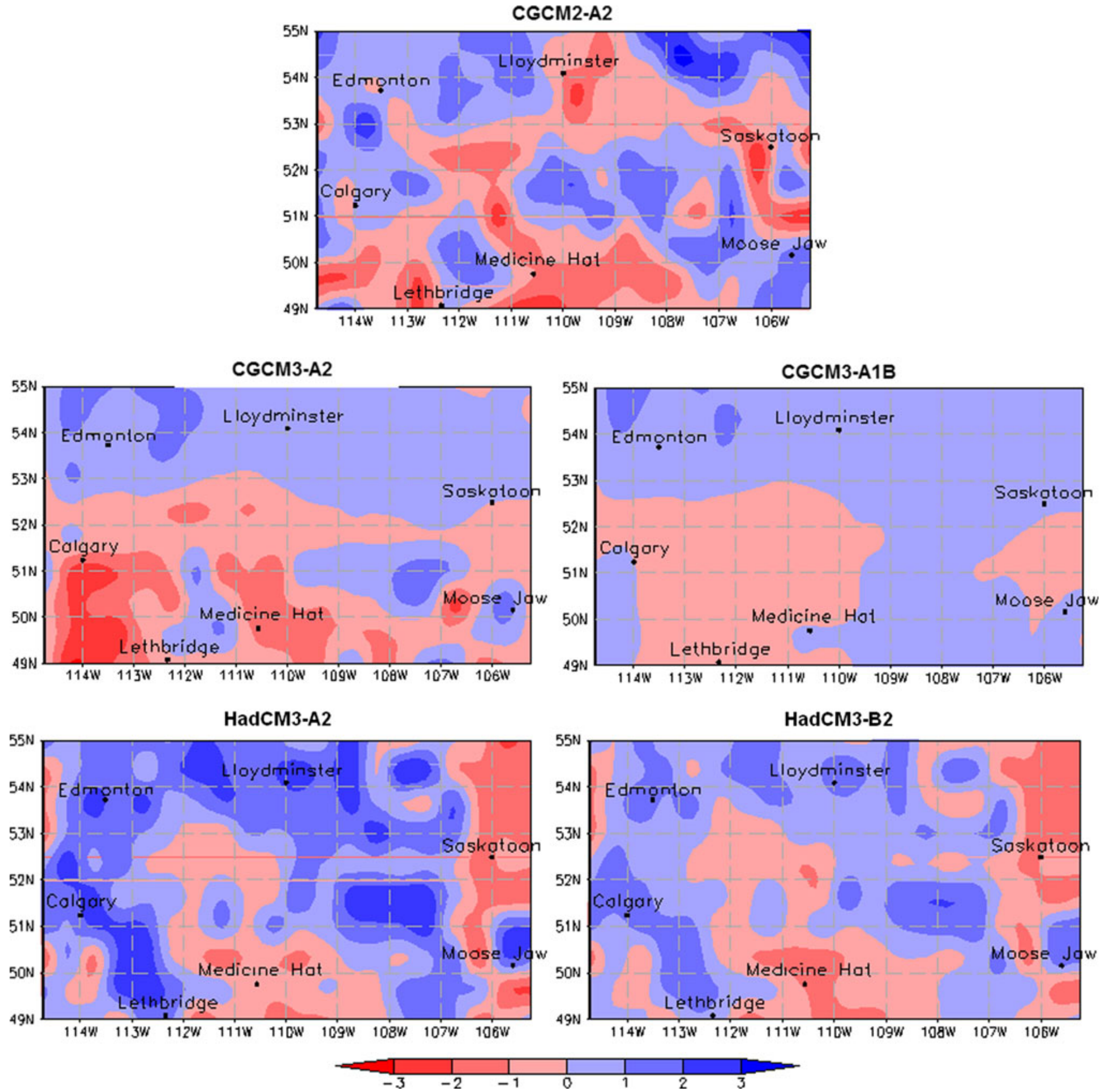

Fig. 12 Same as Fig. 11 but for summer SPI

are defined as periods when the PDSI and SPI are negative. In terms of mean drought duration, PDSI and SPI values indicate that droughts were on average, longer during the pre-instrumental period as compared to the twentieth century (more so for SPI). Future PDSI, however, reveals considerably longer droughts of over three times that experienced in the instrumental record (8.4 vs. 2.4). Consistent with earlier findings, drought durations based solely on precipitation (as measured by the SPI), show much different results with these durations slightly decreasing in the future. This reflects the slight increases in mean AOGCM precipitation projections, however, as shown in Figs. 9b, 12 and 13b, there is considerable variability in future SPI among the various runs. It is interesting to note that SPI droughts were on average, longer during the pre-instrumental record suggesting drier conditions prior to 1900. An examination of multi-year droughts (≥3, 5, and 10 consecutive years) in Table 5 shows similar findings in that these extended dry periods tended to be more frequent during the pre-instrumental and projected future (for PDSI) periods as compared to the instrumental record. For example, PDSI droughts of ≥5 years occurred

