INTERNATIONAL JOURNAL OF CLIMATOLOGY
Int. J. Climatol. (2017)
Published online in Wiley Online Library
(wileyonlinelibrary.com) DOI: 10.1002/joc.4967

Royal Meteorological Society

An assessment of historical and projected future hydro-climatic variability and extremes over southern watersheds in the Canadian Prairies

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ABSTRACT: Since human activities and ecosystem health require adequate, reliable water supplies, hydro-climatic variability and extremes pose serious threats to society and the environment. Previous studies have shown that the Canadian Prairies normally experience considerable hydro-climatic variability, including periodic droughts and excessive moisture conditions, which are mainly caused by mid-tropospheric circulations that disrupt expected precipitation and temperature patterns. However, no investigations have specifically focused on both past and future hydro-climatology over watersheds within the region. Evaluation of the Standardized Precipitation Evapotranspiration Index reveals considerable inter-annual and decadal-scale variability over the study regions of the Oldman and Swift Current Creek Watersheds, with no discernible trends during the last ∼100 years. There is also an indication of increased variability since the mid-1980s. Assessment of the 500 hPa circulation patterns associated with identified hydro-climatic extremes shows that major droughts are related with higher frequencies of distinctive ridging patterns over the Prairie region, and lower incidences of zonal/troughing patterns (the former significantly increasing over the last 60 years). Excessive moisture conditions have opposite patterns. Projections from two (a drier/warmer and wetter/cooler) Regional Climate Models indicate an uncertain future in the selected watersheds ranging from a substantial increase in drought with a higher degree of inter-annual variability, to relatively no change from current conditions. Furthermore, future changes to key atmospheric circulations suggest that those patterns associated with extreme dry conditions will continue in the future and in some cases, increase in frequency. Results from this analysis have improved the understanding of historical hydro-climatic extremes in western Canada and have provided insight into potential future occurrences of these extremes as driven by changes to key surface climate and synoptic-scale atmospheric circulation patterns.

KEY WORDS hydro-climatology; droughts; excessive moisture; Canadian Prairies; extremes; variability; 500 hPa circulation; adaptation

Received 21 September 2016; Revised 16 November 2016; Accepted 22 November 2016

1. Introduction

The occurrence of extreme dry conditions or drought, as well as prolonged wet periods, often results in serious impacts to a region's natural environment, economy, and society. Persistent, large-area droughts are among the costliest natural disasters, having major effects on sectors such as agriculture, industry, forestry, recreation, human health and society, and ecosystems (Bonsal *et al.*, 2011). For example, during the 2001 and 2002 drought years over Canada, the country's Gross Domestic Product fell by an estimated $5.8 billion, while previously reliable water supplies such as streams, wetlands, dugouts, reservoirs, and groundwater were placed under stress and often failed (Wheaton *et al.*, 2005, 2008). Although many areas of Canada periodically experience drought, western regions in the rain-shadow of the Rocky Mountains are more drought-prone due to their naturally high precipitation variability and distance from the ocean. During the past two centuries, several long-duration episodes have been documented in the region (Bonsal *et al.*, 2011). Traditionally, excessive wet periods were of less concern, but recent large-area extreme events such as the Assiniboine River Basin flood of 2011 (Brimelow *et al.*, 2014, 2015) have resulted in considerable impacts including threats to safety, damage to infrastructure, over-topping of reservoirs, and agricultural crop losses. Previous investigations have shown that most of western Canada has experienced significant warming (particularly, during winter and spring) and substantial inter-decadal precipitation

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variability during the instrumental record (approximately the last 100 years). Seasonally, the period 1950–2012 was associated with significant decreases in winter precipitation and little change during spring, summer, and autumn. There was also a significant decrease in the snow to rainfall ratio (Vincent *et al.*, 2015). Furthermore, over the last decade, rapid transitions from extreme dry to wet (and vice versa) conditions over the southern Prairies have occurred (Szeto *et al.*, 2011).

Hydro-climatic extremes are caused by disruptions to an expected precipitation pattern and in the case of drought, can be intensified by unusually high temperatures. The major factor in the onset and perpetuation of drought generally involves anomalous circulation patterns in the mid troposphere. Over the Canadian Prairie ecozone, growing season (May to August) extended dry periods were associated with a persistent circulation pattern that includes a large-amplitude ridge centred over the area. The ridging creates ‘blocking conditions’ that displace cyclonic tracks and associated moisture advection (from the Pacific Ocean and Gulf of Mexico) away from the area (Chakaravarti, 1976; Dey, 1982; Liu *et al.*, 2004). Conversely, excessive wet conditions are associated with a collapse of the ridge and thus a higher frequency of zonal flow over the Prairie region. The upper-level jet stream is often displaced southward in a west–east alignment along the Canada–United States border causing surface level cyclones to be steered over the Prairies. The wet conditions are aided by the advection of moist air into the Prairies from the southern United States and the Gulf of Mexico (Dey, 1977; Shabbar *et al.*, 2011).

Global and regional climate models (GCMs/RCMs) project future increases of summer continental interior drying and associated risk of droughts. The greater risk is ascribed to further increases in temperature and resultant evapotranspiration not being offset by precipitation increases (Trenberth, 2011; Collins *et al.*, 2013). Investigations into future droughts across the southern Canadian Prairie provinces (from an ensemble of GCMs) indicated the prevalence of more frequent summer drought in the latter half of the 21st century with persistent dry, warm conditions expected after about 2040 (Bonsal *et al.*, 2013). Results also revealed that multi-year droughts lasting 10 or more years are more likely than what has been historically observed. The fourth generation Canadian RCM showed similar findings over the southern Canadian Prairies for the period 2041–2070 (PaiMazumder *et al.*, 2013). Less work has been carried out on future excessive moisture conditions. One Canada-wide study examined changes to short-duration intense precipitation events (Mailhot *et al.*, 2012) using several RCM runs from the North American Regional Climate Change Assessment Program (NARCCAP; Mearns *et al.*, 2009, 2012). They documented that over the southern Canadian Prairies, 20-year return periods of annual maximum daily precipitation increased by 12–18%. On longer annual scales, overall future precipitation/water resource projections suggest that in Canada, the north will become wetter and the south drier, however, the boundary between wet and dry shows substantial inter-model variability (Maloney *et al.*, 2014). Furthermore, limited research has been carried out regarding changes to synoptic circulation patterns that affect hydro-climatic extremes.

This study contributes to the Canadian component of the Vulnerability and Adaptation to Climate Extremes in the Americas (VACEA) research project. VACEA is an interdisciplinary (social and natural sciences) and multi-collaborative investigation of vulnerability and adaptation to climate extremes in rural agricultural and indigenous communities in Canada, Argentina, Brazil, Chile, and Colombia (Sauchyn *et al.*, 2016). The research framework follows a vulnerability assessment model, whereby exposure and sensitivity to climate extremes and adaptive capacity are investigated for selected rural agricultural communities, and then re-evaluated in the context of projected climate changes. In western Canada, the research focuses on the Oldman (OM) and the Swift Current Creek (SCC) watersheds, part of the South Saskatchewan River Basin. The study communities are Pincher Creek and Taber in the OM, and Shaunavon and Rush Lake in the SCC (Figure 1).

Although previous studies have examined the occurrence and to some extent the atmospheric causes of hydro-climatic variability and extremes over western Canada, none have specifically analysed both past and future hydro-climatology over the OM and SCC watersheds. Using the Standardized Precipitation Evapotranspiration Index (SPEI) (Vicente-Serrano *et al.*, 2010) as a hydro-climatic indicator and an atmospheric typing procedure, the main objective is to assess the occurrence and atmospheric causes of historical and future hydro-climatic variability and extremes within the OM and SCC basins at a variety of temporal scales. Data and methodology are described in Section 2, while Section 3 assesses the occurrence and atmospheric causes of extreme hydro-climatic events during the instrumental (1900–2011) and future (2041–2070) periods, respectively. Concluding remarks are provided in Section 4.

2. Data and methods

2.1. Study area and data sources

The OM and SCC watersheds (Figure 1) are located in the southern Canadian Prairies with the former having its headwaters in the Rocky Mountains and the latter being primarily influenced by runoff from the prairie landscape. The OM basin contains forest, grasslands, and agriculture with 60% of the watershed characterized as cultivated land and approximately 20% of that land is irrigated (Oldman Watershed Council, 2010). The SCC watershed contains dryland agriculture that is dependent on spring runoff and spring/summer rain. Data sources for the variables described below are given in Table 1.

