Adaptation According to Mode of Climate Variability: A Case Study from Canada's Western Interior

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Abstract

Successful economies, and sustainable communities, are adapted to the historical mean state of the climate of the region and, to a large extent, to the historical interannual and seasonal variability, with which there is much experience. This adaptation involves familiar strategies, for example, irrigation, and the

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W. Leal Filho (ed.), *Handbook of Climate Change Adaptation*,
DOI 10.1007/978-3-642-38670-1_93

corresponding policies, programs, and best practices. There is less experience, however, and therefore fewer adaptation options, in dealing with decadal to multi-decadal modes of climate variability and with unprecedented climate extremes. This scale of variability and extreme events requires a different suite of adaptations that generally are not supported by existing policy and programming. This asymmetry in historical and planned adaptation is illustrated with a case study from Canada's western interior, which has a climate characterized by differences in temperature and precipitation between seasons and years that are among the largest on earth. This chapter examines the interannual to multi-decadal variability of the past millennium, extremes of the past 100 years, and projections of climate change. Municipalities and industry must recognize these multiple modes of variability as they pursue adaptation planning to minimize the impacts of climate change, including unprecedented drought and excess moisture.

Keywords
Western Canada • Climate change and variability • Asymmetric adaptation

Introduction

Communities and economies are vulnerable to the adverse effects of climate change. This vulnerability is a function of (1) exposure to climate hazards and their impacts and (2) social conditions that determine (a) sensitivity, the degree to which a system is affected by climate-related stimuli, and (b) adaptive capacity, the ability of a system to adjust to climate risks and opportunities by increasing its resilience or coping range (Smit and Johanna 2006). Adaptive capacity depends on access to financial, social, and natural resources and institutions, the management of current and past stresses, and the ability of institutions and individuals to learn from experience and to anticipate and plan for future change (Armitage 2005). When exposed to the impacts of climate change, the adaptive response will depend largely on the capacity of a community to deal with the impacts and risks. Thus, vulnerability is determined mostly by social factors, and exposure to climate change is often treated as given in the assessment of social vulnerability. These determinants of vulnerability to climate change are illustrated in Fig. 1. According to this common conceptual framework, the assessment of vulnerability to future climate conditions begins with an understanding of sensitivity and adaptation to past and current climate events and variability.

The box labeled "Future Climate Conditions" in Fig. 1 is a climate change scenario, "a plausible future climate that has been constructed for explicit use in investigating the potential consequences of anthropogenic climate change" (IPCC-TGCIA 2007). Climate change scenarios can be simple arbitrary adjustments to climate variables, or they can consist of climate data derived from other locations or times in the past (analogues), where/when the climate is/was similar to the future conditions anticipated at the current location. However, the most robust and precise

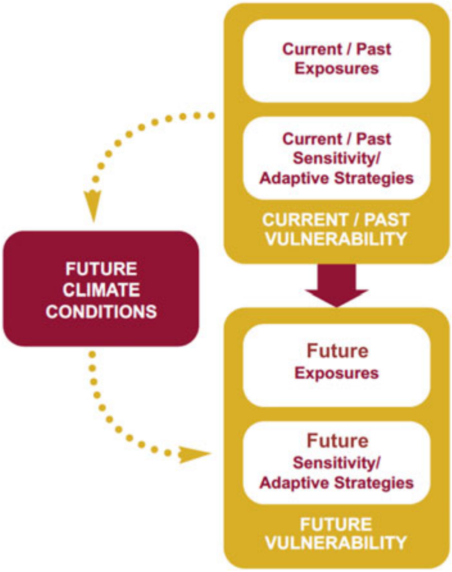


Fig. 1 The standard conceptual framework or vulnerability assessment model (After: Smit and Johanna,2006)

climate scenarios are derived from global climate models (GCM), "the only credible tools currently available for simulating the response of the global climate system to increasing greenhouse gas concentrations" (IPCC 2007). The conventional approach to deriving climate change scenarios from GCMs, recommended by the IPCC Task Group on Scenarios for Climate Impact Assessment (IPCC-TGCIA 1999, 2007), is illustrated in Fig. 2 using a time series of modeled mean annual temperatures from the Canadian Prairies. According to this standard method, a climate change scenario is the difference in average climate between past and future 30-year periods. This approach reflects a historical lack of confidence in the reliability of short-term (annual to decadal) climate projections. A 30-year mean is the equivalent of a climate normal; it masks the short-term variability and represents the most reliable output from climate models.

GCM projections are less reliable over shorter time frames and smaller spatial domains and for precipitation and other variables related to atmospheric circulation and dynamics. Regional aspects of climate change are controlled by atmospheric circulation patterns, such as the location of the jet stream, but unfortunately the model simulation of the dynamical response of the climate system to anthropogenic forcing is highly uncertain. Climate models simulate the thermodynamics of the climate system and thus temperature, snowmelt, sea ice extent, sea level rise, etc., with greater confidence and consistency. In many regions, however, the most challenging impacts of climate change are not trends in temperature-related variables but rather shifts in the distribution of water supplies and changes in the frequency and severity of extreme weather events (e.g., flooding and drought).

Researchers and practitioners have long recognized the more immediate and challenging impacts are climate extremes and variability, departures from mean

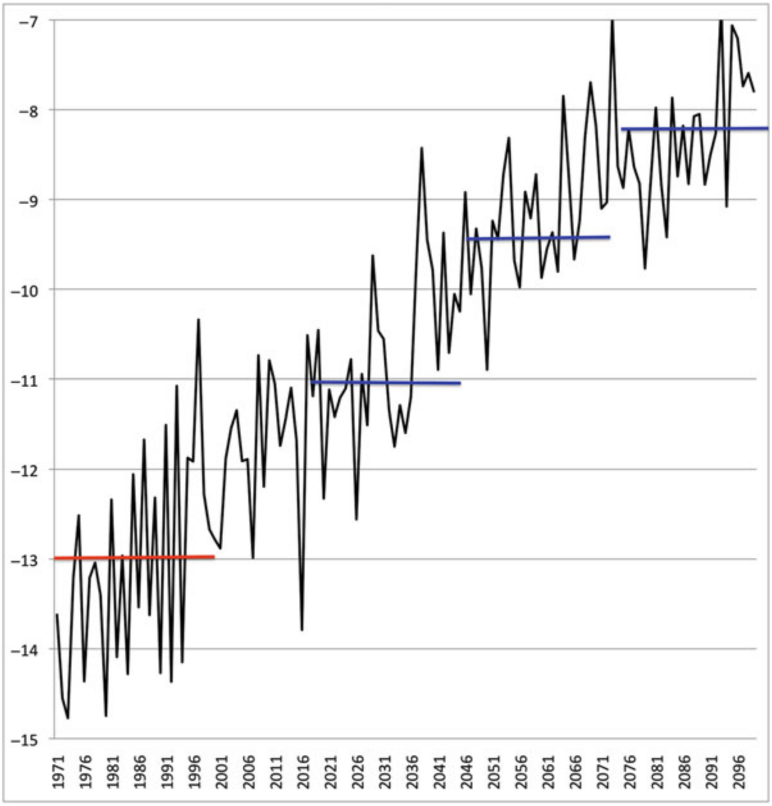


Fig. 2 Mean winter surface air temperature (° C) for the Canadian Prairies from the model CGCM3 (T47) using the SRES A1B greenhouse gas emission scenario. A climate change scenario is the difference (or ratio in the case of precipitation) between the mean value for the baseline period 1971–2000 (*red line*) and the 30-year mean values (*blue lines*) for 2010–2039 (the 2020s), 2040–2069 (the 2050s), and 2070–2099 (the 2080s)

conditions, whether natural (internal) variability or the consequences of global warming. This was clearly pointed out in the 1990s in papers such as “Extreme events in a changing climate: Variability is more important than averages” by Katz and Brown (1992) and “Relative impacts of human-induced climate change and natural climate variability” by Hulme et al. (1999). Much more recently, Deser et al. (2012) pointed out that future climate will be dominated by natural variability for the foreseeable future, and this limits the capacity of climate models to provide predictions of the response of climate regimes to anthropogenic forcing. They demonstrated for North America that natural climate variability “poses inherent limits to climate predictability and the related goal of adaptation guidance” although “other locations with low natural variability show a more predictable future in which anthropogenic forcing can be more readily identified.”

