Historical comparison of the 2001/2002 drought in the Canadian Prairies

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ABSTRACT: Over the west-central Canadian Prairies, precipitation was well below normal for a remarkable 8 consecutive seasons from September 2000 through August 2002. The precipitation deficits were associated with severe agricultural, hydrologic, and socio-economic impacts over much of the area. This study compares the spatial extent and severity of the 2001/2002 Canadian Prairie drought to previous droughts during the period of instrumental records. The Standardized Precipitation Index (SPI) and Palmer Drought Severity Index (PDSI) show that the worst and most prolonged Prairie-wide droughts during the period 1915–2002 occurred in the early part of the 20th century. Over the agricultural region of the Prairies, 2001 and 2002 generally ranked high in terms of spatial extent and severity of drought; at some stations the 2001/2002 drought was the most severe one on record. More importantly, it followed a prolonged lack of dry years, and this likely contributed to the severity of its impacts. Results from this study are an initial step toward the quantification and better understanding of both past and future drought occurrence over interior regions of North America.

KEY WORDS: Drought · Canadian Prairies · Standardized Precipitation Index · SPI · Palmer Drought Severity Index · PDSI · Climate change

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1. INTRODUCTION

Since most human activities, as well as ecosystem health, depend on an adequate supply of water, droughts pose a serious threat to society and the environment. Prolonged widespread drought has adverse effects on agriculture, industry, municipalities, recreation, and aquatic ecosystems, because it depletes soil moisture, reduces stream flow, and lowers lake, reservoir and groundwater levels. This affects numerous economic activities, e.g. by decreased agricultural production and hydroelectric power generation, and increased freshwater transportation costs. Drought also causes environmental damage such as reduced water quality, wetland loss, soil erosion and degradation, and habitat destruction. In light of the economic and environmental significance of drought, scientific concern has been expressed regarding impacts of climate change on future drought frequency, duration, and severity in various regions of the globe (Arnell et al. 2001).

Simply stated, drought is a prolonged period of abnormally dry weather that depletes water resources for human and environmental needs (AES 1986). However, each drought is different, depending on factors such as area affected, duration, intensity, antecedent conditions, and the region's capability to adapt to water shortage. In general, the definition of drought depends on the user and the geographical region in question. For example, a meteorological drought often occurs when there is significantly below-normal precipitation over an extended period, frequently intensified by anomalously high temperatures that increase evapotranspiration. The degree of moisture shortage and the length of time it takes for a meteorological drought to develop varies from region to region (Maybank et al. 1995). Meteorological drought often leads to other types of drought, including agricultural (periods during which soil moisture is insufficient to support crops), hydrologic (prolonged periods of unusually low surface run-off and shallow groundwater levels), and

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socio-economic drought (an unusual shortage of water that produces an adverse effect on society and the economy) (Maybank et al. 1995).

Most areas of Canada periodically experience drought, but the agricultural regions of the Canadian Prairies (see Fig. 1) are more drought-prone, mainly due to their location in the lee of the Rocky Mountains, and their economy is more vulnerable due to its dependence on agriculture. In any given year, there is usually some region within the Prairies that has a precipitation deficiency, but it is the large area (Prairie-wide) droughts that have the greatest impacts (O'Brien 1994). Using a variety of drought indicators at various temporal scales, several studies have identified multi-year large-area droughts over the Canadian Prairies during the instrumental record: in the 1890s, 1910s, 1930s, 1960s, and 1980s (e.g. Phillips 1990, Chipanshi et al. 2006); while the worst 20th century agricultural droughts were in 1936–1937, 1961, 1984–1985 and 1988 (O'Brien 1994). Nkemdirim & Weber (1999) used the Palmer Drought Severity Index (PDSI) to compare the southern Canadian Prairie droughts of the 1930s and the 1980s. They determined that although the area under mild drought was 16% larger in the 1930s as compared to the 1980s, the region impacted by extreme drought was larger in the 1980s. A paleoclimatic study by Sauchyn & Skinner (2001) used tree-ring chronologies to extend the drought record of the southwestern Canadian Plains back to 1597. They determined clusters of drought years occurring in the 1690s, 1720s, 1750s–1760s, 1790s–1800s, 1820s, and 1850s–1860s.