2.2. Historical hydro-climatic variability and extremes

Several drought/moisture indices are available to assess hydro-climatic variability. These range from those

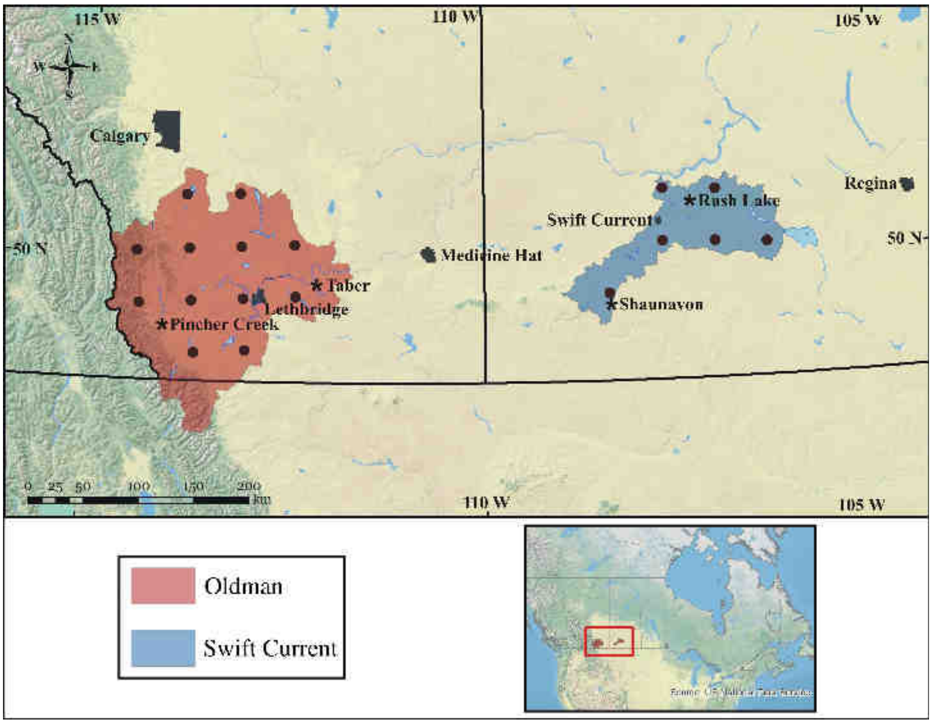


Figure 1. OM and SCC basin study areas along with the four VACEA study communities (Pincher Creek, Taber, Shaunavon, and Rush Lake). Locations of the 50 km temperature and precipitation grids from CANGRD are also provided.

Table 1. Data sources used in this study.

Variable	Input parameters	Source	Period
Historical summer and water year SPEI	Monthly temperature and precipitation	CANGRD	1950–2011
Future summer and water year SPEI	Monthly temperature and precipitation from two NARCCAP RCM/GCMs	CRCM-CCSM (drier/warmer) WRFG-CGCM3 (wetter/cooler)	2041–2070
Historical summer atmospheric synoptic types	Daily 500 hPa geopotential heights	NCEP/NCAR reanalysis	1950–2011
Future summer atmospheric synoptic types	Daily 500 hPa geopotential heights from two NARCCAP RCM/GCMs	CRCM-CCSM (drier/warmer) WRFG-CGCM3 (wetter/cooler)	2041–2070

that only consider precipitation (e.g. the Standardized Precipitation Index (SPI); McKee *et al.*, 1993), to more complex water balance approaches that use precipitation and temperature to derive potential evapotranspiration (PET), antecedent soil moisture, and runoff (e.g. the Palmer Drought Severity Index (PDSI); Palmer, 1965). This study utilizes the SPEI (Vicente-Serrano *et al.*, 2010), which evaluates the deviation of moisture deficit calculated as the difference between precipitation and PET. SPEI has advantages over the SPI and PDSI since it incorporates both temperature and precipitation (the former being especially important for warm-season drought), and can be calculated at a variety of temporal scales (unlike PDSI that is derived at a monthly time-step). Various estimates of PET are available ranging from strictly temperature based approaches including those proposed by Thornthwaite (1948) and Hargreaves and Samani (1982), to comprehensive methods (accounting for aerodynamic factors) such as Penman–Monteith (Monteith, 1981). The latter is generally considered to be the most robust, but when data availability are limited to monthly temperature and precipitation (as in this study), the Thornthwaite method has been frequently used (Hernandez and Uddameri, 2014). This study therefore incorporates the Thornthwaite PET calculation as originally proposed by Vicente-Serrano *et al.* (2010). Classifications for SPEI are provided in Table 2.

Table 2. SPEI classifications.

Classification	SPEI
Extreme drought	≤−2.0
Severe drought	>−2.0 to −1.5
Moderate drought	>−1.5 to −1.0
Near normal	−1.0 to +1.0
Moderate excessive moisture	+1.0 to <+1.5
Severe excessive moisture	+1.5 to <+2.0
Extreme excessive moisture	≥+2.0

Source: Vicente-Serrano *et al.* (2010).

Monthly climatic input to the historical SPEI is from the Canadian CANGRD data set. These data originate from the 338 temperature and 464 precipitation stations in the Adjusted and Homogenized Canadian Climate Data (AHCCD) set, where temperature homogeneity problems caused by station relocation and changes to instrumentation and observing practices have been addressed (Vincent *et al.*, 2012). AHCCD precipitation values were adjusted for known measurement issues such as wind under-catch, evaporation, and wetting loss (Mekis and Vincent, 2011). For CANGRD, the station data were gridded, with a spatial resolution of 50 km, using the Gandin optimal interpolation technique (see Zhang *et al.*, 2000; Vincent *et al.*, 2015).

SPEI values from the nearest 50 km grid to the four VACEA communities (Figure 1) are determined for two temporal scales. The first includes the 3-month summer (June–July–August) when climatic extremes often impact agricultural production over the study area. The second is the 12-month water year (October–September) that is relevant to longer-scale hydrologic related impacts (e.g. water availability). These SPEI are assessed for temporal trends (using the Mann–Kendall test; Mann, 1945; Kendall, 1975) and changes to inter-annual variability (using 30-year running standard deviations) over the period 1900–2011. Extreme dry and wet summers are identified and used in the atmospheric synoptic typing analysis as described below.

2.3. Future hydro-climatic variability and extremes

Future SPEI are determined using monthly temperature and precipitation output from two RCM runs used in NARCCAP (Mearns *et al.*, 2009, 2012). This international program produced high-resolution, climate-change data using several RCMs driven by a set of atmosphere–ocean general circulation models (AOGCMs) over a domain covering the conterminous United States and most of Canada at a 50 km resolution. The RCMs were forced by the boundary conditions from the AOGCMs using the Special Report on Emission Scenarios (SRES) A2 emissions scenario (Nakicenovic *et al.*, 2000). To examine the potential range in future conditions, two specific model runs (a drier/warmer and wetter/cooler projection) were chosen for the Canadian component of the VACEA project based on RCM-simulated trends in the Climate Moisture Index (CMI; Hogg, 1997) over western Canada for the period 1971–2070. With drought being a particular hazard in this region, it is important to use an index, which combines the effects of temperature and precipitation to select scenarios of climate change, rather than considering these variables individually. The CMI, which measures effective precipitation over potential evapotranspiration (i.e. P-PET) meets these criteria and in this case, was calculated over the May–June–July period to determine moisture conditions during the main growing season. Analysis of the results from all RCMs indicated that the Weather Research and Forecasting Model driven by the Canadian Global Climate Model Version 3 (WRFG-CGCM3) represented the largest increasing trend (+0.41 mm year^{-1}) and the Canadian RCM driven by the Community Climate System Model (CRCM-CCSM) had the largest decreasing trend (−0.66 mm year^{-1}) of CMI over the 1971–2070 period. Once these RCM–GCM combinations had been identified, monthly data for precipitation and maximum/minimum temperature were bias-corrected based on the quantile mapping methods of Boé *et al.* (2007) and Teutschbein and Seibert (2013). Henceforth, the CRCM-CCSM is referred to as the drier, warmer scenario and the WRFG-CGCM3 as the wetter, cooler scenario.

For each community, summer and water year SPEI changes are determined by comparing the modelled future values (from 2041 to 2070) to the modelled baseline values (from 1971 to 2000). Changes in average values and year-to-year standard deviations are calculated and assessed for significant changes to mean and variance using the *t*-test and *f*-test, respectively both at the 0.05 significance level.