Figure 3 is another, more detailed, illustration of the use of climate and social scenarios for impact and adaption assessment and specifically for informing the formulation of policy. The distinction between “top-down” and “bottom-up” approaches has implications for relative roles of researchers from different disciplines and the stage at which local information is introduced. The top-down approach begins with scenarios of global climate and environmental response to anthropogenic forcing and global trends in socioeconomic variables that dictate emissions of greenhouse gases. These global scenarios are then downscaled and applied to the assessment of regional impacts and adaptation options. This approach is typical of multinational climate change assessment that informs international policy, notably the Intergovernmental Panel on Climate Change (IPCC) and the Kyoto Protocol, respectively. Typically, as shown in Fig. 3, stakeholders are engaged to frame regional or national socioeconomic scenarios and adaptation strategies. The strength, and weakness, of the top-down approach is that it relies on the expertise of natural and social scientists to frame the problems and thus chose the appropriate variables and sources of data.

As climate change scientists, the authors of this chapter are familiar and comfortable with a top-down approach, where information about past and future climate variations is generated and delivered largely outside the context of specific vulnerabilities of local communities. The climate change scenarios are projections of trends in those climate variables that are most readily analyzed with the most confidence and precision and that the scientists consider most relevant in terms of the regional climate regime. We have also been engaged, however, in multidisciplinary impacts and adaptation research projects that have taken a “bottom-up” approach to integrating climate science, structural institutional conditions and agency, and the perspectives of stakeholders and decision makers. For example, Diaz et al. (2009) applied the vulnerability framework in Fig. 1 to a multicollaborative study of institutional adaptation to climate change in northern Chile and western Canada. This work highlighted the central role of public institutions in developing adaptive capacity to climate change, but it also demonstrated significant gaps in knowledge and governance practices that lead to a deficit in adaptive capacity.

The bottom-up approach is well suited to the local and regional scales at which the impacts occur and adaptations are identified and implemented. The initial step in Fig. 3 of collecting baseline climate and environmental and socioeconomic data produces a profile of communities that include problems (vulnerabilities) and variables informed by knowledge of local conditions. The bottom-up approach thus combines the observation of local climate change and impacts, and adaptive capacity, with data on projected impacts derived from downscaled outputs from climate and environmental models and adaptation/socioeconomic scenarios. From the perspective of climate science, there is one major implication of the bottom-up approach. Because the relevance of climate variables depends on local conditions, including the perspectives and observations of local people, the most relevant climate risks and variables often are not those that can be analyzed and modeled with confidence and precision. The most serious and relevant climate risks often are understood with the least certainty.

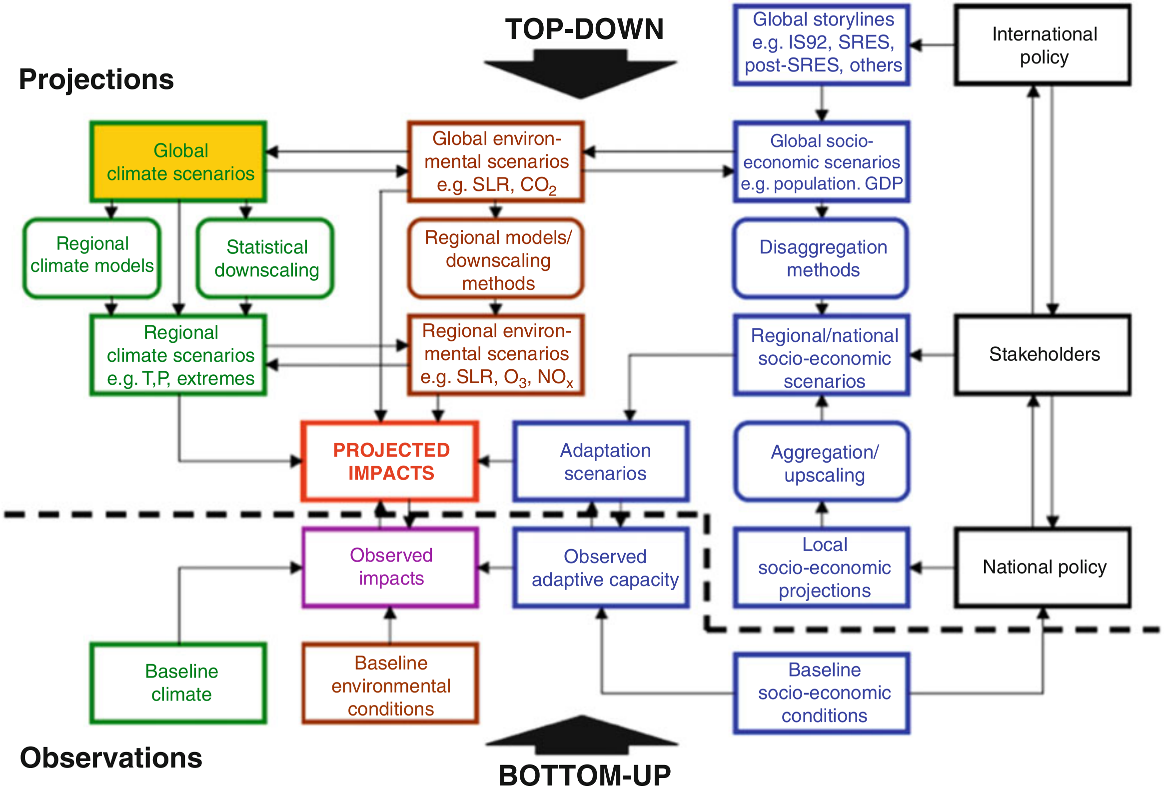


Fig. 3 The *top-down* and *bottom-up* approaches to informing climate change policy with climate and socioeconomic scenarios and related source of data. Information above the dashed is projections and output from models; below the line are observations and the results of data collection in the field (Source: IPCC-TGCIA (2007))

This brief overview of the use of climate change scenarios for the assessment of climate change vulnerability, impacts, and adaptation is an important context for this chapter that explores the disparity between these standard practices in research and application and our experience with the study and scientific support of planned adaptation to climate fluctuations over a range of frequencies or modes of variability. This chapter examines the adaptation strategies adopted by rural agricultural communities in the context of the climate variability of the past millennium, climate extremes of the past 100 years, and anticipated shifts in variability and extremes in a warming climate. We discuss the extent to which rural agricultural communities recognize multiple modes of climate variability and are engaged in adaptation planning to minimize the impacts of drought and excess moisture.

The Case Study: The Canadian Prairies

This chapter argues that the best adaptive adjustments to practices and policies are conditional on the mode of variability to which a community is exposed. Canada's western interior makes an ideal case study to present and demonstrate this argument. It is exposed to an extremely variable climate and some significant projected climate change impacts. Furthermore, the resource-based economy is sensitive to the impacts of climate change on ecological goods and services and particularly water. Among the regional resource industries, this chapter is focused on agriculture. More than 80 % of Canada's agricultural land is in the Prairie Provinces of Alberta, Saskatchewan, and Manitoba. The agriculture sector has an adaptive capacity that has been described as high, which is attributable in large part to a history of adaptation to climate risks.

While the frost-free growing season is relatively short and precipitation is low, ranging on average from 300 to 500 mm per year, the greater challenge for commercial agriculture is the climate variability from year to year. A good indication of the degree of this climate variability is the interannual variation (coefficient of variation) in the climate moisture index (CMI), a measure of the ratio of precipitation to atmospheric water demand (evapotranspiration). An analysis of a global dataset by the Water Systems Analysis Group at University of New Hampshire (wwdrii.sr.unh.edu) showed that the highest year-to-year fluctuations in CMI occur along the humid and dry transition between forest and grassland ecosystems. These areas are characterized by periodic, severe droughts and thus are vulnerable to water stress and/or scarcity. The most extensive regions of extremely variable hydroclimate are in north-central Asia and the northern Great Plains of North American and specifically the Canadian Prairies.