By several standards, 2001 and 2002 can be considered drought years over much of the Canadian Prairies, with consistently negative precipitation departures of 10% to 50% below normal over the entire region (Bonsal & Wheaton 2005). During 2001, dry conditions were most severe in Alberta and western Saskatchewan, and they extended farther eastward into Manitoba in 2002. Well below normal precipitation persisted for every season from autumn 2000 through summer 2002, beginning in autumn 1999 in west-central Alberta. The 2001/2002 drought did not experience extreme positive temperature anomalies over the Prairies, however, with values only averaging around 0.5 to 1.0°C above normal. Furthermore, the highest positive temperature anomalies were observed during autumn and winter, while spring and summer were associated with small positive or even negative values. In terms of atmospheric circulation, the 2001/2002 drought was related to a northward extension of persistent drought producing circulation anomalies that impacted the continental USA. This differed from patterns associated with previous severe, multi-season Prairie droughts (e.g. 1961 and 1988) in that the circu-

lation during 2001 and 2002 lacked the distinct meridional flow over the North Pacific and North America that has been associated with previous dry periods over western Canada (Bonsal & Wheaton 2005).

Wheaton et al. (2005) documented and evaluated the climatology, potential causes, impacts, and adaptation strategies associated with the 2001/2002 Canadian drought with an emphasis on agricultural and water sectors. They determined that the persistence of dry weather had severe impacts, including almost complete agricultural crop production losses, land and pasture degradation, reduced or non-existent stream flows, decreased hydroelectric production, and significant increases in forest fires. Although similarities to other major drought episodes over the Canadian Prairies were noted, large-area climatological comparisons to the 2001/2002 episode were not extensively addressed.

The main objective of this study is to compare the spatial extent and severity of the 2001/2002 Canadian Prairie drought to previous droughts during the period of instrumental record. The analysis was carried out on a Prairie-wide basis using 2 different drought indicators, namely the PDSI and the Standardized Precipitation Index (SPI) at several temporal scales. This study compares the recent drought to past episodes, and also provides insight into future drought probability in the Prairies, given the prospect of climate change. The data and methodology are described in Section 2, while Section 3 presents historical comparisons of the 2001/2002 drought with previous droughts. The paper concludes with a summary and discussion in Section 4.

2. DATA AND METHODOLOGY

2.1. Data

Monthly mean temperature and precipitation data for climate stations within and in proximity to the Canadian Prairies were taken from the Adjusted Historical Canadian Climate Data set (available at: www.cccma.bc.ec.gc.ca/hccd/). These stations contain variable record lengths with earliest series for a few locations extending back to the 1890s, and most stations having values through 2002. For temperature, homogeneity problems caused by station relocation and changes to instrumentation and observing practices have been addressed using a regression model technique (Vincent 1998, Vincent & Gullett 1999). Precipitation values were adjusted to account for gauge undercatch, wetting loss, and trace events (Mekis & Hogg 1999).

The historical analysis of Prairie droughts requires climate stations with long enough series to include

known droughts in the early 20th century, and sufficient density to provide adequate spatial coverage of the agricultural region of the Canadian Prairies. Taking these considerations into account, 21 stations for the agricultural years (September to August) of 1915 to 2002 were incorporated (Fig. 1). These locations were also chosen on the basis of relatively few missing values (<5% for precipitation, and <1% for temperature series). A study area approximating the agricultural growing region of the Canadian Prairies was identified, based on the 21-station network (shaded area in Fig. 1). Nearby stations outside the study area were chosen due to their close proximity to the identified study area and were used to facilitate the gridding procedure described in Section 2.3.

Drought analyses were initiated with data for 1915, based on station density and previously identified drought occurrences. A start period of 1900 or even 1910 provided too few stations to adequately represent the agricultural region. Although initiating the analysis in 1920 provided a few more locations than shown in

Fig. 1, this excluded severe droughts of the late 1910s (O'Brien 1994). Since it is desirable to have continuous PDSI and SPI monthly time series, missing temperature and precipitation values for the entire period were in-filled using the 1971–2000 climatological normals for the month in question. This method has been previously used to calculate drought indices over regions of Canada and should not significantly affect the analyses, due to the infrequency of missing values at the identified 21 stations.