2.4. Atmospheric synoptic typing

The assessment of mid-tropospheric circulation patterns associated with observed hydro-climatic variability and extremes incorporates an atmospheric synoptic typing procedure based on k-means clustering without previous data reduction using principal component analysis (Cuell and Bonsal, 2009). The method has been shown to identify the main characteristics of mid-tropospheric flow over various regions of western Canada. Daily 500 hPa geopotential heights for the period 1950–2011 over the region 45°–60°N and 130°–100°W are obtained from the NCEP/NCAR reanalysis product (Kalnay *et al.*, 1996). The daily heights are classified into six dominant types for the summer period using the procedure outlined in Cuell and Bonsal (2009). Corresponding temperature and precipitation anomalies (from NCEP/NCAR) associated with each type are determined. Each pattern is also assessed for trends and variability during the study period. Note that water year atmospheric analyses are not examined because of the greater range in geopotential heights and climate within the entire year (as opposed to summer). As a result of this range, the average temperature, precipitation, and geopotential height anomalies associated with each synoptic type are not useful for evaluating hydro-climatic extremes during the longer water year period.

Future (2041–2070) 500 hPa circulations from the two aforementioned RCM runs are subjected to the same atmospheric synoptic typing procedure as that used for the historical analysis. Changes to the relevant atmospheric circulation patterns associated with extremes in hydro-climate are then assessed.

3. Results

3.1. Historical hydro-climatic variability and extremes

All summer and water year SPEI time series for the four VACEA communities (Figures 2 and 3) display

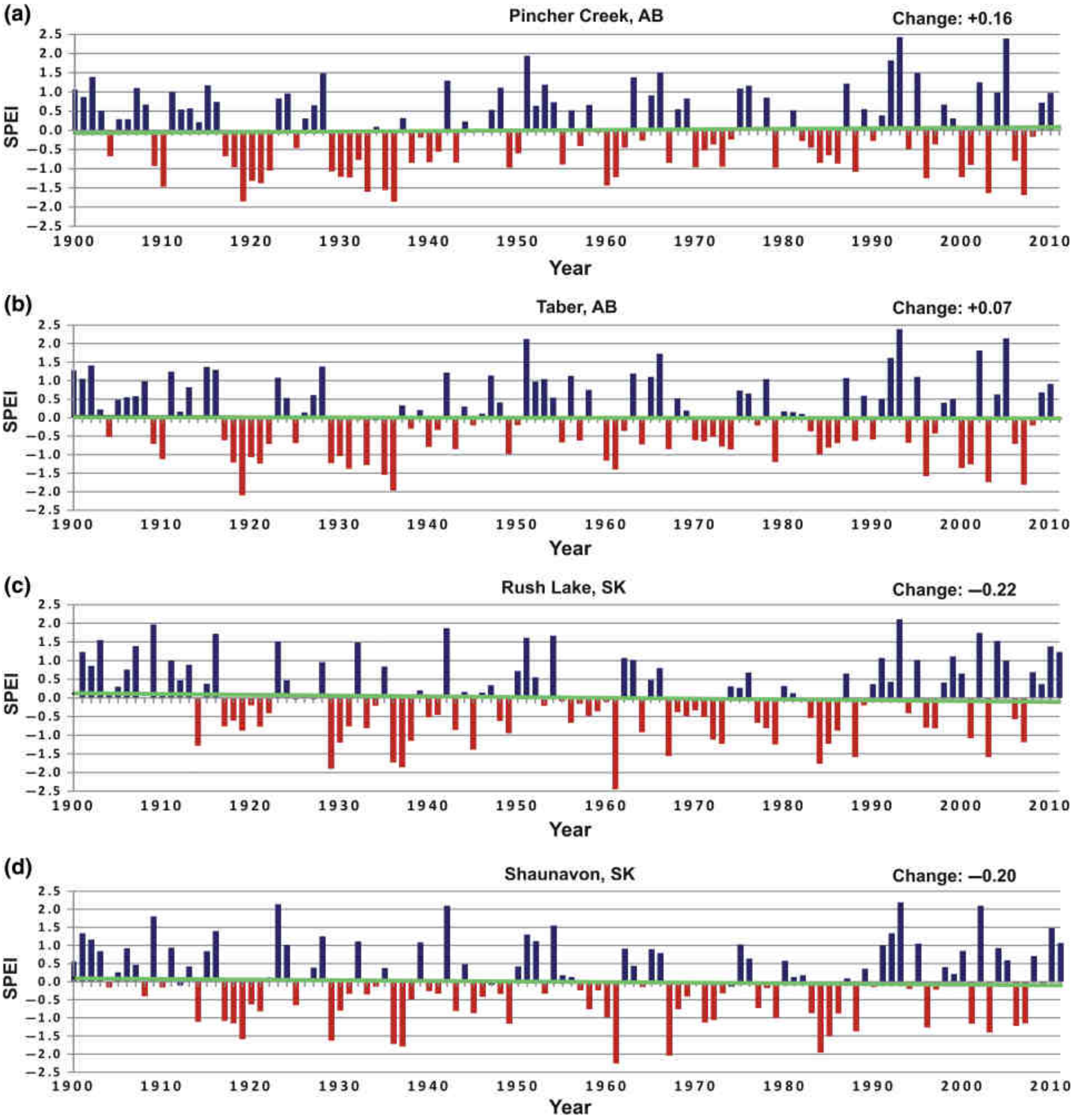


Figure 2. Summer SPEI for the period 1900–2011 over (a) Pincher Creek, AB; (b) Taber, AB; (c) Rush Lake, SK; and (d) Shaunavon, SK. Negative values indicate drier, warmer conditions and vice versa. Linear trends from 1900 to 2011 are provided.

considerable inter-annual variability, as well as several shifts from multi-year dry, warm conditions to persistent wet, cool periods and vice versa. During summer, all locations were associated with generally wetter/cooler conditions from 1900 to 1915 followed by a primarily extended drier, warmer period through to approximately the late 1940s. Since then, the climate has experienced several back and forth shifts from prolonged dry/warm to wet/cool periods. The two SCC stations differ slightly from those in the OM basin in that the period from 1960 to 1990 was predominantly dry and warm, while from 1990 to 2011, this has shifted to primarily wet and cooler (i.e. several summers with SPEI $> +1.5$). Over the entire record, there has been no significant long-term trend in SPEI although Rush Lake and Shaunavon had slight decreases of around 0.2 over the 112-year study period. The lack of statistically significant trends highlights the role of natural variability in climate over the study region that has been characterized by oscillations of dry, warm and wet, cool periods over the instrumental record of approximately the last 100 years. Note that several dendrochronological studies in the region revealed similar oscillations over the last millennia (Sauchyn and Kerr, 2016).

Figure 2 and Table 3 also reveal that several severe drought (SPEI < -1.5) and severe excessively moist (SPEI $> +1.5$) summers occurred in all the communities while extreme drought/excessively moist events (SPEI < -2.0 or $> +2.0$) were not as widespread. For