Despite these almost marginal climate conditions for commercial agriculture, a viable export industry has developed over the past 100 years. Annual crop yields in the Canadian Prairies are medium to high, relative to the global range (Foley et al. 2011), despite the northerly latitudes and dry and variable climate. This level of crop productivity extends to a latitude of almost 60°N in northern Alberta. The Canadian Prairies are anomalous; in no place else does commercial agriculture

Fig. 4 The landscape of southwestern Alberta in the vicinity of the village of Enchant. This entire landscape is an expression of adaptation to a dry climate. Center pivot irrigation is the dominant feature. An irrigation canal transects the image from the *upper left corner* to the *middle* of the *right edge*. Rain-fed "dryland" crop production is practiced in strips mostly perpendicular to the prevailing winds to prevent wind erosion and preserve moisture (melting snow) (Source: Google Earth)

succeed at a large scale in a continental climate at high latitudes. This agricultural productivity reflects adaptation to make most efficient use of these marginal climate resources. Adaptation of agricultural practices, policies, and structures to a dry cold continental climate is embedded in the history and landscape of the Canadian Prairies. A complete transformation of the native prairie ecosystems was achieved with the adaptation of farming practices imported originally from the more humid climates of Europe and eastern Canada. Figure 4 is satellite image of southwestern Alberta in the vicinity of the village of Enchant. The structures and land use patterns, mostly related to irrigation, reflect the use and management of water. Beyond the area in this image and throughout the Prairie Ecozone, thousands of reservoirs and "dugouts" and thousands of kilometers of shelterbelts (rows of trees and shrubs) are other adaptations to conserve water and soil.

The Euro-Canadian history of the Canadian Prairies is punctuated by the impacts of drought and the adaptations in response. Sensitivity to drought varies according to type, reliability, and accessibility to water supplies and their management. Snow and glacier melt in the Rocky Mountains is the source of water for irrigation in southern Alberta and parts of Saskatchewan and the water supply for most of the population in these two provinces. In terms of land area, however, most prairie agriculture is dryland farming dependent on precipitation and local runoff. These climatic and hydrographic circumstances dictate the exposure of rural communities and economies to climate risk and the relevance of hydroclimatic factors and variables for an assessment of impacts and adaptation. Because climate fluctuates at various scales from seasonal to decadal to longer-term trends, adaptation to mitigate the impacts of climate variability and change requires an understanding of the risks posed by different modes of climate variability in terms of their likelihood and consequences. These scales or modes of variability are not arbitrary or statistically convenient intervals; there are distinct periodicities corresponding to certain external and internal causes of climate variability. At high frequencies, climate varies between seasons and years. Lower-frequency variability is not as well defined, or understood, but there are dominant modes at decadal and multi-decadal scales. Interannual to multi-decadal cycles have been linked to internal behavior of the climate system and specifically to organized interaction between the oceans and atmosphere (e.g., El Niño Southern Oscillation, ENSO, and the Pacific Decadal Oscillation, PDO) and associated teleconnections to regional climate regimes (Bonsal et al. 2001; Lapp et al. 2013). Longer-term climate trends are related to slow changes in the external controls on climate (i.e., radiative forcing) and centennial-scale shifts in climate that are detectable only in paleoclimate records. This entire range of climate variability has been observed in our study area, Canada's western interior.

The Historical Record of Seasonal to Interannual Variability and Trends

Climate Variables

Annual and seasonal means of temperature and precipitation, derived from instrumental weather data, define the "normals" for a regional climate regime. In terms of climate risks, however, the most relevant variables are those that impose constraints and threaten productivity and livelihoods. Table 1 is a list of these most relevant agroclimatic variables and indices of climate extremes for the rural communities and agricultural economy of the Canadian Prairies. In a recent analysis of trends in some of these variables, Qian et al. (2012) found that the growing season has lengthened, frost-free days have increased, cold stress has decreased, and heat units are greater than in earlier decades. For example, growing season length has increased about 16–20 days across the southern prairies from 1911–1940 to 1971–2000. Changes in water deficit in the growing season were not statistically significant, and only a few stations had a significant difference in the variances of agroclimatic variables. They concluded that adaptation should include the use of new crop varieties that can benefit from longer and warmer growing season, while withstanding increased risks of heat damage.

Data for the analysis of the climate indices in Table 1 are available from the National Land and Water Information Services (NLWIS) in the form of a daily 10 km gridded climate dataset (1950–2010) for the Canadian landmass south of 60°N. These data were interpolated from the 7,514 climate stations in the Canadian Climate Data Archives (Hutchinson et al. 2009). We used the rank-based

Table 1 The most relevant climate indices for rural communities and the agricultural economy of the Canadian Prairies

Variable	Description	Units
Tmax >= threshold temperature	Annual count when the daily maximum temperature >= chosen threshold temperature, e.g., 25 °C	Days
Tmax <= threshold temperature	Annual count when the daily maximum temperature <= chosen threshold temperature, e.g., 2 °C	Days
Tmin >= threshold temperature	Annual count when the daily minimum temperature >= chosen threshold temperature, e.g., 5 °C	Days
Tmin <= threshold temperature	Annual count when the daily minimum temperature <= chosen threshold temperature, e.g., 0 °C	Days
Frost days	Annual count when daily minimum temperature < 0 °C	Days
Growing season length	Annual count between first span of at least 6 days with Tmean >5 °C and first span after July of 6 days with Tmean < 5 °C	Days
Heat wave days	Count of days in a year that are 5 °C higher than during the 1961–1990 period	Days
Ice days	Annual count when daily maximum temperature <0 °C	Days
Max Tmax	Monthly maximum value of daily maximum temp	°C
Max Tmin	Monthly maximum value of daily minimum temp	°C
Min Tmax	Monthly minimum value of daily maximum temp	°C
Min Tmin	Monthly minimum value of daily minimum temp	°C
Cool nights	Percentage of days when TN < 10th percentile	%
Cool days	Percentage of days when TX < 10th percentile	%
Warm nights	Percentage of days when TN > 90th percentile	%
Warm days	Percentage of days when TX > 90th percentile	%
Consecutive dry days	Maximum number of consecutive days with RR < 1 mm	Days
Accumulated precipitation over 5 days	Annual maximum sum of 5-day precipitation	Mm
Simple precipitation intensity index	Annual fraction of annual precipitation sum divided by the number of precipitation days > 1 mm	Mm
Very wet years	Annual total precipitation when above the 1961–1990 period 95th percentile	Years
Annual precipitation	Annual sums of daily precipitation	mm
Warm spell duration indicator	Annual count of days with at least six consecutive days when TX > 90th percentile	Days
Cold spell duration indicator	Annual count of days with at least six consecutive days when TN < 10th percentile	Days
Diurnal temperature range	Monthly mean difference between TX and TN	°C
Max 1-day precipitation amount	Monthly maximum 1-day precipitation	mm
Max 5-day precipitation amount	Monthly maximum consecutive 5-day precipitation	mm
Simple daily intensity index	Annual total precipitation divided by the number of wet days (defined as precipitation >= 1.0 mm) in the year	mm/ day

(*continued*)

Table 1 (continued)

Variable	Description	Units
Number of heavy precipitation days	Annual count of days when daily precipitation >= 10 mm	Days
Number of very heavy precipitation days	Annual count of days when daily precipitation >= 20 mm	Days
Number of days above nn mm	Annual count of days when daily precipitation >= nn mm, nn is user defined threshold	Days
Consecutive wet days	Maximum number of consecutive days with precipitation >= 1 mm	mm
Very wet days	Annual total PRCP when RR > 95th percentile	mm
Extremely wet days	Annual total PRCP when RR > 99th percentile	mm
Annual total wet-day precipitation	Annual total PRCP in wet days (RR >= 1 mm)	mm
Growing degree days >= 0 °C	Annual sum of daily temperatures >= 0 °C	°C
Growing degree days >= 5 °C	Annual sum of daily temperatures >= 5 °C	°C
Growing degree days >=10 °C	Annual sum of daily temperatures >=10 °C	°C
Beginning day of growing season	First day of span of at least 6 days with Tmean >5 °C	°C
End day of growing season	Last day of span of at least 6 days with Tmean <5 °C	°C

Table 2 Trends of selected climate indices for some selected locations in the Canadian prairies (confidence level in brackets)

Location	Annual frost days (days)	Growing season (days)	Heat wave duration index (days)	Annual precipitation (mm)	Growing degree days over 5 °C (°C)
Pincher Creek	−24 (99 %)	+17 (80 %)	+13 (90 %)	−58 (<80 %)	+126 (90 %)
Lethbridge	−9 (90 %)	+21 (95 %)	+19 (99 %)	−76 (90 %)	+132 (95 %)
Taber	−12 (95 %)	+33 (99 %)	+19 (95 %)	−10 (<80 %)	+183 (99 %)
Swift Current Creek	−17 (99 %)	+9 (<80 %)	+12 (90 %)	+2 (<80 %)	+136 (90 %)

nonparametric Mann–Kendall statistical test to analyze the significance of trends in these hydrometeorological time series. Table 2 lists trends in selected climate indices for some selected locations in the Canadian Prairies.