2.2. Drought indices

Although no universally accepted definition for drought exists, numerous indices have been incorporated to quantify its severity. Meteorological approaches range from indices that only consider precipitation (e.g. SPI), to more complex methods that incorporate a water balance approach using precipitation, potential evapotranspiration, antecedent

Fig. 1. Locations and names of climate stations used; shaded: Canadian Prairie study area. BC: British Columbia (Stations 1–3); ON: Ontario (Station 21)

soil moisture, and runoff (e.g. PDSI). Agricultural drought indices relate to soil moisture availability and include for example, the Crop Moisture Index (Palmer 1968) and the Computed Soil Moisture Index. Hydrologic indicators such as the Surface Water Supply Index (Shafer & Dezman 1982) and the Palmer Hydrological Drought Index generally use groundwater levels, stream flow, snow pack, and soil moisture as input variables. However, long-term (i.e. 20th century) values of these hydrologic-related variables (including soil moisture) are not available over the entire Prairie study area, and as a result, this investigation uses the SPI and PDSI. Both measures have been used to assess drought conditions over various regions of North America and have the advantage of only requiring monthly temperature and precipitation as input variables.

The PDSI indicates the physical severity of drought and is useful for longer-term (i.e. seasonal to annual) agricultural and hydrologic applications. Developed by Palmer (1965), it was intended to measure the cumulative departure of moisture supply from a water balance viewpoint. It has been used over North America for both monitoring drought (e.g. the Climate Prediction Center, Agriculture and Agri-Food Canada) and for making operational water management decisions. The calculation requires monthly precipitation and temperature, and the station's latitude for estimating evapotranspiration. Initially, a hydrologic accounting (by months) is carried out for a long series of years. The results are then summarized to obtain coefficients that depend on the station's climate. In this study, the entire period 1915–2002 was used to derive these coefficients for each station. The data series were then reanalyzed (using the derived coefficients) to determine the amount of moisture required for normal climate during each month. PDSI values typically range between +4 and –4, negative values indicating a shortage of water (Guttman 1998, Keyantash & Dracup 2002). Classifications of drought based on the PDSI are given in Table 1. Note that the calculated monthly 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 SPI (McKee et al. 1993) is a meteorological drought index that interprets observed precipitation as a standardized departure with respect to a precipitation probability distribution function. Unlike PDSI, it can be computed over any duration. The first step is to determine a probability density function that describes the long-term (1915–2002) series of observations. McKee et al. (1993) suggested the 2-parameter gamma

Table 1. Moisture classifications based on the PDSI (Palmer 1965) and SPI (McKee et al. 1993)

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

density function, which is the same procedure incorporated in this analysis. Other functions, including Pearson Type III, have also been used (e.g. Guttman 1999). The cumulative probability of an observed precipitation amount (for the desired time period) is then computed based on the density function. The inverse normal (Gaussian) function is then applied to this probability resulting in an SPI value. The SPI is also a dimensionless value where negative values indicate drought (Guttman 1998, Heim 2002). Drought intensities based on various SPI classes are given in Table 1.

Some researchers have recently questioned the use of PDSI in studying drought, due to its complex structure, exceptionally long memory, and applicability across climatically diverse regions (e.g. Guttman 1998, Keyantash & Dracup 2002). They recommend the SPI as a superior drought indicator, since it is easy to interpret and can be applied universally to any location at several different temporal scales. The use of both the PDSI and SPI approaches in our study allows for a comparison of 2 commonly used drought indices in their ability to characterize the severity and spatial extent of the 2001/2002 drought and its relationship to past drought occurrences over the Prairies. In addition, since the PDSI incorporates temperature in its calculation, it may be more applicable to identifying droughts that have been influenced by anomalously high temperatures.

2.3. Methodology

Droughts occur on a variety of temporal scales ranging from shorter agricultural droughts lasting months to seasons, to hydrologic droughts of one to several years, to mega-droughts lasting several years to decades. For comparisons of the 2001/2002 Canadian Prairie drought, this investigation focused on summer

(June–July–August), 1 yr, and 2 yr durations. Since the 2001/2002 dry period was initiated as far back as 1998 in some regions of the Canadian Prairies (Wheaton et al. 2005), a 5 yr interval was also examined. The 1, 2, and 5 yr periods are based on the agricultural year defined as September through August. Therefore, 2002 refers to the period September 2001 to August 2002 and the 1915–2002 study period runs from September 1914 through August 2002. For PDSI, the derived monthly indices were averaged to obtain the summer, and 1, 2, and 5 yr values.