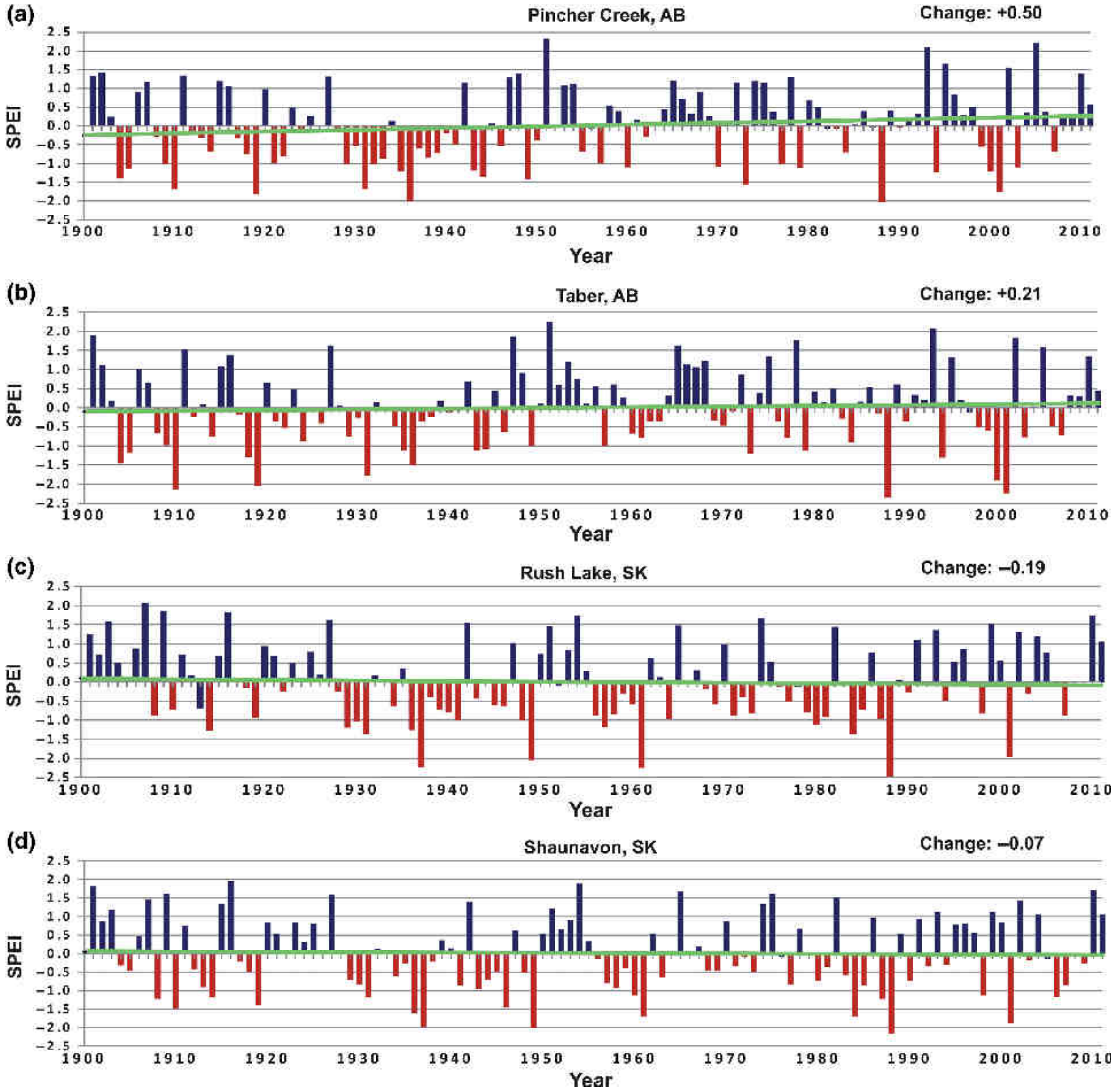


Figure 3. Water year SPEI for the period 1901–2011 over (a) Pincher Creek, AB; (b) Taber, AB; (c) Rush Lake, SK; and (d) Shaunavon, SK. Negative values indicate drier, warmer conditions and vice versa. Linear trends from 1900 to 2011 are provided.

example, 1961 had extreme negative SPEI for the SCC locations, but not for those in the OM. The 1951, 1993, and 2002 summers had the most positive SPEI in the OM communities. In fact, 1993 was associated with the highest SPEI value for all four communities indicating very widespread wet conditions during that summer.

The water year results in Figure 3 are similar to the summer findings with considerable year-to-year and multi-year variability. Pincher Creek has a stronger positive trend in SPEI from 1900 to 2011, which is primarily the result of the drier, warmer conditions in the early 20th century and for the most part, wetter, cooler periods at the end of the period. However, the trend is not statistically significant. Regarding extreme years, as with the summer, there are several severe drought and severe excessive moist years in both the SCC and OM basin communities while extreme drought/excessive moist occurrences are not as common. The well-documented drought year of 1988 stands out as the most negative SPEI for all four locations during the entire record. It is also interesting to note that the most extreme water years (both negative and positive) often do not exactly match those that occurred in summer (e.g. in 1988), however, as alluded to previously, the inter-decadal positive and negative oscillations are similar for both periods.

To assess inter-annual variability over the last century, the running 30-year standard deviation of summer SPEI from 1900 to 2011 (Figures 4(a)–(d)) shows a slight increase since around the mid-1980s over all locations (more so over the OM communities) when standard deviations prior to this date were for the most part, <1.0 and increased to near 1.2 by the end of the study period. This

Table 3. Negative (dry, warm) and positive (wet, cool) extreme SPEI summers for the period 1950–2011 over the OM and SCC basins. Extremes are the three most negative and positive SPEI averaged over all four communities from 1950 to 2011. SPEI values for each community are also provided.

Negative extremes						Positive extremes					
Year	Ave	PC	Tab	RL	Shau	Year	Ave	PC	Tab	RL	Shau
1961	−1.83	−1.22	−1.40	−2.45	−2.26	1993	2.28	2.43	2.39	2.11	2.19
2003	−1.59	−1.64	−1.74	−1.59	−1.40	1951	1.74	1.94	2.12	1.61	1.30
2007	−1.46	−1.69	−1.81	−1.19	−1.15	2002	1.72	1.25	1.81	1.74	2.10

PC: Pincher Creek; Tab: Taber; RL: Rush Lake; Shau: Shaunavon.

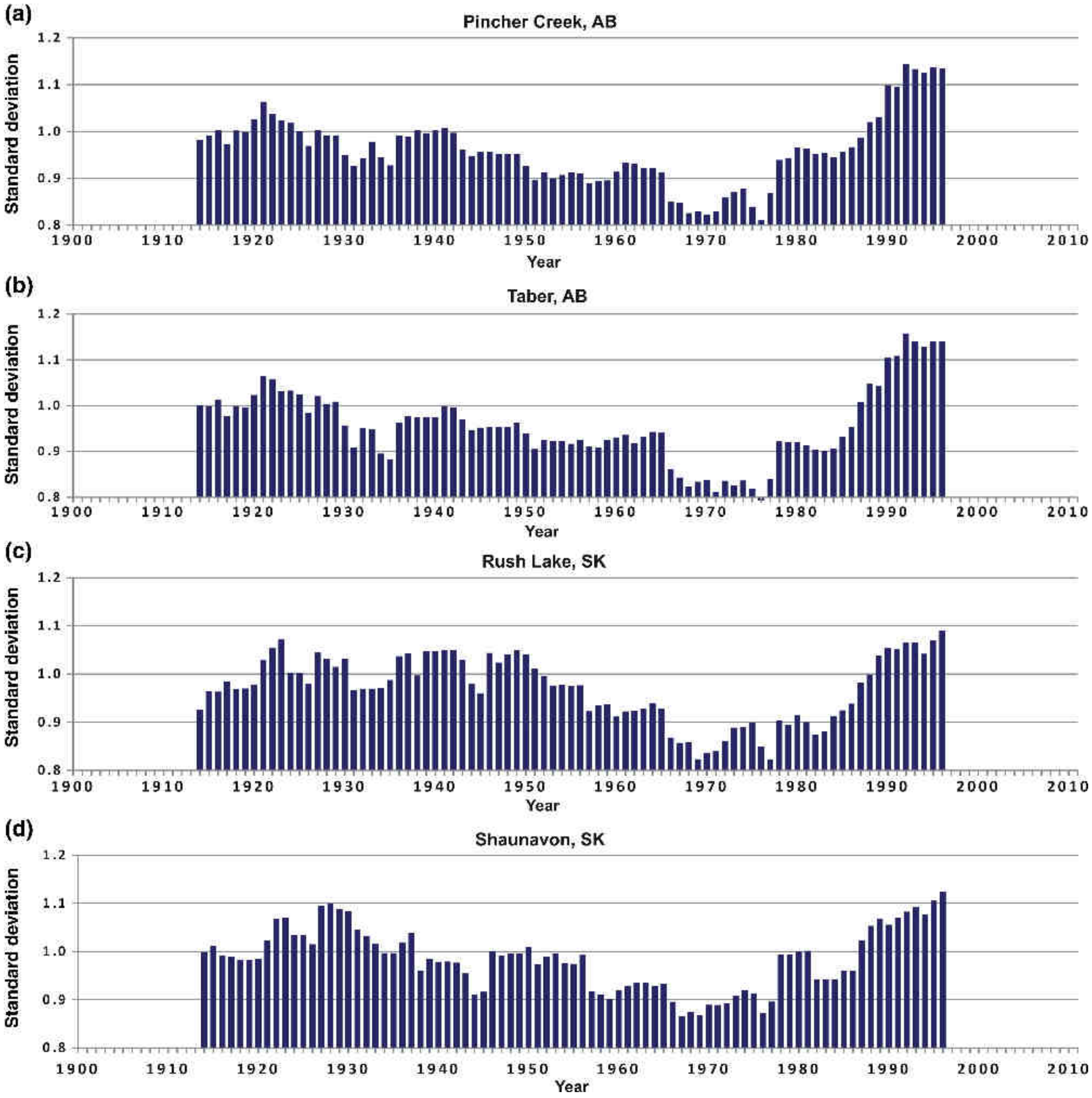


Figure 4. Running 30-year inter-annual, standard deviation of summer SPEI for the period 1900–2011 over (a) Pincher Creek, AB; (b) Taber, AB; (c) Rush Lake, SK; and (d) Shaunavon, SK. Each value corresponds to the mid-point of the 30-year period.