It is evident from this trend analysis that climate change has already impacted prairie agro-hydrological conditions in terms of fewer frost days, a longer growing season, more heat waves, a decline in precipitation in Alberta, and an increase in growing degree days over 5 °C. Figure 5 shows the interannual variation around a

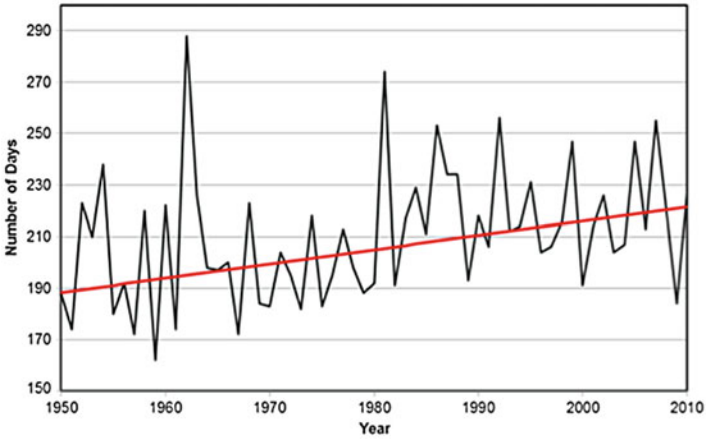


Fig. 5 Time series of the length of the annual growing season and nonparametric trend line for Taber, Alberta. There is considerable interannual variation

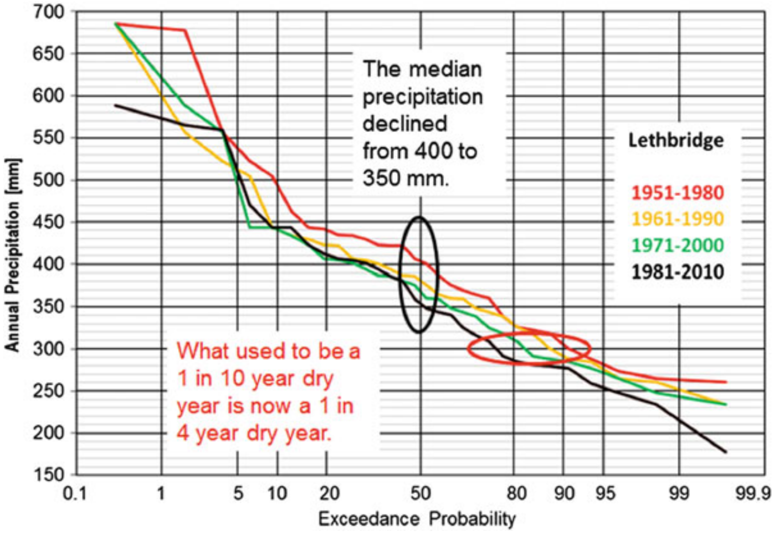


Fig. 6 The exceedence probabilities of four climate normal periods reveal a trend in median annual precipitation at Lethbridge, Alberta. It has declined from 400 mm per year in the period 1951–1980 to a median of 350 mm per year in the period 1981–2010. There is also an increased risk of having a low precipitation year. The probability of 300 mm or less of annual precipitation has increased from once every 10 years in the period 1951–1980 to more than once in 4 years in the 1981–2010 period. This has effects on the sustainability of rain-fed agriculture

trend of increasing growing season length for the town of Taber, Alberta. Figure 6 shows how precipitation normals have changed at Lethbridge, Alberta.

Several indices (usually specific to certain types of drought) have been devised to quantify moisture variability and, subsequently, assess the occurrence of drought

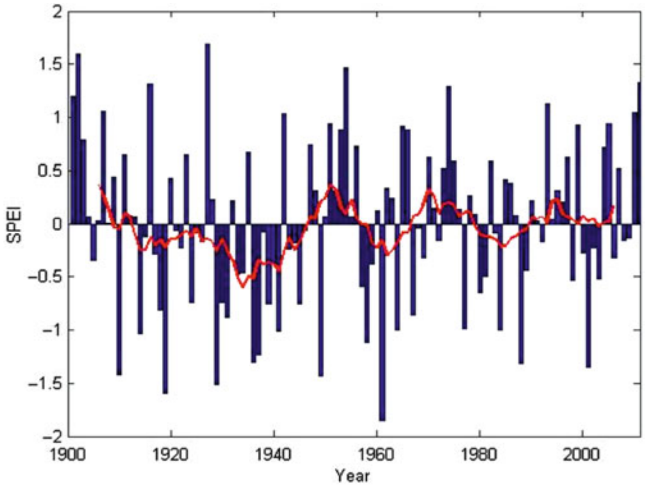


Fig. 7 Areally averaged, agricultural year (September to August) SPEI values over the southern Canadian Prairies (49°N–54°N, 115°W–100°W) for the period 1900–2011. The *red line* denotes the 11-year running mean

and excessive moisture patterns over various regions of the globe including the Canadian Prairies (see Bonsal et al. (2011) for a comprehensive review). A recently developed index, namely, the Standardized Precipitation Evapotranspiration Index (SPEI) (Vicente-Serrano et al. 2010), has been gaining popularity in the literature since it incorporates both precipitation and temperature in its calculation and can be computed for any region of the world at multiple time scales. Figure 7 shows areally averaged, agricultural year (September to August) SPEI values over the southern Canadian Prairie Provinces for the period 1900–2011. Note that negative values represent drier conditions, while positive SPEI correspond to wetter than normal periods. The time series reveals considerable interannual and inter-decadal fluctuations with no discernible long-term trend. Major large-scale droughts occurred during the late 1910s, most of the 1930s and early 1940s, 1958–1961 (with 1961 being the driest year on record), most of the 1980s, and the early 2000s. Conversely, excessive moisture conditions were observed during the early 1900s, much of the 1950s, the 1970s, the late 1990s, and most recently in 2010–2011. Figure 7 reemphasizes the high degree of natural variability in prairie moisture conditions during the instrumental period of record.

Hydrologic Variables

For a region of high natural hydroclimatic variability, such as the Canadian Prairies, it is reasonable to ask if global warming trends can be detected in relatively short instrumental records. Given the economic, environmental, and historical significance of water and the impacts of periodic drought, water levels gauges were

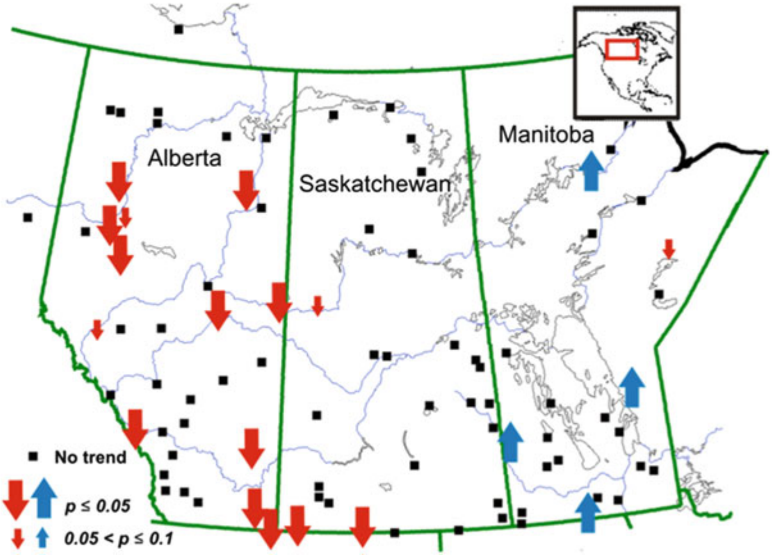


Fig. 8 Geographic pattern of trends in 86 naturally flowing mean-daily streamflow records from the Canadian Prairie Provinces as assessed by a modified Mann–Kendall test. A *red down* (*blue up*) *arrow* denotes a decreasing (increasing) trend; a *black square* denotes no trend

installed at many locations beginning in the early twentieth century. St. Jacques et al. (in press) performed a modified Mann–Kendal trend analysis on 86 naturally flowing streams with active gauges drawn from across the three Prairie Provinces (Fig. 8). The results show a distinct geographic pattern with streamflow generally decreasing in Alberta, some gauges recording increasing flow in Manitoba and few trends in Saskatchewan. The eastern Prairies are responding differently to climate change than the west, with increasing streamflows in Manitoba. These increasing flows have also been detected in neighboring North Dakota.