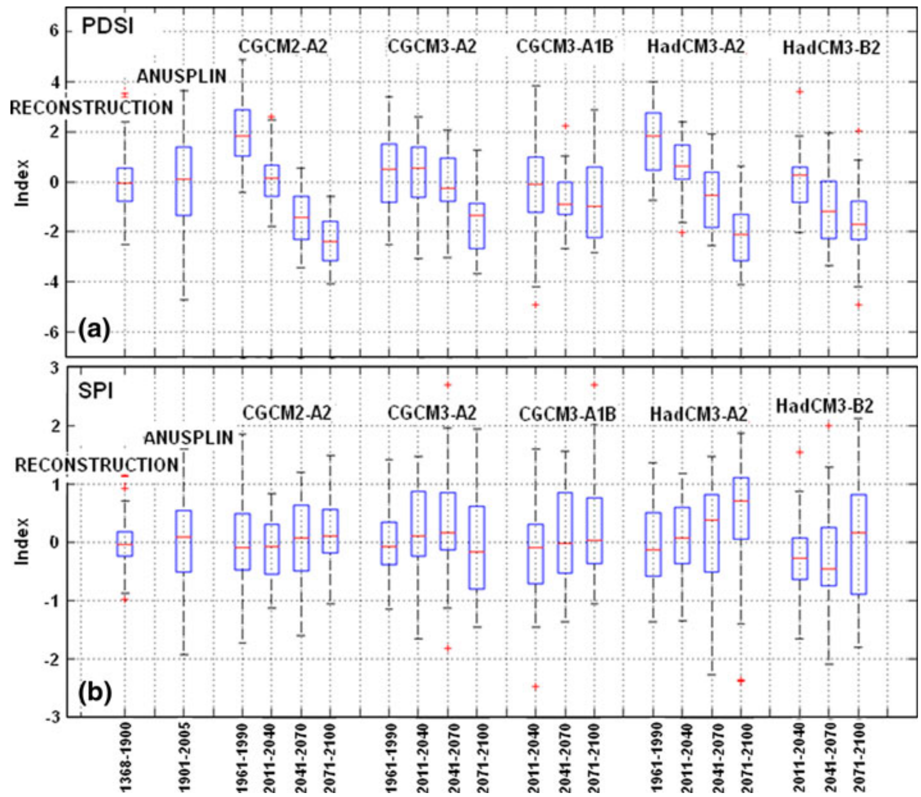

Fig. 13 Box and whisker plots of areally-averaged summer **a** PDSI and **b** SPI values over the Canadian Prairie study area for the period 1365–2100. Plots are provided for indices based on tree-ring reconstructions from 1365 to 1900, monthly ANUSPLIN data from 1901 to 2005, and each of the five AOGCM runs (see Table 3) for the current period (1961–1990), as well as, the three future time slices (2011–2040, 2041–2070, and 2071–2100). Median values are represented by *red lines* with the *bottom* and *top* of each *box* signifying the inter-quartile range (IQR). *Whiskers* indicate the 1.5 IQR data values and outliers are given by *red crosses*

Table 5 Areally-averaged drought duration characteristics associated with pre-instrumental, instrumental, and projected future periods (mean of the five scenarios) over the Canadian Prairie study area

Period	Data	Drought mean duration (seasons)		Frequency of multi-year droughts (per 100 yrs)					
		PDSI	SPI	≥3 years		≥5 years		≥10 years	
				PDSI	SPI	PDSI	SPI	PDSI	SPI
Pre-instrumental 1365–1900	Reconstruction	2.8	3.2	5.6	7.3	3.0	3.2	1.1	0.2
Instrumental 1901–2005	Monthly ANUSPLIN	2.4	2.0	5.7	5.7	1.9	1.9	1.0	0.0
Future 2011–2100	Mean of five future AOGCM scenarios	8.4	1.8	4.2	5.3	4.2	0.0	3.1	0.0