One objective of this study was to quantify the severity and spatial extent of historical drought over the entire Canadian Prairie. Since the stations in Fig. 1 are not uniformly distributed within this region, the derived PDSI and SPI values from individual stations were spatially interpolated to a 50×50 km grid using a cubic spline interpolation procedure resulting in 291 grids. The spatial extent of the 2001/2002 and other historical droughts were quantified by determining the area (percentage of grids) encompassed by the thresholds for severe drought ($\text{PDSI} \leq -3.0$; $\text{SPI} \leq -1.5$) and extreme drought ($\text{PDSI} \leq -4.0$; $\text{SPI} \leq -2.0$), on a summer, and 1, 2, and 5 yr basis. Average PDSI and SPI values for all grids were also calculated to quantify the severity of the drought. These parameters were then used to compare the 2001/2002 drought with other droughts in the study period and to determine its rank in terms of spatial extent and severity.

3. RESULTS

3.1. Drought in 2001/2002

Figs. 2 & 3 show SPI and PDSI values for various periods associated with the 2001/2002 drought. The 2 yr period of 2001/2002 (Fig. 2e) was associated with severe ($\text{SPI} \leq -1.5$) and extreme ($\text{SPI} \leq -2.0$) drought centered in the northern portions of the study region.

Fig. 2. Standardized Precipitation Index (SPI) for the 2001/2002 drought in the Canadian Prairies. Summer: June to August; years are agricultural year (September to August)

Fig. 3. Palmer Drought Severity Index (PDSI) for the same time periods as in Fig. 2

The extreme south and most of Manitoba had near normal values. In 2001, the drought was concentrated in the central regions of Alberta and Saskatchewan (Fig. 2c). There was a pronounced northward shift of dry conditions in 2002, while the southwestern Prairies had wetter than normal conditions, especially during summer (Fig. 2b). Daily precipitation values for the climate stations in this area (not shown) reveals that 2 major early summer events on June 8–11 and June 16–19, 2002, accounted for >90% of the entire summer's normal precipitation. For the most part, the rest of the summer was drier than normal in this area.

Although negative SPI occurred during the summers of 2001 and 2002 (Fig. 2a,b), the more extreme values for the 1 and 2 yr time intervals suggest persistent dry conditions for this entire period. This agrees with Bonsal & Wheaton (2005), who found that well below normal precipitation was recorded for 8 consecutive seasons from autumn 2000 through summer 2002 in the west-central Prairies. The 5 yr SPI values in Fig. 2f reveal drier than normal conditions over the central Prairies (west-central Saskatchewan). However, there is virtually no area affected by severe drought.

The PDSI results in Fig. 3 show similar large-scale spatial patterns, but with the driest conditions in 2002. This is likely due to the PDSI containing a long-term memory of previous moisture conditions. As a result, the 2002 PDSI is determined by dry conditions during 2001 and 2002. The summer and 1 yr values of the 2002 PDSI show strongest drought conditions over the north-central Prairie region with severe ($\text{PDSI} \leq -3.0$) drought encompassing most of Saskatchewan and western Alberta. The 2 and 5 yr periods also had drier than normal conditions, but were not as severe, compared to the SPI.

3.2. Historical comparison

On a Prairie-wide basis, the spatial extent and severity of the 2001/2002 drought was exceeded on several occasions, particularly from 1915 through the mid-1930s. For SPI, droughts in the early part of the record often covered a much larger area and were more severe than those of 2001 and 2002 (Figs. 4 & 5, Table 2). Individual drought years in the 1960s and the 1980s (particularly, 1961 and 1988) also tended to equal or exceed the 2001/2002 drought. The year 1929 stands out with the most severe summer and 1 yr drought, with an extraordinary 70% of the grids encompassed by severe drought (50% by extreme drought) during summer, and even more grids encompassed for the agricultural year (Table 2). Average SPI values for the entire study area were near -2 . In comparison, the 1 yr values associated with 2001 ranked

5th and 7th in percentage area covered by severe and extreme drought and 7th in terms of average SPI (-1). The year 2002 ranked 12th, 10th, and 14th, respectively. The droughts of 2001 and 2002 were, however, the worst 1 yr episodes since 1961. The 2 yr period of 2001–2002 ranked even higher with 40% of the grids impacted by severe drought (5th rank), and 24.4% by extreme drought (near 1st rank), and 6th rank for average SPI. This was the most serious 2 yr drought since the mid-1930s. For summer, the years 2001 and 2002 did not rank highly in terms of drought spatial extent and severity, due to the wetter than normal conditions over the southwestern Prairies during the summer of 2002 (Fig. 2b). For the 5 yr interval, 1998 to 2002 ranked well below the dry periods of the 1920s and 1930s.