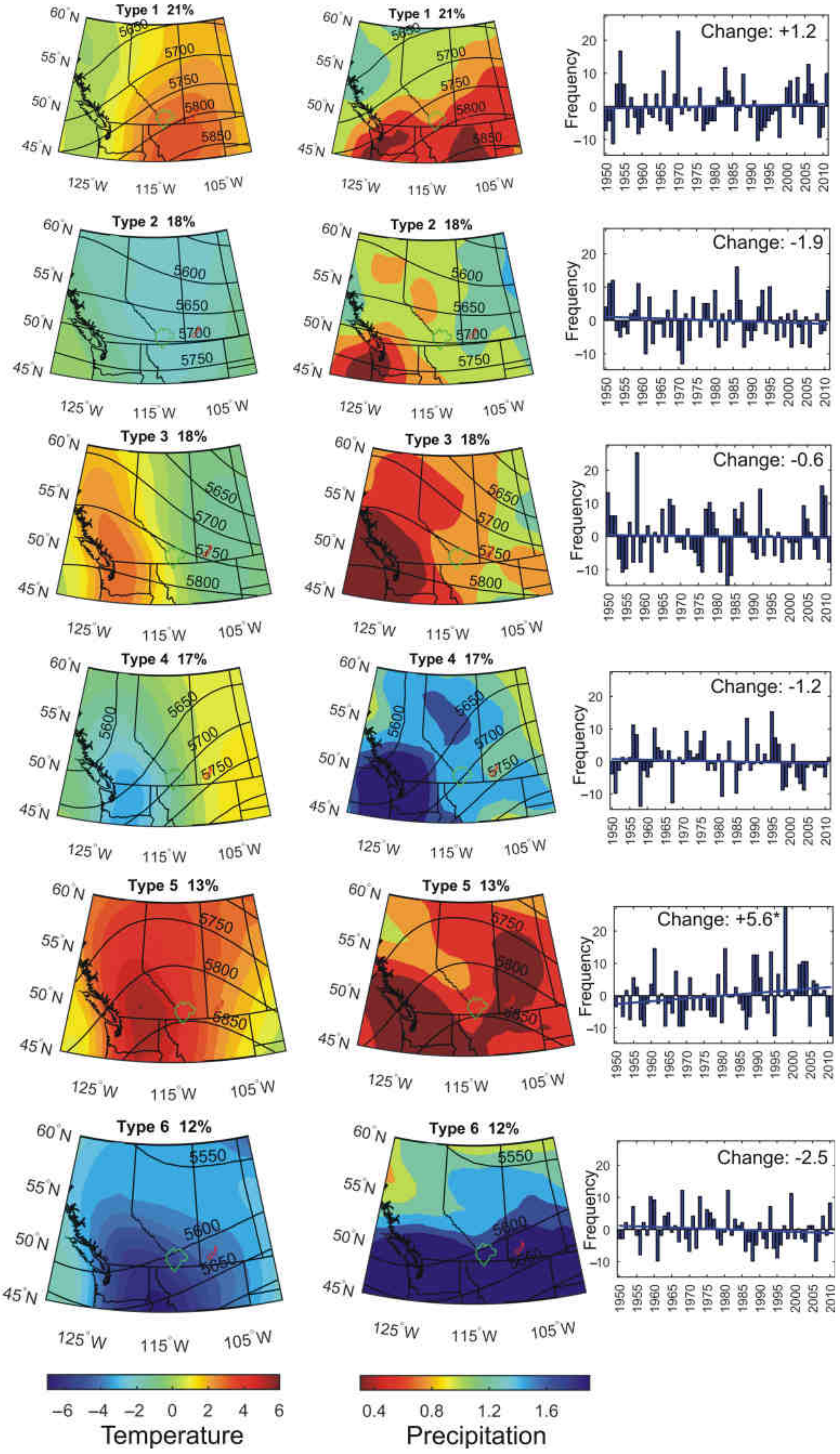


Figure 5. Six summer 500 hPa synoptic types for the period 1950–2011. Geopotential heights are in metres. Column 1 shows corresponding surface temperature anomalies (°C) while column 2 displays precipitation anomalies (as a factor of normal with 1.0 equal to the normal). Column 3 provides the frequency of occurrence (as departures from normal) for each summer including linear changes over the 1950–2011 period. Asterisks signify significant trends at the 0.05 level. All anomalies are based on the 1950–2011 mean.

Table 4. Characteristics of the six summer 500 hPa synoptic types for the period 1950–2011.

Type	Frequency (%)	Atmospheric flow	Climate	Linear trend
1	21	Ridging in eastern study area	Warm, dry	No trend
2	18	Zonal, west to east	Near average	No trend
3	18	Northwesterly flow	Dry, warm in west; near normal in east	No trend
4	17	Troughing over the west; ridging in far east	Wet, cool in west, warmer in east	No trend
5	13	Large-amplitude ridge over study area	Very dry and warm	Increasing (significant)
6	12	Trough, southwesterly flow	Cold, wet	Slight decrease (insignificant)

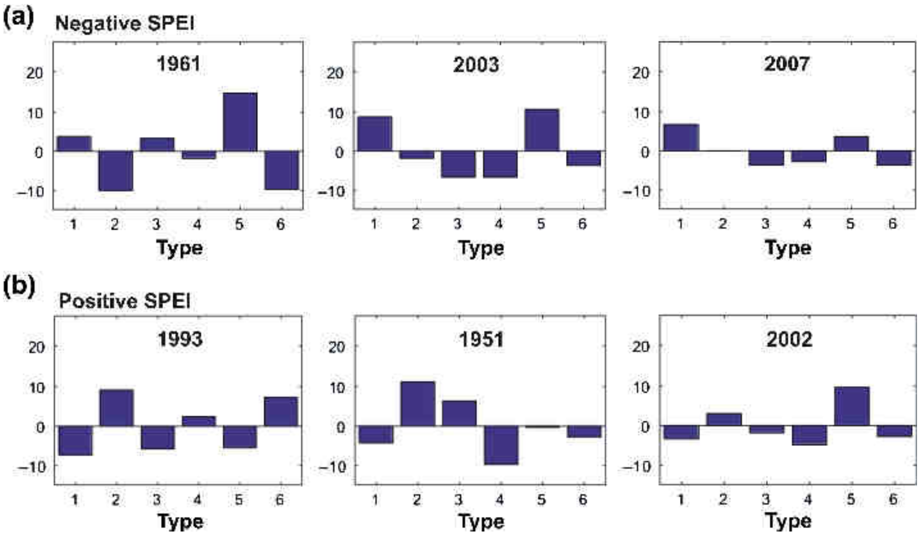


Figure 6. Relative frequency (difference from normal based on the 1950–2011 mean) of atmospheric types associated with (a) extreme negative and (b) extreme positive SPEI summers.

increase is evident in Figure 2, which shows considerable year-to-year changes during approximately the last 20 years of the time series (particularly in the Alberta communities). This is consistent with the rapid transition from extreme dry to wet conditions over the southern Canadian Prairies in the first decade of the 2000s (Szeto *et al.*, 2011), but whether the apparent increase in Figure 4 is a shift towards more variable hydro-climate is not clear and requires further investigation. The water year standard deviation values also show an increase at the end of the study period, but they are not as pronounced as summer (not shown).

3.2. Atmospheric circulation

Daily 500 hPa geopotential heights during the summers of 1950–2011 are classified into six synoptic types (Figure 5; Table 4). Corresponding anomalies of temperature and precipitation, as well as, historical time series (given as departures from normal) are provided. These six types capture the expected range of synoptic-scale circulation patterns over the region including ridging, troughing, and zonal flows. In particular, Type 5 (that occurs 13% of the time) displays a large-amplitude ridge with its axis over the centre of the study area. The corresponding temperature and precipitation anomalies are characterized by drier and warmer conditions over both study basins, which is expected since the ridge creates blocking conditions that displace cyclonic tracks and associated moisture away from the area, and are also associated with descending air currents and resultant high surface temperatures during the summer (Dey, 1982; Bonsal *et al.*, 1999; Liu *et al.*, 2004). Type 1 (21%) also displays ridging, however, the axis is displaced eastward as compared to Type 5. This flow produces drier and warmer than normal conditions over the OM and SCC basins, but not as severe as Type 5.