Further analysis of mean annual streamflow in Alberta for 102 watersheds reveals that 60 time series have negative trends; 14 watersheds had a negative streamflow of over 1 % per year, which means that after 10 years, over 10 % less streamflow would be available if these trends were to continue. The detection of a statistically significant trend does not necessarily imply a trend of practical significance and vice versa. For example, a statistically significant negative trend of 0.1 % per year may be negligible for the water users, while a negative trend of 2 % per year may be of low statistical significance (e.g., 80 % confidence level), given the length of the record and variability around the trend, but have large practical implications within 10 or 20 years. Therefore, the magnitudes of possible streamflow trends need to be reported.

Figure 9 is an example of declining mountain streamflow. The annual hydrograph of the Bow River at Banff, Alberta, has a declining trend (red line). It also exhibits high interannual variability, related to ENSO, and decadal shifts between periods of higher and lower flow, related to the PDO. Runoff from the

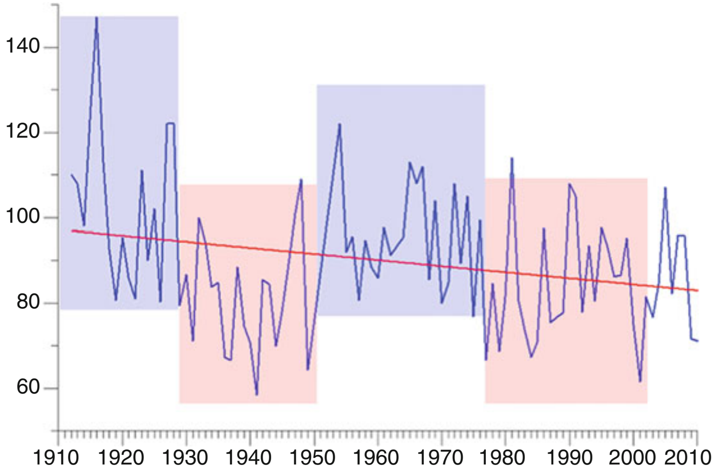


Fig. 9 Mean annual flow (m^3/s) of the Bow River at Banff, Alberta, 1911–2010. The *red line* represents a trend of decreasing annual flow. The *shaded rectangles* represent periods of higher (*blue*) and lower (*red*) flow related to the phase of the PDO

Rocky Mountains is mostly from melting snow. Winter precipitation in western Canada is higher when the PDO is in a negative phase (1890–1924, 1947–1976) and lower when the PDO is in a positive phase (1925–1946, 1977–2008) (Mantua et al. 1997). Streamflow records that span 1½–2 cycles of the PDO, such as the annual time series for the Bow River in Fig. 9, are likely to have declining trends that are the effect of climate change rather than an artifact of multi-decadal periodicity in flow (St. Jacques et al. 2010).

Paleo-Record of Interannual to Multi-decadal Variability

The trends and variability in recorded climate and hydrology documented above (Table 2, Figs. 5, 6, 7, 8, and 9) have important implications for agricultural production and the supply and management of water. This analysis revealed, however, that the detection and interpretation of trends are complicated by the large degree of interannual and decadal variability, including the ~60 year PDO cycle. Paleoclimatic time series provide a longer-term historical context for the interpretation of instrumental data and climate model projections. Tree rings from the subhumid margins of semiarid environments, such as the Canadian Prairies, are especially good proxies of the water budget and measured variables such as precipitation and streamflow (Sauchyn et al., 2011). Using standardized tree-ring width data, the water year (Oct–Sep) flow of the Bow River at Banff was reconstructed from 1107 to 2007 (Fig. 10). The tree-ring data explain about 40–50 % of the variance in the gauge record back to about1650, and then the R^2 declines to about 30 %. Most of the unexplained variance is the underestimation of

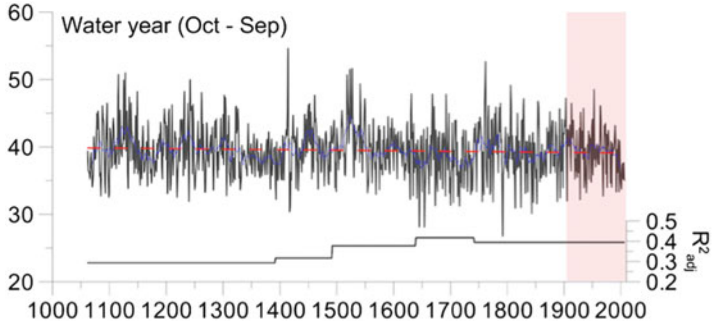


Fig. 10 Water year (Oct–Sep) flow of the Bow River at Banff from 1107–2007 as reconstructed from tree rings. The *pink* portion is the period of instrumental observation used for the calibration of the tree-ring width data. The *dashed red line* is at the level of the mean flow (m^3/sec) for the full reconstruction

high flows, while, on the other hand, tree rings are a good proxy of low flow and drought. The proxy streamflow time series in Fig. 10 indicates that the period of instrumental observation (1911–2007, highlighted with pink shading) is not fully representative of the long-term hydrologic regime. Although 1929–1941, the 1980s and early 2000s stand out as periods of frequent low annual flows, there is a larger range of annual flow prior to the onset of Euro-Canadian settlement and the direct observation of weather and climate. These pre-instrumental low flow periods include the prolonged drought of the mid-nineteenth century when John Palliser declared a large part of the Canadian Prairies “forever comparatively useless” and the extreme low flow of 1796 when to the north at Fort Edmonton furs could not be moved by canoe, “there being no water in the [North Saskatchewan] river” (2003).

The Bow River streamflow reconstruction displays considerable variability around the mean flow depicted with the red dashed line. A spectral (wavelet) analysis reveals that there are two dominant scales of variability in the long-term proxy records of calendar year (Fig. 11a) and water year (Fig. 11b) flow. There is intermittent strong spectral power in the range of 4–12 years, very likely in response to the El Niño Southern Oscillation (ENSO) and also possibly the influence of the 11-year solar cycles of the regional hydroclimate. There also is strong intermittent variability around 60 years, that is, the low frequency of the PDO.

Future Exposure

Ensemble Streamflow Projections

With concern about future flows of the large rivers arising from the Rocky Mountains, there have been various attempts to apply climate model output to projecting future flows. One approach is statistical downscaling: for example,

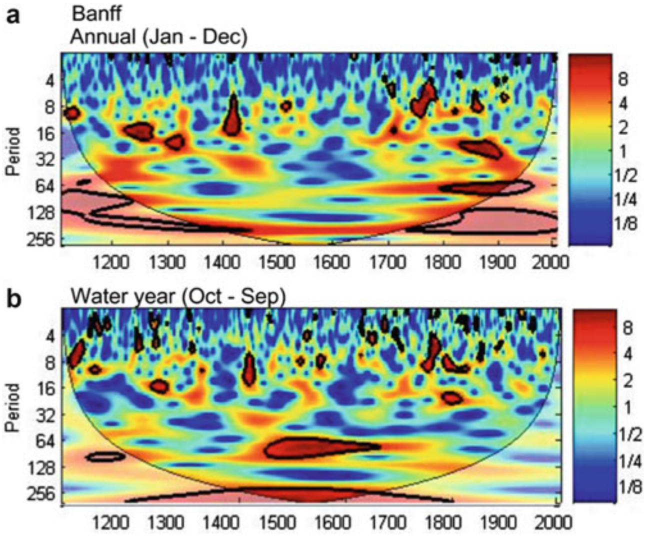


Fig. 11 Wavelet plots derived from the spectral analysis of the Bow River reconstruction: (a) calendar year (Jan–Dec); (b) water year (Oct–Sep). Strong modes of variability are depicted in *red*

streamflow in the South Saskatchewan River Basin can be modeled as a function of the ocean–atmosphere oscillations (St. Jacques et al. 2010) that drive the natural variability of the regional hydroclimatic regime. St. Jacques et al. (2013) drove generalized least squares (GLS) regression models of annual streamflow, using output from an ensemble of 50 runs of ten GCMs from the Phase 3 of the Coupled Model Intercomparison Project (CMIP3) to produce projected streamflows for the twenty-first century. They chose these ten GCMs because they adequately modeled the atmosphere–ocean climate oscillations that affect southern Alberta, i.e., the PDO, ENSO, and Arctic Oscillation. Shown in Fig. 12 are (a) projected flows for the South Saskatchewan River at Medicine Hat and (b) empirical cumulative frequency distributions for three selected years. If business as usual water usage and anthropogenic climate change continue, flows will continue to decline. The curves in Fig. 12b also suggest an increasing probability of extreme low flows.