Overall findings for the PDSI correspond to those of the SPI in that the majority of the worst droughts occurred early in the record (Figs. 6 & 7, Table 2). However, unlike SPI, 2002 ranked very high on a summer and 1 yr basis. In fact, it ranked 1st for 1 yr drought based on percentage area encompassed by severe drought, 3rd for extreme drought, and 2nd in terms of the average PDSI value; 2001 was less severe than 2002 (cf. Fig. 3). The years 1919 and 1988 ranked as the most severe summer droughts on the Prairies, while 1919, 1930, and 2002 were the most serious 1 yr episodes. With the exception of 1988, 1989, and 2002, most other severe summer and 1 yr droughts occurred early in the century, and the most severe 2 and 5 yr period droughts were in the 1920s and 1930s.

Although some inter-decadal variability is observed, it is clear that the most serious and prolonged droughts occurred in the early part of the record (Figs. 6 & 7). This trend is also apparent in the SPI, but is less pronounced. The SPI also tends to be associated with more inter-annual variability, which is likely the result of the influence of meteorological conditions during the current period of interest, while the PDSI has a long-term memory of previous moisture conditions.

Indications into the large-scale spatial variability of drought patterns within the region are provided in Figs. 8 & 9 which show 1 yr SPI and PDSI values for selected severe droughts. In terms of SPI, the years 1929 and 1961 ranked as two of the worst drought years on record (Table 2) while 1919 and 1988 (which were also highly ranked) have been identified by other studies as being particularly severe Prairie drought years (O'Brien 1994, Bonsal & Wheaton 2005). In 1929, there were severe to exceptional drought conditions over almost the entire Prairie region with driest conditions in Manitoba and the northern agricultural zone. The 1961 drought was also associated with negative SPI over most of the

Fig. 4. Standardized Precipitation Index (SPI). Percentage of grids with severe drought (SPI ≤ -1.5) during 1915–2002. Values for the 2001/2002 drought are in black

Fig. 5. Standardized Precipitation Index (SPI). Average values for all grids during 1915–2002. Values for the 2001/2002 drought are in black

Table 2. Ranking of the top 10 droughts over the Canadian Prairies during 1915–2002, based on the Standardized Precipitation Index (SPI) and Palmer Drought Severity Index (PDSI). Rankings include percentage of grids with severe and extreme drought (see Table 1 for definitions), and average values for all grids during summer, 1 yr, 2 yr and 5 yr periods. **Bold:** 2001 and 2002 drought (rankings in parentheses)