Conversely, Type 6 (12%) is associated with substantially wetter and cooler conditions over the study area. The atmospheric flow consists of a troughing pattern that allows surface level cyclones to be steered over the study area (Dey, 1977; Shabbar *et al.*, 2011). Type 4 also has a wetter climate over much of the area and is cooler in the west and warmer in the east. It is characterized by a trough over the western study region and a concurrent ridge over the extreme east, thus explaining the differing surface climates between the two basins. The other two patterns (Types 2 and 3) are zonal in nature with the former having a west to east flow and near normal precipitation and

Table 5. Changes in SPEI mean and standard deviation between the current (1971–2000) and future (2041–2070) periods based on the drier, warmer (CRCM-CCSM) and wetter, cooler (WRFG-CGCM3) RCM simulations for the four VACEA communities. (a) Summer and (b) water year.

Community	Future scenario	Change in mean	Change in standard deviation
(a) Summer			
Taber, AB	Drier, warmer	−0.95*	+0.86*
	Wetter, cooler	−0.08	−0.08
Pincher Creek, AB	Drier, warmer	−0.60	+0.83*
	Wetter, cooler	−0.35	−0.12
Shaunavon, SK	Drier, warmer	−0.64*	+0.34
	Wetter, cooler	+0.04	−0.13
Rush Lake, SK	Drier, warmer	−1.16*	+0.82*
	Wetter, cooler	+0.34	−0.14
(b) Water year			
Taber, AB	Drier, warmer	−0.24	+0.33
	Wetter, cooler	−0.03	+0.02
Pincher Creek, AB	Drier, warmer	−0.35	+0.76*
	Wetter, cooler	−0.03	−0.40*
Shaunavon, SK	Drier, warmer	−0.45	+0.38
	Wetter, cooler	+0.45	+0.39
Rush Lake, SK	Drier, warmer	−0.59*	+0.20
	Wetter, cooler	+0.32	−0.01

*Significant difference at the 0.05 level using the Student's *t*-test for the mean and the *f*-test for the standard deviation.

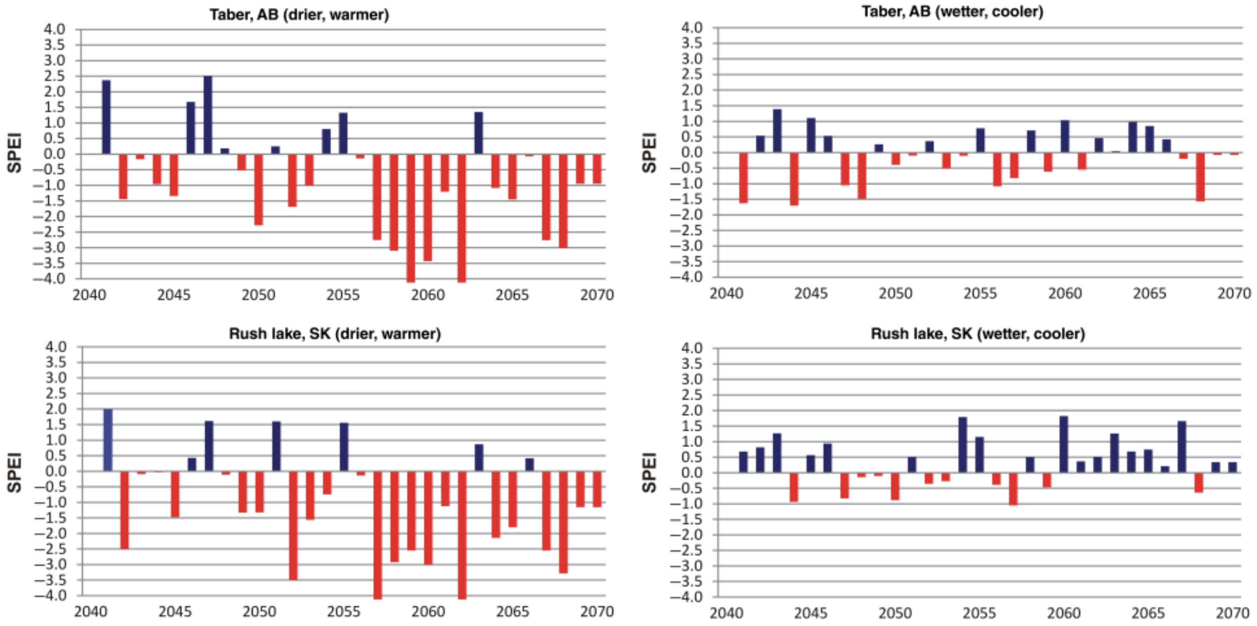


Figure 7. Selected examples of projected future (2041–2070) areally averaged summer SPEI values.

temperature, and the latter associated with a slight northwesterly component to the flow resulting in drier, warmer climate in the west and near normal conditions in the east.

The time series in Figure 5 show considerable year-to-year variability for all types with the majority having no discernible long-term trend (similar to the summer SPEI series in Figure 2). However, the ridging Type 5 (associated with very dry, warm conditions) is significantly increasing at the 0.05 level (by almost 6 days per summer over the 62-year study period). There have, however, been fewer occurrences of Type 5 over the last couple of summers in the record (2010–2011) coinciding with the positive SPEI values in Figure 2. The cold-wet troughing pattern (Type 6) shows a slight decreasing trend, but it is not significant.

An assessment of relative occurrence of the synoptic types during the most extreme negative and positive SPEI summers affecting all four communities is carried out to determine which atmospheric patterns are associated with hydro-climatic extremes (Figure 6). Extreme summers are identified as the three most negative and positive SPEI averaged over all four locations (Table 3). Note that these extremes are from the period 1950–2011 to coincide with 500 hPa atmospheric data availability. The graphs reveal that even during such extreme summers, there is considerable variability in the occurrence of

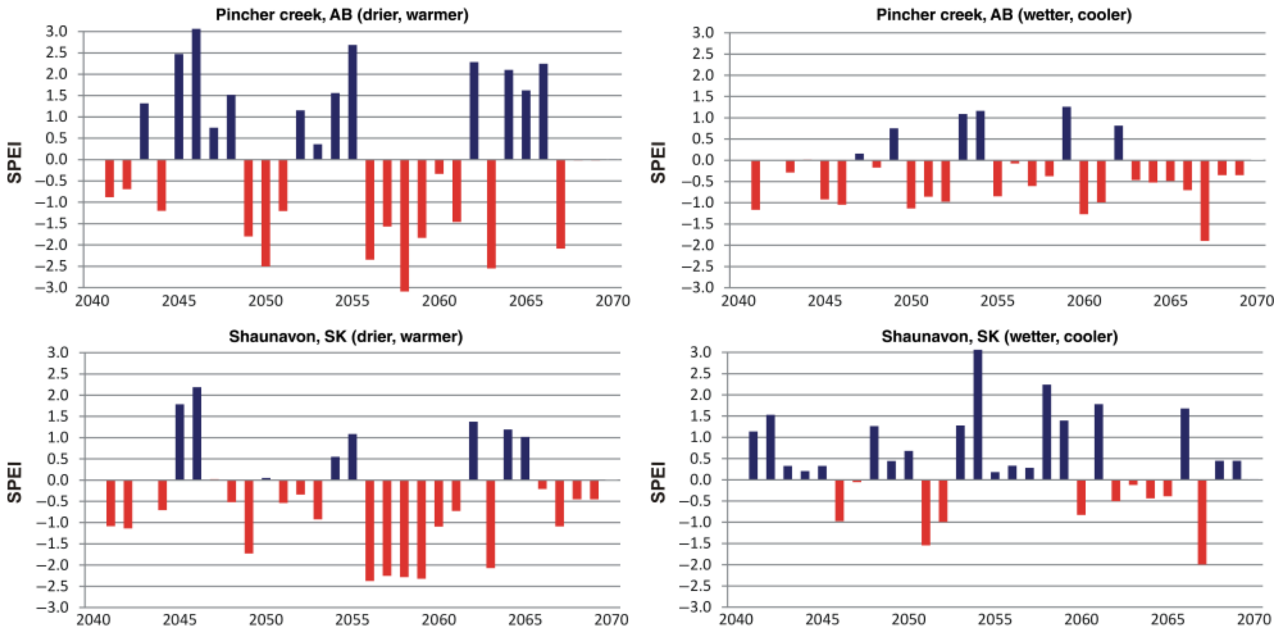


Figure 8. Selected examples of projected future (2041–2070) areally averaged water year SPEI values.

synoptic types, however, some tendencies are evident. For example, there is a notable increase in the ridging Type 5 and Type 1 during the drought summers of 1961, 2003, and 2007, which accounts for the extreme negative SPEI over all of the communities. All of these summers have fewer occurrences of Type 6 and Type 4 (both being associated with wetter than normal conditions), while Type 2 and Type 3 (zonal and northwesterly flow) are more variable.