An alternative approach to projecting future streamflows is the use of physically based hydrologic models with GCM-derived temperature and precipitation as predictors. This method has been applied to the South Saskatchewan River Basin (e.g., Lapp et al. 2009; Shepherd et al. 2010; Larson et al. 2011; MacDonald et al. 2011; Tanzeeba and Gan 2012), and all models projected declining surface water availability for the region. Given that two different methods (statistical versus dynamical) are projecting lower flows in the South Saskatchewan River Basin, there is reason for concern about future surface water supplies in this region where surface water is already over-allocated in some tributaries.

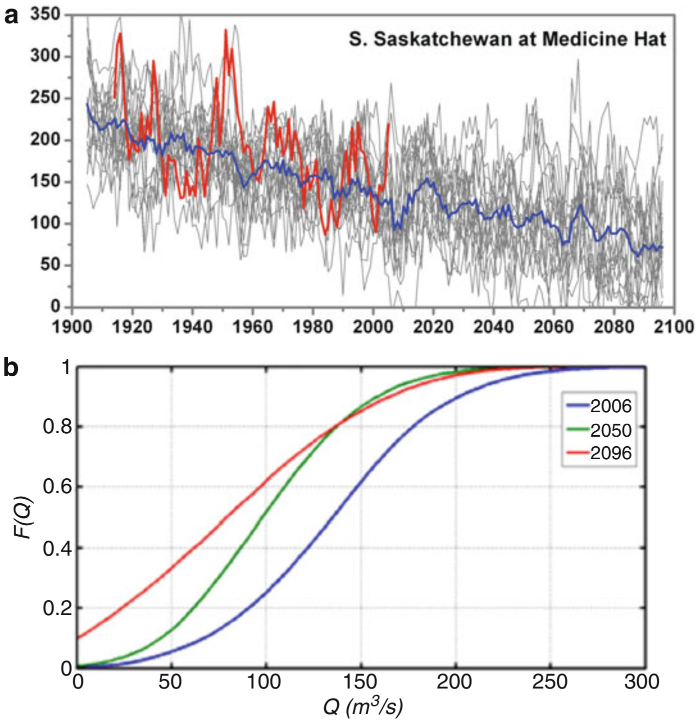


Fig. 12 (**a**) South Saskatchewan River twentieth-century simulations (1900–2005) and twenty-first-century projections (2006–2096 daily mean flows (m^3/s), averaged over the year, smoothed by five-point binomial filters) under the SRES B1, A1B, and A2 emission scenarios. The *red line* is the observed record, the *grey lines* are the individual model runs, and the *blue line* is the all-model mean of the GCM runs. (**b**) Empirical cumulative frequency distributions of projected lightly smoothed (5-year binomial smoother) annual discharges for the South Saskatchewan River

Climate Projections

An assessment of the vulnerability of the Canadian Prairies to climate change is not complete without scenarios of the projected changes in the regional climate as a consequence of anthropogenic global warming. For the purpose of this chapter, climate change scenarios were derived from four global climate models (GCMs) and two higher-resolution regional climate models (RCMs). These models are identified in Table 3. Output from these model runs was obtained from Canadian Climate Change Scenario Network (CCCSN), which is the Canadian repository for climate model output.

The modeling of twenty-first-century climate is based on scenarios of future greenhouse gas (GHG) emissions. For the Fourth IPCC Assessment Report (AR4), the climate model projections were based on the SRES (Special Report on Emission Scenarios) GHG scenarios, labeled B2, A1B, and A2 (Table 3). The "best case" B1 scenario is optimistic and highly unlikely to transpire given recent and historic

Table 3 List of chosen climate models

Model	Country	Resolution	# Twenty-first-century runs			PDO correlation
			B1	**A1B**	**A2**	
CGCM3.1(T63)	Canada	2.8° × 2.8°	1	1	0	0.82
ECHAM5/MPI-OM	Germany	1.875° × 1.865°	2	2	1	0.82
MRI-CGCM2.3.3	Japan	2.8° × 2.8°	5	5	5	0.83
NCAR-PCM	USA	2.8° × 2.8°	2	2	2	0.84
CRCM4.2.3	Canada	0.44° × 0.44°	0	0	1	NA
PRECIS1.8.2	UK	0.44° × 0.44°	0	1	0	NA

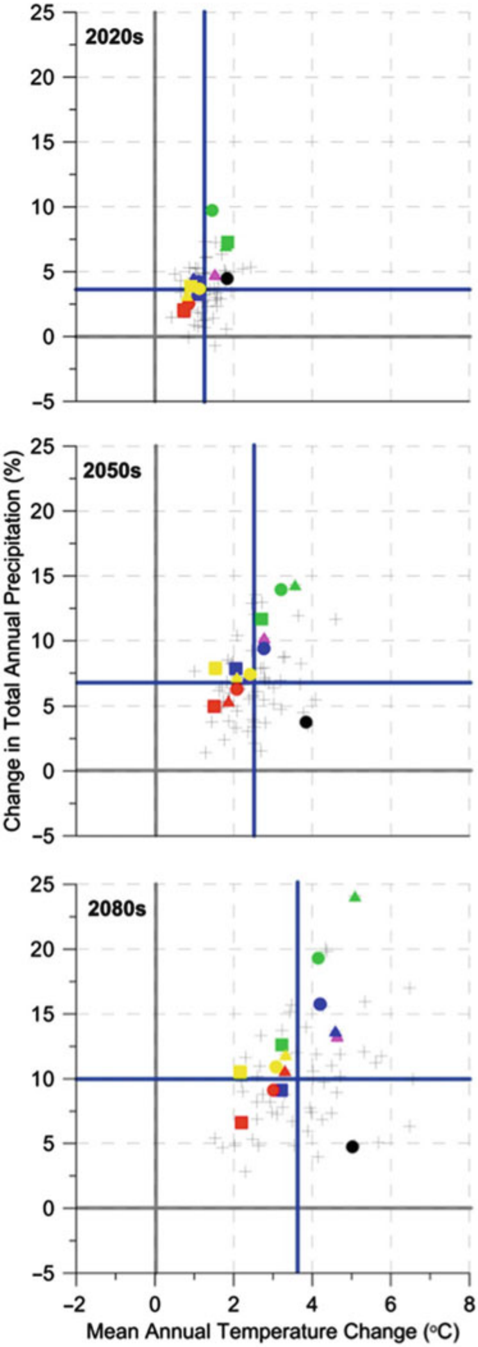
GHG emissions and the failure of national governments to achieve a global agreement for the mitigation of climate change. Emission scenario A1B represents the “most likely” future anthropogenic climate forcing; it assumes a mix of technological developments with some use of fossil fuels. SRES A2, the “worst case” or “business as usual” scenario, characterizes a future where socioeconomic trends carry on as at present.

The CCCSN provides output for 65 IPCC-AR4 GCM experiments and for seven runs of RCMs. Reducing this large array of model output to a manageable subset of plausible climate change scenarios, was based on two criteria: (1) projections that span the full range of simulated climate and (2) models that are able to reasonably simulate the ENSO and PDO, since these sea surface temperature oscillations account for much of the interannual to decadal variability in the climate of western Canada. The three scatter plots in Fig. 13 provide a summary of projected changes in mean annual temperature and total annual precipitation, relative to the climate of the baseline period 1971–2000, for the three future time periods 2020s (2011–2040), 2050s (2041–2070), and 2080s (2071–2100). Data from the 65 GCM and seven RCM experiments are plotted. The solid blue lines show the median projected increases in temperature and precipitation. As the twenty-first-century advances, the projected changes increase in magnitude, precipitation by 15–20 % and temperature by 5 °C. The range of values, the departures from the median, also increase reflecting increasing uncertainty in future concentrations of atmospheric greenhouse gases and in the response of the climate system to these higher levels of GHGs.

Figure 13 highlights the 14 chosen experiments: four GCMs by three emission scenarios, plus two RCM runs using single emission scenarios. The output from the selected experiments spans the range of future climates projected by the full set of IPCC-AR4 and RCM model runs.