Period	Rank	SPI			Average for all grids			PDSI							
		Severe drought Year	Grids (%)	Year	Extreme drought Year	Grids (%)	Year	Severe drought Year	Grids (%)	Year	Extreme drought Year	Grids (%)	Year	Average for all grids Year	PDSI
Summer	1	1929	69.6	1929	49.8	1929	-1.88	1919	67.8	1919	49.8	1919	49.8	1919	-4.05
	2	1961	50.5	1961	36.7	1961	-1.70	1988	54.8	1988	43.8	1988	43.8	1988	-3.31
	3	1967	34.3	1967	17.0	1936	-1.32	2002	50.9	2002	33.6	1937	33.6	1937	-3.07
	4	1936	32.9	1937	14.8	1967	-1.18	1937	49.8	1931	30.0	1931	30.0	1931	-3.00
	5	1937	29.3	1979	8.1	1917	-0.94	1931	47.3	1915	27.6	1915	27.6	1961	-2.38
	6	1919	24.7	1958	7.8	1937	-0.86	1915	44.5	2002	23.7	2002	23.7	2002	-2.35
	7	1979	17.0	1918	7.1	1958	-0.82	1929	36.7	1929	22.6	1929	22.6	1929	-2.22
	8	1917	15.9	1936	5.3	1979	-0.82	1961	33.7	1929	21.9	1918	21.9	1918	-2.19
	9	1941	14.8	1939	4.6	1984	-0.81	1924	35.9	1961	15.2	1989	15.2	1989	-2.18
	10	1918	14.5	1920	3.2	2001	-0.67	1980	27.9	1980	11.3	1915	11.3	1915	-2.13
1 Year	1	2001 (11)	13.1	2001 (-)	0	2001 (10)	-0.67	2001 (19)	17.3	2001 (17)	8.1	2001 (31)	8.1	2001 (31)	-1.09
	2	2002 (20)	6.4	2002 (12)	2.5	2002 (53)	0.26	2002 (3)	50.9	2002 (6)	23.7	2002 (6)	23.7	2002 (6)	-2.35
	1	1929	76.3	1929	59.0	1929	-2.08	2002	48.8	1930	28.3	1919	28.3	1919	-3.12
	2	1961	49.5	1961	21.9	1961	-1.51	1919	46.6	1919	26.5	2002	26.5	2002	-2.62
	3	1919	46.3	1937	17.7	1919	-1.36	1930	43.8	2002	18.0	1930	18.0	1930	-2.61
	4	1924	36.4	1919	15.5	1924	-1.16	1989	35.3	1929	14.5	1989	14.5	1989	-2.42
	5	2001	33.2	1924	13.4	1936	-1.07	1937	31.1	1931	14.5	1937	14.5	1937	-2.26
	6	1937	26.5	1958	12.0	1958	-0.99	1988	31.1	1923	12.4	1931	12.4	1931	-2.16
	7	1988	24.0	2001	9.5	2001	-0.97	1924	28.3	1932	12.4	1988	12.4	1988	-2.13
	8	1984	23.7	1988	8.8	1917	-0.92	1931	24.4	1989	12.4	1932	12.4	1932	-1.85
2 Year	1	1915	21.9	1915	8.1	1937	-0.91	1932	23.3	1924	12.0	1938	12.0	1938	-1.83
	2	1917	21.6	2002	7.4	1918	-0.90	1929	22.3	1988	11.0	1920	11.0	1920	-1.64
	1	2001 (5)	33.2	2001 (7)	9.5	2001 (7)	-0.97	2001 (27)	7.1	2001 (17)	2.8	2001 (45)	2.8	2001 (45)	-0.12
	2	2002 (12)	19.8	2002 (10)	7.4	2002 (14)	-0.74	2002 (1)	48.8	2002 (3)	18.0	2002 (2)	18.0	2002 (2)	-2.62
	1	1929–1930	61.5	1929–1930	24.5	1929–1930	-1.58	1919–1920	32.2	1929–1930	16.3	1930–1931	16.3	1930–1931	-2.38
	2	1918–1919	55.5	1936–1937	24.5	1918–1919	-1.53	1929–1930	31.8	1931–1932	13.4	1919–1920	13.4	1919–1920	-2.38
	3	1936–1937	42.8	2001–2002	24.4	1936–1937	-1.36	1930–1931	31.8	1918–1919	12.4	1918–1919	12.4	1918–1919	-2.31
	4	1928–1929	41.0	1928–1929	23.3	1917–1918	-1.27	1988–1989	31.8	1988–1989	11.3	1988–1989	11.3	1988–1989	-2.28
	5	2001–2002	39.6	1918–1919	20.8	1928–1929	-1.22	1937–1938	27.2	1923–1924	11.0	1937–1938	11.0	1937–1938	-2.04
	6	1917–1918	27.6	1917–1918	16.3	2001–2002	-1.16	1918–1919	24.7	1919–1920	10.2	1931–1932	10.2	1931–1932	-2.01
5 Year	1	1919–1920	25.8	1958–1959	13.1	1919–1920	-1.08	1931–1932	22.3	1930–1931	9.5	1929–1930	9.5	1929–1930	-1.92
	2	1958–1959	21.9	1988–1989	7.4	1957–1958	-0.96	1923–1924	20.5	1922–1923	8.1	1938–1939	8.1	1938–1939	-1.72
	3	1930–1931	18.4	2000–1901	7.4	1958–1959	-0.86	1924–1925	19.1	1937–1938	7.1	1989–1990	7.1	1989–1990	-1.65
	4	1957–1958	15.2	1957–1958	5.7	1930–1931	-0.83	1922–1923	16.6	1924–1925	6.0	1939–1940	6.0	1939–1940	-1.53
	1	2001–2002 (5)	39.6	2001–2002 (3)	24.4	2001–2002 (6)	-1.16	2001–2002 (15)	11.0	2001–2002 (17)	1.1	2001–2002 (11)	1.1	2001–2002 (11)	-1.37
	2	1917–1921	46.6	1917–1921	23.0	1917–1921	-1.40	1929–1933	13.8	1929–1933	2.8	1937–1941	2.8	1937–1941	-1.64
	3	1936–1940	44.2	1957–1961	14.5	1936–1940	-1.32	1928–1932	11.7	1922–1926	2.5	1929–1933	2.5	1929–1933	-1.59
	4	1915–1919	35.3	1929–1933	12.4	1957–1961	-1.21	1922–1926	10.6	1928–1932	2.1	1918–1922	2.1	1918–1922	-1.55
	5	1929–1933	32.5	1936–1940	12.4	1929–1933	-1.19	1921–1925	10.2	1921–1925	1.1	1919–1923	1.1	1919–1923	-1.51
	6	1928–1932	29.0	1918–1922	11.7	1915–1919	-1.15	1930–1934	7.8	1930–1934	1.1	1936–1940	1.1	1936–1940	-1.38
	7	1957–1961	28.3	1928–1932	11.3	1928–1932	-1.05	1927–1931	7.1	1923–1927	0.4	1938–1942	0.4	1938–1942	-1.32
	8	1918–1922	26.1	1934–1938	7.4	1916–1920	-1.04	1920–1924	6.7	1920–1924	1.30	1930–1934	1.30	1930–1934	-1.30
	9	1926–1930	21.9	1915–1919	6.4	1918–1922	-1.03	1923–1927	6.7	1923–1927	1.21	1935–1939	1.21	1935–1939	-1.21
	10	1934–1938	21.9	1926–1930	6.4	1934–1938	-0.85	1926–1930	6.4	1926–1930	1.20	1917–1921	1.20	1917–1921	-1.20
	1	1927–1931	19.8	1935–1939	6.0	1933–1937	-0.82	1935–1939	6.0	1935–1939	1.19	1916–1920	1.19	1916–1920	-1.19
	1998–2002 (29)	4.9	1998–2002 (22)	0.7	1998–2002 (22)	-0.34	1998–2002 (23)	1.1	1998–2002 (-)	0	1998–2002 (27)	-0.55