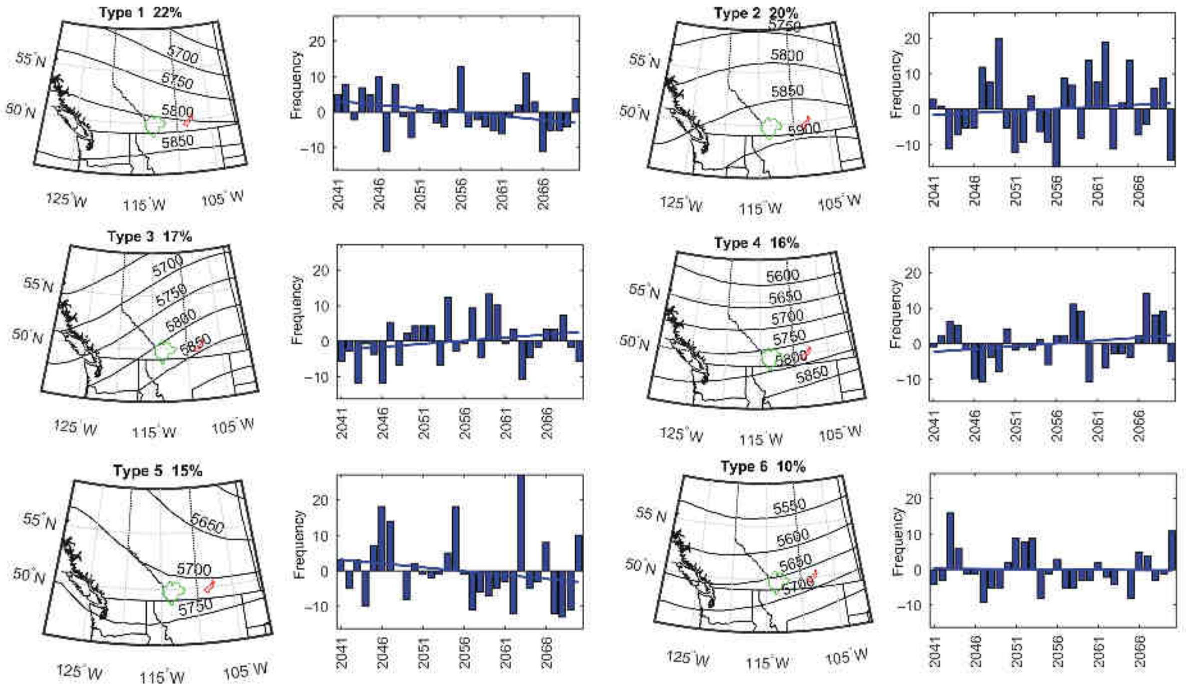
Excessive wet summers (1993, 1951, and 2002) appear to have less consistency in terms of synoptic patterns, but generally have fewer occurrences of Types 1 and 5 (except for 2002), and are mostly dominated by a higher occurrence of Type 2 and in 1993, Type 6 (although considerable variability is apparent). The preceding demonstrates that the most extreme summers (particularly, drought and to a lesser extent excessive wet) are influenced by the relative occurrence of characteristic dry, warm and wet, cooler atmospheric circulation patterns. Furthermore, there is a significant increasing trend in the strong ridging pattern over the last ~60 years and a slight decrease in the troughing Type 6 circulation.

3.3. Future hydro-climatic variability and extremes

Table 5 shows the range of projected changes to the mean and standard deviation of summer and water year SPEI as simulated by the drier, warmer and wetter, cooler RCMs for the four VACEA communities from 2041 to 2070. Figures 7 and 8 provide associated time series for selected examples. For summer, all locations show a large mean decrease in SPEI for the drier, warmer scenario ranging from −0.60 at Pincher Creek to −1.16 in Rush Lake. With the exception of Pincher Creek, these changes are significant. This directly translates into a higher frequency and severity of future drought as evidenced on the left side of Figure 7 where almost permanent summer aridity occurs from the mid-2050s onward. The wetter, cooler projection has a broader range in SPEI projections including a smaller increase in droughts in Pincher Creek, relatively no change in Taber and Shaunavon, and an increase in SPEI over Rush Lake (Figure 7). The drier, warmer scenario is also associated with the greatest changes in variability with three of the four communities having significant increases. The wetter and cooler scenario generally shows small decreases in future variability. These differences in year-to-year variability between the two RCM projections are clearly evident in Figure 7. The preceding therefore suggests an increasingly uncertain future in drought/excessive moisture risk in the two basins ranging from considerably worse conditions involving a substantial increase in summer drought with a higher degree of inter-annual variability to relatively no change from current conditions. Since current conditions can cause problems and present challenges for adaptation, the potential for future drought and variability increases would certainly increase the level of challenge without considerable improvements in capabilities.

The water year changes in Table 5(b) and Figure 8 are not as pronounced as compared to summer. The drier, warmer scenario shows smaller decreases in mean SPEI for all communities indicating an increased frequency and severity in future droughts, but as shown on the left side of Figure 8, the SPEI values are not as severe as those for summer. Only Rush Lake has a significant change to mean SPEI. All communities are projected to see an increase in variability for the drier, warmer scenario (again not as high as summer), with the value at Pincher Creek being significant. The wetter and cooler projection is associated with little SPEI change in the OM basin, and a small insignificant increase (i.e. wetter conditions) in the SCC communities. There is little change in variability with

(a) CRCM-CCSM



(b) WFRG-CGCM3

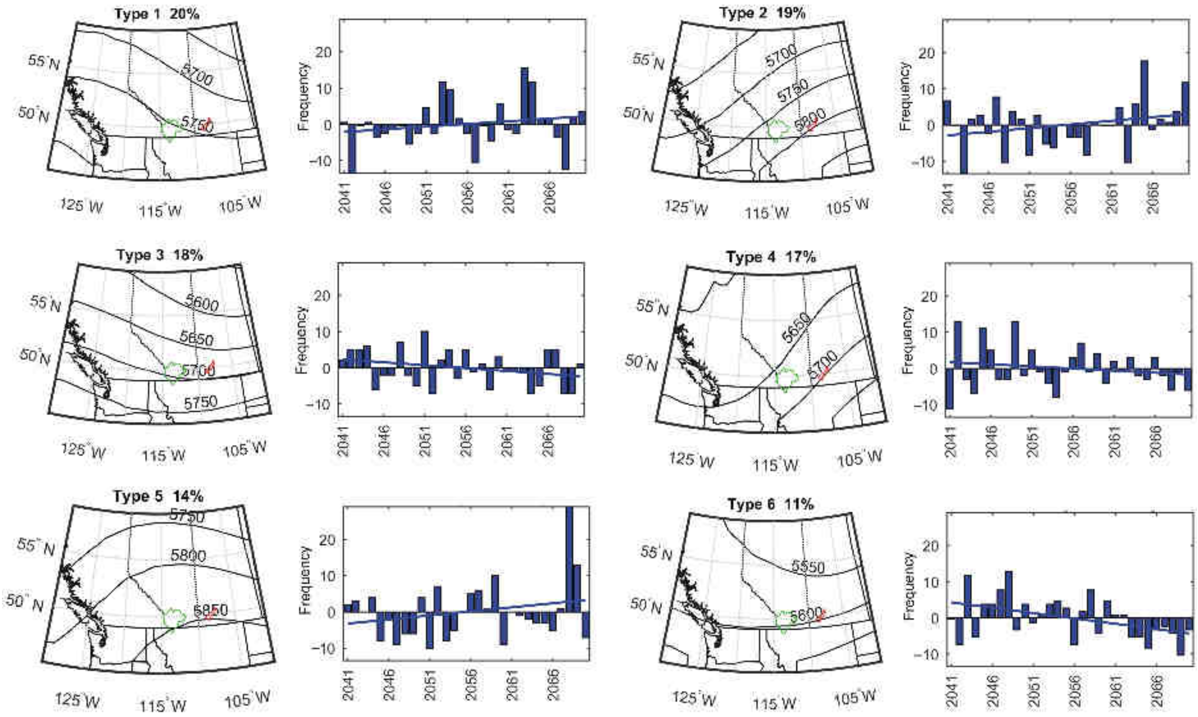


Figure 9. Six summer 500 hPa synoptic types for the period 2041–2070 from (a) the drier, warmer (CRCM-CCSM) simulation and (b) the wetter, cooler (WRFG-CGCM3) simulation. Geopotential heights are in metres. Departures from the 2041–2070 normal for each summer are given.

the exception of Pincher Creek, which shows a significant decrease. In summary, the water year also exhibits uncertainty with regard to the mean and variability of future hydro-climatic conditions although Figure 8 does indicate extended dry water year periods for the warm, dry scenario that would also cause adaptation challenges.