The mean duration of drought corresponds to the average number of consecutive summers with a negative value of PDSI/SPI. The frequency of multi-year droughts is defined as the average number of drought events (consecutive summers with negative PDSI/SPI) per 100 years of ≥3 years, ≥5 years, and ≥10 years duration

3.0 times/100 years from 1365 to 1900, only 1.9/100 years in the instrumental, and are projected to increase to 4.2/100 years in the future. The future PDSI 10+ year droughts are also much higher (3.1/100 years). This suggests that twentieth century extended drought conditions have been relatively mild when compared to pre-settlement on the Prairies, but these periods are likely to return (and be even worse) during this century.

4 Summary and conclusions

A unique aspect of this investigation is that it is one of the first to examine drought characteristics on time scales encompassing pre-instrumental, instrumental, and projected future periods together (i.e. from 1365 to 2100). Given the nature of the data, more focus is given to future drought projections, however, important insight into the frequency of pre-instrumental dry periods is also revealed. Overall, results suggest that the 105-year instrumental record experienced fewer extended droughts than the pre-instrumental period of 1365–1900 (Table 5). This is consistent with other studies that examined paleo-drought on the Prairies (e.g. Sauchyn and Skinner 2001; St. George et al. 2009). More importantly, projections based on the PDSI (i.e. incorporating future temperature changes) indicate that Canadian Prairie twenty-first century droughts will be longer and more frequent than those associated with the current twentieth century warming; a similar result to that of Gutzler and Robbins (2010) who determined that future droughts over the western US will be driven to a greater degree by temperature compared to those in the historical record.

Although not a main focus of the study, another important finding involves the prominent differences between the PDSI and SPI for future drought projections with the former indicating drastic increases and the latter little change (although substantial inter-AOGCM variability is present). It is interesting to note that for the most part, this inconsistency is not evident in the pre-instrumental and instrumental record with the PDSI and SPI revealing similar drought periods (Figs. 5, 6, 7). The differences in future drought are directly attributable to the water balance approach and inherent lag effects associated with the PDSI. Results from this index (Sects. 3.3 and 3.4) reveal very dramatic changes to both the temporal and spatial occurrence of summer droughts particularly, during the latter half of the twenty-first century. Furthermore, these dry conditions will occur over most of the study region, and will be of greater intensity and frequency to those observed during both the pre-instrumental and instrumental periods. Although little overall change is projected for SPI, some interesting spatial aspects regarding future summer precipitation on the Canadian Prairies have been identified. For example, Fig. 12 reveals that the south-central portion of the study area may become more susceptible to summer meteorological drought due to the projected reductions in precipitation.

The preceding therefore stresses the importance of considering the combination of potential effects from both precipitation and evaporation changes when assessing future Prairie drought (e.g. by using indices such as the PDSI or the recently proposed Standardized Precipitation Evapotranspiration Index (SPEI), which is mathematically similar to the SPI but includes the effects of temperature (Vicente-Serrano et al. 2010)). The use of SPI or other short-term memory indices that do not explicitly address temperature as an input component, appear to be more conservative for Canadian Prairie drought evaluation under climate change. This complies with Dai (2011) who suggested that total precipitation alone should not be used to measure future changes in aridity or drought, and with Trenberth (2011) who clearly demonstrated that increased heating in the future leads to greater evaporation and thus surface drying, thereby increasing the intensity and duration of drought (particularly, during summer over interior continental regions). By using the two different drought indices with and without the inclusion of temperature, this study also confirms that it is the combined effect of increasing temperature and small changes in precipitation that will likely increase both the occurrence and severity of summer droughts over the course of time.