Fig. 6. Palmer Drought Severity Index (PDSI). Same type of values as in Fig. 4, for $PDSI \leq -3.0$

Fig. 7. Palmer Drought Severity Index (PDSI). Same type of values as in Fig. 5

Fig. 8. Standardized Precipitation Index (SPI) for agricultural years with severe drought

Prairies with the core of the drought centred in eastern Saskatchewan and western Manitoba. Drier than normal conditions encompassed much of the Prairies in 1919; they were not as severe as 1929, however, and the 1919 drought was shifted southward near the Alberta/Saskatchewan border. During 1988, the most serious drought conditions occurred in the southern Prairies and in particular, southern Manitoba. In comparison, the 1 yr SPI values for 2001 and 2002 (Fig. 2c,d) show that the driest conditions associated with this drought were centred over Alberta and western Saskatchewan. In addition,

normal precipitation over the Prairies (not shown), these similarities indicate the long persistence associated with PDSI values. The 1919 PDSI (Fig. 9a) shows severe to exceptional drought conditions over the west-central Prairies. The most severe drought is shifted north in comparison to the SPI (cf. Fig. 8c). The year 1937 has also been identified as a drought year on the Prairies by Maybank et al. (1995), and this is clearly evident in Fig. 9c, where severe drought is shown over eastern Alberta and western Saskatchewan. This pattern reflects the dry conditions over this region during 1936 and 1937 (not shown).

Fig. 9. Palmer Drought Severity Index (PDSI) for agricultural years with severe drought

the spatial extent and severity of the 2001/2002 drought was less, compared to the drought years of 1929, 1961 and 1919 (consistent with Table 2).

PDSI values during the extreme drought years of 1919, 1930, 1937, and 1989 are provided in Fig. 9. These maps, along with those in Fig. 3, show once again that individual droughts have considerable spatial variability within the Prairie region. They also reveal relationships between the SPI and PDSI indices used to analyze drought in this study. The spatial drought patterns of the PDSI in 1930 and 1989 (Fig. 9b,d) are similar to the SPI patterns for 1929 and 1988 (Figs. 8a,d). Although 1930 and 1989 were also associated with below

4. SUMMARY AND DISCUSSION

This study examined the 2001/2002 Canadian Prairie drought in the context of historical drought occurrences. The SPI and PDSI as drought indicators revealed that the worst and most prolonged Prairie-wide droughts during the instrumental record (1915–2002) have occurred in the early part of the 20th century (1915 through the 1930s), with individual drought years also in 1961 and 1988. The spatial extent and severity of the 2001/2002 drought ranked below the early episodes, however, for most periods analyzed it was one of the top 10 worst droughts during the instrumental period. More importantly, it followed a prolonged ab-

sence of dry years, which likely contributed to the severe impacts of the 2001/2002 drought. In terms of SPI, 2001 and 2002 were the worst 1 yr droughts since 1961, and the worst 2 yr drought since 1929–1930; for PDSI, 2002 was one of the worst 1 yr droughts on record (Table 2).