3.4. Future atmospheric circulation

Figure 9 shows the six projected future summer synoptic patterns from (a) the drier, warmer CRCM-CCSM scenario, and (b) the wetter, cooler WRFG-CGCM3 scenario. Results are summarized in Table 6. A qualitative comparison reveals that both RCMs project similar

Table 6. Comparison of observed summer 500 hPa synoptic types (1950–2011) to those projected by the drier, warmer (CRCM-CCSM) simulation and the wetter, cooler (WRFG-CGCM3) simulation for the period 2041–2070.

Observed	Atmospheric flow	CRCM-CCSM	WRFG-CGCM3
Type 1; 21%	Ridging in eastern study area	Type 3; 17%	Type 2; 19%
Type 2; 18%	Zonal, west to east	Type 4; 16%	Type 3; 18%
Type 3; 18%	Northwesterly flow	Type 1; 22%	Type 1; 20%
Type 4; 17%	Troughing in west; ridging in far east	Not identified	Type 4; 17%
Type 5; 13%	Large-amplitude ridge	Type 2; 20%	Type 5; 14%
Type 6; 12%	Trough, southwesterly flow	Type 6; 10%	Type 6; 11%

circulations to the observed (Figure 5) including the characteristic ridging, zonal, and troughing patterns. In particular, both simulations include a ridge centred over the study area (Type 2 in the CRCM-CCSM; Type 5 in the WFRG-CGCM3) that resembles the Type 5 pattern in Figure 5 for 1950–2011. As expected, this type occurs more often in the drier, warmer scenario (20 *vs* 14% in the wetter, cooler run; compared with 13% during the observational period), with the time series of the CRCM-CCSM showing several summers with higher than normal occurrences of this pattern. This coincides with the multiple negative SPEI summers shown in Figure 7. In addition, the ridging pattern shows an increasing tendency over the 30-year future period in both runs. Troughing similar to Type 6 in the observed period is evident in both simulations (Type 6 for each). The average frequency is 10 and 11% for the drier, warmer and wetter, cooler scenarios respectively, as compared to 12% during the observed period. The Type 6 future pattern shows substantial inter-annual variability in the CRCM-CCSM projection and a steady decrease in the WFRG-CGCM3 simulation. The other four types for each future simulation show varying aspects of the circulation similar (although not identical) to those in the observed climate. For example, the northwesterly flow associated with the observed Type 3 is apparent as Type 1 in both CRCM-CCSM and WFRG-CGCM3. This flow is projected to be the most common pattern in the future (Table 6). The ridging over the eastern study area (Type 1 in Figure 5) is also simulated (Types 3 and 2 in Figures 9(a) and (b), respectively) and both projections show a slight increase over the 2041–2070 time frame. The zonal west to east flow with near average precipitation and temperature (Type 2 in Figure 5), has little change in frequency in the future for both runs. Lastly, the observed Type 4 (troughing in west, ridging in far east) is not readily identified in the CRCM-CCSM projection, but is evident as Type 4 in WFRG-CGCM3.

The preceding provides some indications regarding the characteristics and occurrence of future summer mid-tropospheric circulation patterns over the southern Canadian Prairies. Projections from the two RCMs reveal that the general features of observed circulations are apparent in the future, with some changes to the average frequencies of the types. The most notable includes an increase of ridging centred over the study area, particularly in the drier, warmer scenario (increase to 20% from the observed 13%) that would translate into a higher future drought risk in the region. Although the results in Figure 9 offer an indication into changes to relevant circulation patterns, more in-depth analyses including for example, incorporation of additional climate models, development and implementation of an objective assessment that compares simulated and observed synoptic patterns, examination of the sequencing and persistence of future key circulation patterns, comparison of individual types to projected future surface climate, and examination of types during specific periods within the water year (e.g. cold season and warm season) are required to better understand the impact of changes to circulation and resultant future hydro-climatic variability and extremes in this and other regions.

4. Summary and conclusions

This study assessed historical and projected future hydro-climatic variability and extremes over two southern watersheds in the Canadian Prairies as part of the multi-national VACEA project. Results showed that on summer and water year bases, considerable inter-annual and inter-decadal variability in hydro-climate (as measured by the SPEI) has occurred with no discernible long-term trends over the last century. There were, however, several identifiable extremes over all study locations and a suggestion of increased year-to-year variability in the last few decades. Examination of associated summer mid-tropospheric circulation revealed that the relative frequency of characteristic ridging and troughing patterns were associated with dry, warm and wet, cool extreme summers. In addition, since 1950, there has been a significant increase in the ridging pattern responsible for drier and warmer summers in all locations.

Insight into future changes to hydro-climate and associated atmospheric circulation was examined using two bias-corrected RCM-GCM combinations, namely a drier, warmer scenario (CRCM-CCSM) and a wetter, cooler projection (WFRG-CGCM3). Results indicated an uncertain future in drought/excessive moisture risk in the two basins ranging from considerably worse conditions involving a substantial increase in the frequency and severity of drought with a higher degree of inter-annual variability, to relatively no change from current conditions. A preliminary analysis of changes to future summer circulation suggested that similar patterns to those observed in the past will continue over the region, however, average frequency of occurrence will change. The most notable involves more ridging patterns, particularly in the drier, warmer scenario, which would increase the future drought risk in the study area.

The historical findings substantiate the high degree of natural hydro-climatic variability in the southern Prairies including the fact that extreme drought and excessive moisture are inherent to the region. Additional insights to the atmospheric causes of these extremes were provided using a novel atmospheric synoptic typing procedure, which showed that large-amplitude ridging centred over the region has significantly increased over the last ~60 years (although substantial inter-annual variability in this ridging is evident). A continuation of this trend would make the region more susceptible to future extreme dry, warm conditions. Additional research into the causes of these key synoptic patterns including atmosphere–ocean teleconnections over the Pacific (that were shown to influence summer circulation over western Canada; Bonsal *et al.*, 1993; Shabbar *et al.*, 2011) and possible links of mid-latitude extremes to Arctic amplification (Francis and Vavrus, 2012) are required to develop a better understanding of the larger-scale factors influencing hydro-climatic extremes and variability both in these watersheds and over all of western Canada.

The two RCMs in this study were chosen to provide a range of possible future hydro-climate in the region. This range was greater for the SPEI findings (Table 5) compared to the atmospheric circulation results (Table 6). Reasons for this are not clear and may be due to the persistence of particular atmospheric circulations and resultant land-surface feedbacks. These aspects are beyond the scope of this study and will require further research with additional climate models (e.g. CMIP5). In addition, the surface results may be influenced by the choice of hydro-climatic indicator including the various methods for determining PET (which have been shown to impact the magnitude of future hydro-climatic projections in certain regions; Seiller and Anctil, 2016). Nonetheless, persistent dry, warm conditions projected by the CRCM-CCSM (Figures 7 and 8) are a future possibility that would negatively impact all study area communities.

In conclusion, this study has advanced understanding regarding the occurrence and atmospheric causes of hydro-climatic variability and extremes over specific watersheds and associated communities over the southern Canadian Prairies. It has also contributed to the VACEA project, which has used these results to compare past and future Canadian climate extremes to those in Argentina, Brazil, Chile, and Colombia and subsequently, to assess exposure, sensitivity, and adaptive capacity to these extremes in selected rural agricultural and indigenous communities (Sauchyn *et al.*, 2016). Historical variability and extremes have caused many challenges for adaptation including the effective management of water for various sectors and preparing for/coping with the impacts of drought and excessive moisture. The potential for increased variability and prolonged extremes will certainly increase this level of challenge without considerable improvements in capabilities.

Acknowledgements

The VACEA program is led by Drs D. Sauchyn and F. Santibañez. Funding for VACEA is provided by the International Research Initiative on Adaptation to Climate Change, which is managed by Canada's International Development Research Centre (IDRC) and funded jointly by IDRC and the Tri-Council, Canada's three main research granting bodies. The authors are grateful to Chelsea Greenwald and Chad Laughren for assistance with data preparation and presentation. We also thank the two anonymous reviewers for their useful comments towards an improved version of the manuscript.

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