In conclusion, this analysis can be considered an initial step toward quantifying and understanding Canadian Prairie drought occurrence and severity over several centuries as determined from paleo, instrumental, and climate model data sources. More robust and relevant drought evaluation has been gained from the centennial to decadal scale variability assessment, as well as, from the separation of effects between single climatic variables such as precipitation, and the combination of temperature and precipitation effects at the regional scale. Results indicate that observed twentieth century droughts were relatively mild when compared to pre-settlement on the Prairies, but these periods are likely to return (and even worsen) during this century due to the anticipated warming during the course of the twenty-first century. The strong potential for regular or persistent severe future droughts in certain areas of the Prairies highlights the need for future drought contingency plans in the region. The findings also indicate that recovery from multi-year droughts, such as those that have occurred intermittently during the past millennium and are likely to reoccur in some form in the current century, will be much more difficult in the warmer projected climate (Gutzler and Robbins 2010). Future work should include the development of future PDSI or SPEI scenarios using various regional scale downscaling techniques (i.e. dynamical with the use of regional climate model, or other statistical model) from an increased combination of AOGCMs to determine if convergence remains in drought statistics under climate change conditions. This convergence will improve the confidence in regional/local estimates of climate change impacts on future regional-scale droughts.

Acknowledgments The authors would like to acknowledge the Data Access Integration (DAI) Team (http://loki.qc.ec.gc.ca/DAI/), namely Milka Radojevic and Patrice Constanza, for providing data and technical support. Data for this study were made available through the DAI data download gateway, through collaboration between the Global Environmental and Climate Change Centre, the Adaptation and Impacts Research Section of Environment Canada, and the Drought Research Initiative. Financial support from Environment Canada is also gratefully acknowledged. We also acknowledge the Canadian Centre for Climate Modelling and Analysis group of Environment Canada for access to CGCM2/3 output.

References

Bonsal BR, Regier M (2006) The 2001 and 2002 Canadian drought: historical context and potential future occurrence, Environment 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. Clim Res 33:229–242

Bonsal BR, Wheaton EE, Chipanshi A, Lin C, Sauchyn DJ, Wen L (2011a) Drought research in Canada: a review. Atmos Ocean 49:303–319

Bonsal BR, Wheaton EE, Meinert A, Siemens E (2011b) Characterizing the surface dynamics of the 1999–2005 Canadian Prairie drought in relation to previous severe 20th century events. Atmos Ocean 49:320–338

Briffa K, Jones PD (1990) Basic chronology statistics and assessment. In: Cook ER, Kairiukstis LA (eds) Applications in the environmental science. Kluwer Academic Publishers, Dordrecht, pp 137–152

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

Cook ER (1985) A time series analysis approach to tree ring standardization. Dissertation, The University of Arizona, Tucson

Cook ER, Kairiukstis LA (Eds) (1990) Methods of dendrochronology: Applications in the environmental sciences, Kluwer Academic Publishers, Dordrecht 98-105

Dai A (2011) Drought under global warming: a review. Wiley Interdisc Rev Climate 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

Dey B (1982) Nature and possible causes of droughts on the Canadian Prairies—case studies. J Climatol 2:233–249

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

Gachon P, Dibike Y (2007) Temperature change signals in northern Canada: convergence of statistical downscaling results using two driving GCMs. Int J Climatol 27:1623–1641

St. George S, Meko DM, Girardin MP, Macdonald GM, Nielsen E, Pederson GT, Sauchyn DJ, Tardif JC, Watson E (2009) The tree-ring record of drought on the Canadian Prairies. J Clim 22:689–710

Gordon CC, Cooper CA, Senior H, Banks JM, Gregory TC, Johns JF, Mitchell B, Wood RA (2000) The simulation of SST, sea ice extents and ocean heat transport in a version of the Hadley centre coupled model without flux adjustments. Clim Dyn 16:147–168

Guttman NB (1998) Comparing the palmer drought index and the standardized precipitation index. J Am Water Resour Assoc 34:113–121

Gutzler DS, Robbins TO (2010) Climate variability and projected change in the western United States: regional downscaling and drought statistics. Clim Dyn. Published online. doi:10.1007/s00382-010-0838-7

Hessami M, Gachon P, Ouarda T, St-Hilaire A (2008) Automated regression-based Statistical Downscaling Tool. Environ Modell Softw 23:813–834

Hughes MK (2002) Dendrochronology in climatology—the state of the art. Dendrochronologia 20:95–116

Hutchinson MF (2004) ANUSPLIN Version 4.3. Centre for Resource and Environmental Studies, Australian National University. http://cres.anu.edu.au/outputs/anusplin.php. Accessed 23 November 2005