These findings were based on analyses over the entire southern Canadian Prairies, and as such, provided comparisons of larger-scale Prairie droughts. As shown in Figs. 2, 3, 8 & 9, past Prairie droughts have shown considerable spatial variability, with the 2001/2002 episode being concentrated in the west-central Prairie region in 2001 and migrating northward in 2002. Examination of individual climate stations used in this analysis (not shown) revealed that for certain locations, 2001 and 2002 did rank as the worst or near worst drought during the study period. For example, the 2001 and 2001–2002 SPI values were the lowest on record for Prince Albert and Saskatoon, Saskatchewan, and the second lowest on record for Edmonton and Lacombe, Alberta. In terms of PDSI, Saskatoon had a record value of -5.47 for the 2002 agricultural year (previous record was -4.67 in 1988), while Prince Albert, and Banff, Alberta, had the second lowest value in the 88 yr period. The 2001–2002 PDSI value was also record-setting for Medicine Hat and Banff, Alberta.

Due to data restrictions, the historical analysis of droughts was confined to the southern Prairie Provinces. Even so, there were station gaps over the study area (see Fig. 1), and these may have influenced the spatially averaged historical comparisons. The incorporation of gridded monthly temperature and precipitation datasets to calculate PDSI and SPI values over the Canadian Prairies was considered, but it was felt that the methodology used in this analysis provided a more consistent approach, due to the fact that the number of stations used for each time period remains the same. With most gridded products, stations incorporated in the gridding procedure vary, depending on station availability for the period in question. This may, for example, bias results in the latter part of the 20th century, due to the higher density of stations in more recent years. One disadvantage, however, is that the spatial coverage is compromised over certain regions of the study area. Nonetheless, it is still likely that on larger scales the worst droughts on record occurred in the early part of the 20th century.

The SPI and PDSI both reveal similar overall findings, in that the worst droughts have occurred in the early 20th century. However, the ranking of individual drought periods often differs between the indices (Table 2), likely due to the PDSI having a long-term memory of previous moisture conditions and thus being more suited to assess longer-term hydrologic drought. The SPI on the other hand, is reflective of meteorological conditions during the current period of

interest. As a result, the most serious PDSI droughts tend to follow those associated with the SPI (e.g. 1929 and 1930; Figs. 8a & 9a). This is also why for PDSI, 2002 was more severe than 2001 (Fig. 3). Several investigations have evaluated numerous drought indices on various spatial and temporal scales, and have concluded that with respect to meteorological drought, the SPI is the preferred drought indicator, since it is easy to interpret and can be applied universally to any location at various temporal scales (e.g. Guttman 1998, Keyantash & Dracup 2002). Although a lack of precipitation is the main meteorological driver of severe drought conditions, droughts are often enhanced by anomalously high temperatures that increase evaporation. As a result, indices that incorporate temperature (such as the PDSI) may be better suited for assessing droughts that have been influenced by anomalously high temperatures. In addition, since all Global Climate Models (GCMs) project temperature increases over land regions of the Northern Hemisphere, indices that incorporate temperature may be better suited for assessing climate-change impacts on future droughts.

A preliminary analysis of climate change impacts on future droughts over the Prairies (not shown) indicates that the spatial extent and severity of future droughts based on the SPI will not be significantly altered. However, PDSI results differ greatly, in that future droughts are projected to dramatically increase in both spatial extent and severity. These differences are attributed to the PDSI's inclusion of temperature in its calculation. All GCM scenarios project considerable increases to temperature and, in general, small increases to precipitation over the Canadian Prairies (not shown). The higher temperatures translate into greater evaporation and more severe droughts. Since the SPI only takes into account precipitation, droughts using this index are not projected to become more severe in the future. However, further research is required to better quantify future drought occurrence over various regions of Canada. This should include the use of a drought index that accounts for evaporation, but is not greatly influenced by a substantial lag in previous moisture conditions.

In conclusion, this study has analyzed the 2001/2002 Canadian Prairie drought in the context of past droughts over the region. Results revealed that although these droughts were not as severe as those early in the 20th century, they occurred following a prolonged lack of severe droughts. Future research requires more in-depth analyses of both past and potential future drought occurrences at a variety of spatial and temporal scales, including a thorough evaluation of several drought indices. This study is an initial step toward the better understanding of both past and future drought occurrence over interior regions of North America.

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