Whereas this use of scatterplots to display and select output from climate models is common, the second method and criterion applied here is not common but considered necessary given the large degree and impact of internal climate variability in western Canada. Table 3 indicates that for the chosen GCMs, there is a high correlation between modeled and observed characteristics of the ENSO and PDO. These correlations are from Lapp et al. 2011, who evaluated the full set of

Fig. 13 A scatter plot of change in total annual precipitation (%) versus change in mean annual temperature (°C) from 1971 to 2000 for three future time periods, 2020s, 2050s, and 2080s, as projected by 65 GCMs and seven RCM experiments. The subset of 14 experiments chosen for further analysis is represented with colored symbols: *Green*, CGCM3.1(T63); *Blue*, ECHAM5-OM; *Red*, MRI-CGCM2.3.2a; *Yellow*, NCAR-PCM; *Magenta*, CRCM4.2.3; *Black*, PRECIS1.8.2; SRES GHG emission scenarios: ■ – B1; ● – A1B; ▲ – A2



IPCC-AR4 GCMs in terms of their capacity to simulate the spatial and spectral patterns of the ENSO and PDO. Since the spatial domain of RCMs is limited to a subcontinent and does extend to the oceans, this type of analysis is not applicable.

Whereas the colored symbols in Fig. 13 give the projected changes in annual temperature and precipitation averaged over the Canadian Prairies, the climate model output is available for thousands of point locations on a coarse grid for the GCMs and a much finer grid for the RCMs (the resolutions are given in Table 3). Therefore, the projections for each combination of climate variable, future time period, GCM, RCM, and GHG scenario can be mapped. As an example, Figs. 14 and 15 contain maps of projected total annual precipitation and mean annual temperature for the 2050s, relative to the 1971–2000 baselines, and for the three SRES GHG emission scenarios. While there are discrepancies among models, most of them project reduced precipitation in the western and southern prairies and increased precipitation toward the east and north. The temperature projections are much more consistent with a gradient from smaller to larger increases in temperature from southwest to northeast.

Implications for Adaptation Policies and Practices

Historically prairie agriculture has been sustained through the adjustment of land use and management systems to climatic variability (e.g., drought, early frosts, storms) and to take maximum advantage of soil and water resources. The process of adaptation has occurred episodically in response to periodic water scarcity and to changing markets, technology, and transportation systems. Adjustments have included major changes in farming practices and a significant degree of rural depopulation with the abandonment and consolidation of farms. Given a relatively high adaptive capacity and the historical adaptation that established and sustained commercial agriculture in this dry cold climate, the rural economy and communities could withstand much of the anticipated future change in mean climate.

If the degree of anthropogenic climate change exceeds the historical experience, further adaptation will be required. Adaptation in response to changes in mean temperature and precipitation is a familiar process; prairie agriculture became established by adapting crop and livestock production to a cold climate and low annual precipitation (less than 330 mm over a large area). These adaptations included the development of frost- and drought-tolerant crops or cultivars, adjusting the timing of seeding and harvest and, where water supplies permit, irrigation. Agriculture, and irrigation in particular, accounts for more than 70 % of the consumptive use of surface water (Coote and Gregorich 2000). An expansion of irrigated land is often cited as an effective adaptation to the increased summer aridity anticipated under global warming.

The preceding climate model projections suggest that the future climate of the Canadian Prairies will be warmer and even wetter, but the currently warmest and driest areas will be warmer and drier and currently cooler and wetter areas will be warmer and wetter. The best case scenario for this region, where crop, pasture, and

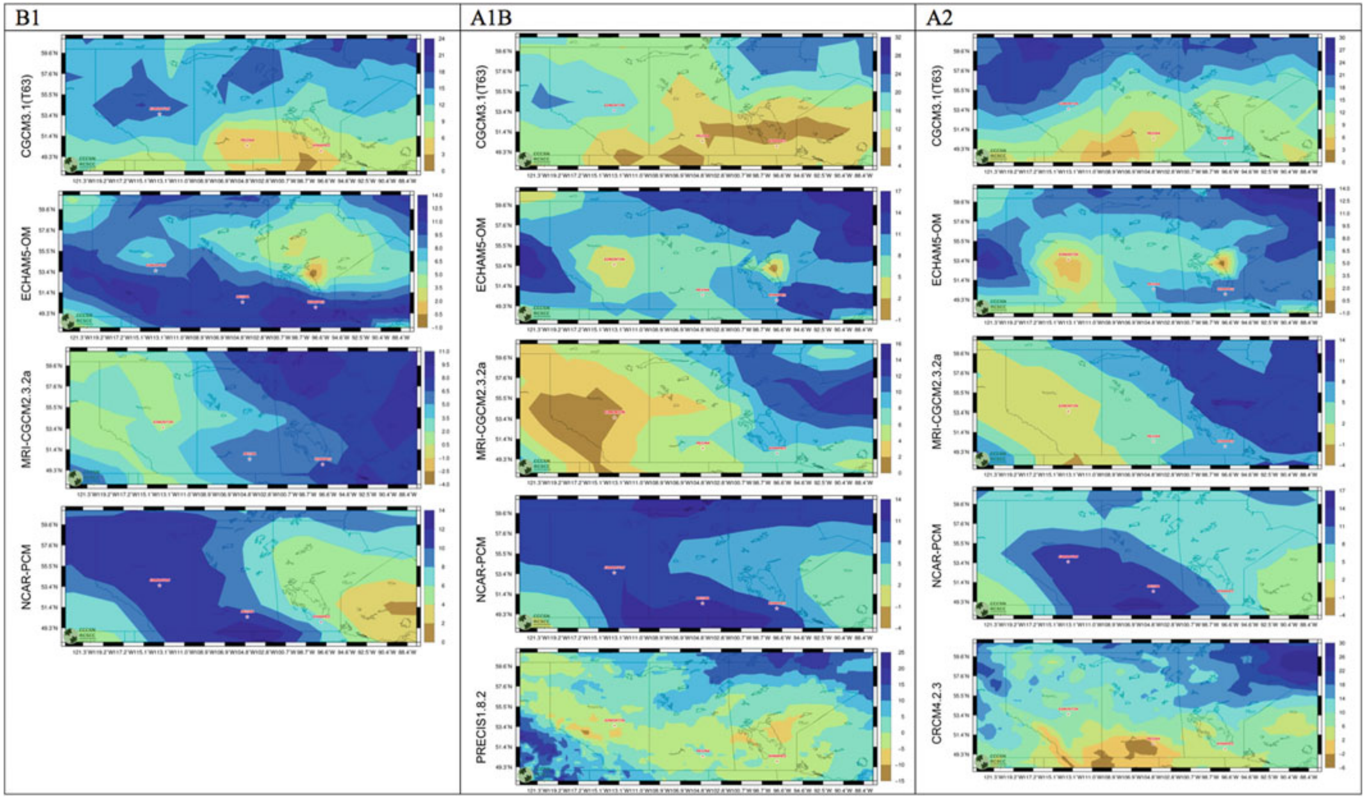


Fig. 14 Projected changes in mean total precipitation for the 2050s (relative to 1971–2000). The climate models and SRES emissions scenarios are identified across the top and along left margin of each map