Hutchinson M, Mckenney DW, Lawrence K, Pedlar JH (2009) Development and testing of Canada wide interpolated spatial models of daily minimum–maximum temperature and precipitation for 1961–2003. J Appl Meteorol Clim 48:725–741

Jeong DI, St-Hilaire A, Ouarda TBMJ, Gachon P (2012) CGCM3 predictors used for daily temperature and precipitation downscaling in southern Québec, Canada. Theor Appl Climatol 107:389–406. doi:10.1007/s00704-011-0490-0

Kim SJ, Flato GM, Boer GJ, McFarlane NA (2002) A coupled climate model simulation of the last glacial maximum, part 1: transient multi-decadal response. Clim Dyn 19:515–537

Kim SJ, Flato GM, Boer GJ (2003) A coupled climate model simulation of the last glacial maximum, part 2: approach to equilibrium. Clim Dyn 20:635–661

Kistler R, Kalnay E, Collins W, Saha S, White G, Woollen J, Chelliah M, Ebisuzaki W, Kanamitsu M, Kousky V, Van den Dool H, Jenne R, Fiorino M (2001) The NCEP-NCAR 50-year reanalysis. Bull Am Meteorol Soc 82:247–267

McKee TB, Doeskin NJ, Kleist J (1993) The relationship of drought frequency and duration to time scales. In: Proceedings of the 8th conference on applied climatology, 17–22 January 1993. Am Meteorol Soc, Boston, MA, pp 179–184

McKenney DW, Pedlar JH, Papadopol P, Hutchinson MF (2006) The development of 1901–2000 historical monthly climate models for Canada and the United States. Agric Forest Meteorol 138:69–81

Meehl GA, Stocker TF (2007) Global climate projections. In: Climate change 2007: the physical science basis, intergovernmental panel on climate change. Cambridge University Press, Cambridge, UK, pp 747–845

Meko D (2011) Geos 585A, applied time series analysis. GEOSa11.m. http://www.ltrr.arizona.edu/~dmeko/geos585a.html. Accessed 23 November 2005

Nakicenovic N, Alcamo J, Davis G, de Vries B, Fenhann J, Gaffin S, Gregory K, Grübler A, Jung TY, Kram T, La Rovere EL, Michaelis L, Mori S, Morita T, Pepper W, Pitcher H, Price L, Raihi K, Roehrl A, Rogner HH, Sankovski A, Schlesinger M, Shukla P, Smith S, Swart R, van Rooijen S, Victor N, Dadi Z (2000) IPCC special report on emissions scenarios. Cambridge University Press, Cambridge, UK

Palmer WC (1965) Meteorological drought. Res Paper No 45. Weather Bureau, Washington, DC

Pope VD, Gallani ML, Rowntree PR, Stratton RA (2000) The impact of new physical parameterizations in the Hadley Centre climate model—HadCM3. Clim Dyn 16:123–146

Quiring SM, Papakyriakou TN (2005) Characterizing the spatial and temporal variability of June–July moisture conditions in the Canadian Prairies. Int J Climatol 25:117–138

Sauchyn DJ, Beaudoin AB (1998) Recent environmental change in the southwestern Canadian Plains. Can Geog 42:337–353

Sauchyn DJ, Kulshreshtha S (2008) Prairies. In: Lemmen DS, Warren FJ, Lacroix J, Bush E (eds) From impacts to adaptation: Canada in a changing climate 2007. Government of Canada, Ottawa, ON, pp 275–328

Sauchyn DJ, Skinner WR (2001) A proxy record of drought severity for the southwestern Canadian plains. Can Water Resour J 26:253–272

Schär C, Lüthi D, Beyerle U (1999) The soil-precipitation feedback: a process study with a regional climate model. J Climate 12:722–741

Stewart RE, Pomeroy J, Lawford R (2011) The drought research initiative: a comprehensive examination of drought over the Canadian Prairies. Atmos Ocean. Published online. doi:10.1080/07055900.2011.622574

Sushama L, Khaliq N, 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) Changes in precipitation with climate change. Clim Res 47:123–138

Vicente-Serrano SM, Begueria S, Lopez-Moreno JI (2010) A multiscalar drought index sensitive to global warming: the standardized precipitation evapotranspiration index. J Clim 23:1696–1718

Watson E, Luckman BH (2005) Spatial patterns of preinstrumental moisture variability in the southern Canadian Cordillera. J Clim 18:2847–2863