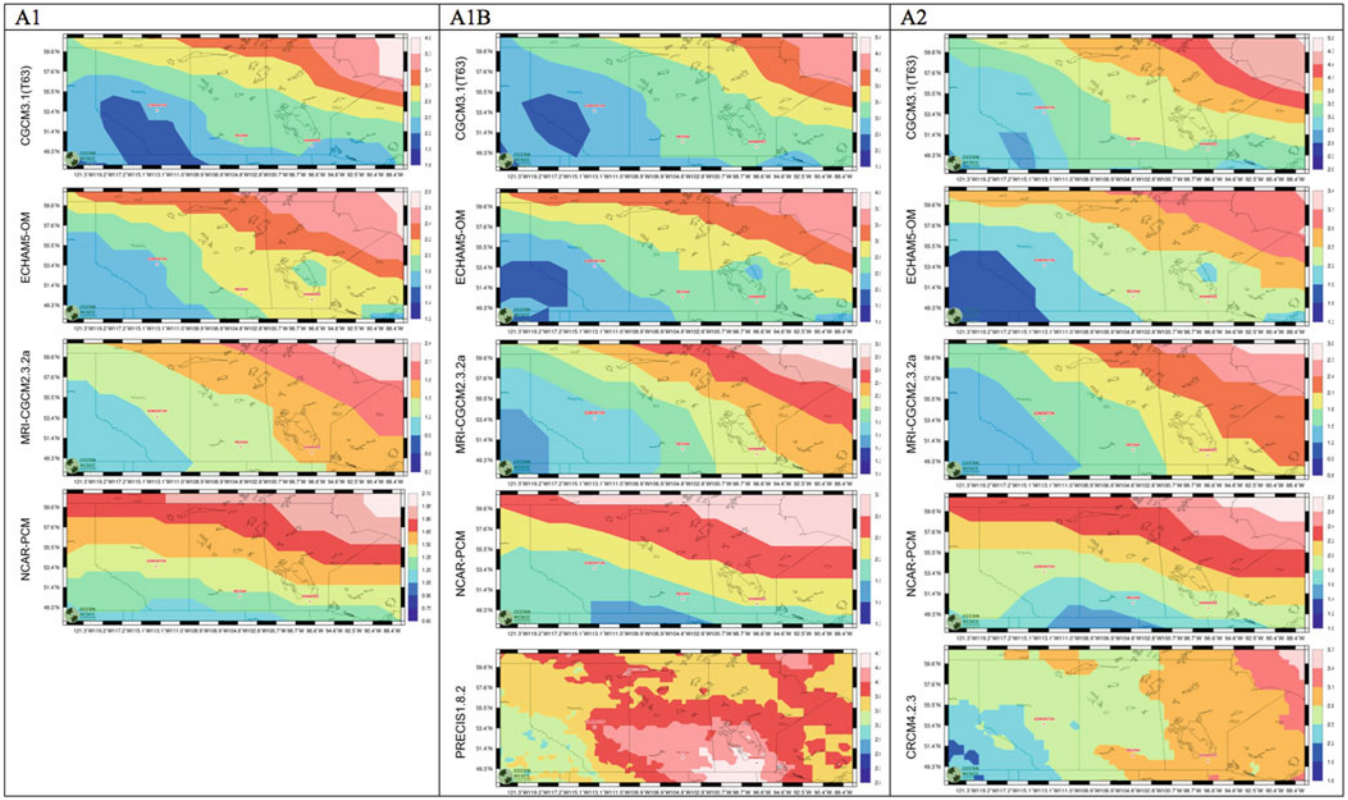


Fig. 15 Projected changes in mean annual temperatures for the 2050s (relative to 1971–2000). The climate models and SRES emissions scenarios are identified across the top and along left margin of each map

forest productivity is limited by the length of the frost-free growing season, is projections of enhanced precipitation with moderate increases in temperature and water loss by evapotranspiration. Higher productivity would result from the longer growing season, higher temperatures and concentrations of CO_2, elevated water use efficiency, and accelerated growth and maturation of crops before peak summer aridity. Higher temperatures will result, however, in potentially higher rates of evapotranspiration and, for more hours per year, cause water loss that exceeds any marginal increase in precipitation. A warmer growing season is also a more favorable environment for exotic pests, weeds, and disease vectors. These problems have technological solutions, although these technologies may be costly relative to agricultural revenues from extensive farming.

Whereas changes in average conditions can be addressed with familiar strategies, the more challenging circumstances are insufficient soil and surface water either seasonally to annually (drought) or in the longer-term (aridity) if certain thresholds are exceeded. The most severe recent drought in western Canada was during the period 1999–2003. Throughout western Saskatchewan and central and northern Alberta, most climate stations recorded the least precipitation for any single year in 2001 and for any three-year period during 2001–2003. As the impacts of drought in 2001–2002 rippled through the economies of Alberta and Saskatchewan, the loss in gross domestic product (GDP) was about $4.5 billion (Wheaton et al. 2008). A media survey by Wittrock and Wheaton (2007) showed that the most common adaptive responses were related to crops, livestock, and then water and economics. Spring and late summer were peak times for the discussion of adaptation. Innovative adaptations included water sharing agreements and modification of farming equipment. Even with considerable adaptation, negative impacts of this drought were considerable, and adaptations were costly (Wheaton et al. 2008). This suggests that some thresholds for adaptation capacity may have been exceeded for this drought. Yet the paleoclimate record, including the tree-ring reconstruction in this chapter, indicates that the worst droughts withstood by the modern economies and communities were of short duration compared to prolonged dry periods recorded by the tree rings. The greatest climate risk to the Canadian Prairies is the recurrence of drought of longer duration and/or severity than has occurred since Euro-Canadian settlement of the region.

As drought persists, soil and surface water deficits grow with increasingly serious consequences. Thus, duration is probably the key determinant of drought impacts. Nemanishen (1998) described the challenge of "Coping with Consecutive-Year Droughts":

> Modern farming technologies and practices now enable farmers to cope with single-year droughts. Most of the light lands in the drought prone areas are now either community pastures or seeded to permanent cover. Yet even with modern technologies, the current wheatlands are not able to yield sufficient returns to justify cropping in the second drought year. During the consecutive-year droughts, the precipitation deficit accumulates and leads to the depletion of the soil moisture in the root zone to a depth of a metre or more. . . . There is no technology, apart from irrigation, which can sustain either cereal grain or hay production during extended drought periods in the Palliser Triangle.

Even irrigation is ineffective under conditions of prolonged hydrological drought. Groundwater is an alternative to surface water as, in other parts of the world, it is the major source of irrigation water. However, shallow aquifers are sensitive to climate change and variability. Deeper groundwater is less responsive to climate variation, but in western Canada, it tends to be of poor quality, with high concentrations of dissolved minerals. There are few existing strategies other than government-funded assistance programs to sustain agriculture and rural communities through a drought of unprecedented duration that likely will exceed the coping capacity of prairie producers and agricultural institutions. Sustained drought, which occurred in the centuries prior to introduction of European agriculture to the Canadian Prairies, is almost certain to reoccur. The key questions are when and to what extent will global warming amplify the severity (intensity and duration). As discussed earlier in this paper, drought in western North America has been linked to large-scale anomalies in atmosphere–ocean circulation and specifically the ENSO and PDO. Thus, a scientific question of considerable relevance and intense investigation is how will the warming of the oceans and atmosphere, and the loss of arctic sea ice, modify the frequency and intensity of ENSO and the PDO and the strength of the teleconnections to regional climate variability? Even in the absence of this knowledge, we at least know that when a long and/or intense drought transpires in the coming decades it will occur in a warmer climate where demand for water from natural and human systems will be intensified.

Conclusion

Traditional cultures and economies are tied to the annual and seasonal cycles. The term 'climate' is from the Greek *klima* meaning inclination, referring to the sun's declination, which varies on an annual cycle and is the cause of seasonality. Even today, as illustrated here using the case of the rural communities in the Canadian Prairies, modern economies are adapted mostly to seasonal and interannual variability, the scale with which we have the most experience. This adaptation involves familiar strategies and the corresponding policies, programs and best practices. Familiar agricultural practices include storage of water and irrigation to compensate for seasonal and interannual variability in the availability of water.

There are, however, other modes of climate variability requiring a different set of adaptations. Rural communities have less experience, and therefore fewer adaptation options, in dealing with decadal to multi-decadal modes of climate variability and with unprecedented climate extremes. These scales of climate variability and extreme events require adaptations that generally are not supported by existing policy and programming. This chapter examined decadal modes of climate variability and the adaptations required to minimize the impacts of prolonged drought and excessive moisture. If, in the short-term, natural variability continues to dominate the regional climate regime, then we should at least recognize the significance of inter-decadal variability and that there may be two sets of appropriate adaptations according to phase of the PDO, and the tempo of other teleconnections. But as we move forward through this century, the anthropogenic signal is likely to become increasingly apparent and expressed not only in terms of rising average temperatures, but also as a shift in climate variability and the severity of extreme weather events.

The most common perception of anthropogenic climate change is a monotonic upward trend in temperature resulting from a perturbation to the earth's radiative balance. This view reflects a simplified reporting of climate science and the scientific basis of climate projections – models that simulate the global response of the climate system to a change in external forcing. As important as the degree of climate changes is the timing – major climate impacts could occur with minimal changes to annual averages and totals if the distribution of heat and water shifts between seasons and years. Equating regional climate change to global warming is problematic, where changes in local temperatures and precipitation depart from the weather expected in a constantly warming world. Sun and Frank (2012) suggested, "It is time to look seriously at an alternative hypothesis, which is that the defining feature of global warming will be changes in the magnitude of climate variability." This alternative conceptualization of climate change certainly facilitates the communication and planning of adaptation in regions like the Canadian Prairies.

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