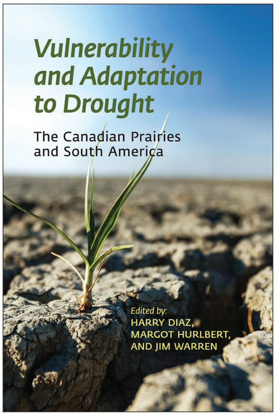

VULNERABILITY AND ADAPTATION: The Canadian Prairies and South America Edited by Harry Diaz, Margot Hurlbert, and Jim Warren

ISBN 978-1-55238-820-4

Acknowledgement: *We acknowledge the wording around open access used by Australian publisher,* **re.press**, *and thank them for giving us permission to adapt their wording to our policy* http://www.re-press.org

PART 2

PAST AND FUTURE DROUGHT: LESSONS FROM CLIMATE SCIENCE

CHAPTER 2

CANADIAN PRAIRIES DROUGHT FROM A PALEOCLIMATE PERSPECTIVE

David Sauchyn and Samantha Kerr

Introduction

Recurring drought is characteristic of the climate of the Canadian Prairies (Bonsal et al. 2011). It has serious consequences given the sub-humid climate (potential evapotranspiration exceeds precipitation in an average year) and predominance of agricultural land use in this region, which accounts for more than 80% of Canada's agricultural land. The impacts of snowpack deficits, soil moisture depletion, and decreased streamflow and lake levels on the agricultural sector, and on water supplies in general, are well documented (e.g., Bonsal et al. 2011; Wheaton et al. 2008). Prolonged drought is especially damaging because its impacts are cumulative and can lower the resistance of ecosystems and soil landscapes to disturbance from hydroclimatic events to a point that thresholds of landscape change are exceeded and recovery of natural systems can take decades or centuries (Wolfe et al. 2001).

Drought is understood as a deficit of water: "Drought originates from a deficiency of precipitation over an extended period of time—usually a season or more—resulting in a water shortage for some activity, group, or environmental sector" (National Drought Mitigation Center 2006). According to this typical definition, a drought exists when the water deficit crosses a threshold in terms of duration and degree. These thresholds are a function of regional social and historical circumstances: sensitivity to water shortages and the adaptive capacity to deal with their adverse impacts. While precipitation and water level data are used to measure *meteorological* and *hydrological* drought, respectively, whether a drought is occurring depends on whether it is having an impact. The impacts of *socio-economic drought*, and specifically *agricultural drought*, range from a lack of soil moisture for dryland farming to the eventual depletion of water stored for irrigation.

In the Canadian Prairies, aridity and drought define the landscape and have punctuated the human history with periodic impacts and adaptation. Since ecosystems and rural communities in the driest areas are adapted to drought, and weeks without rain are characteristic of the summer climate, a season is probably an appropriate minimum duration for defining drought in this region. Summer water deficits are the norm for a semi-arid climate, and thus a season without much rain is tolerable, provided there is either access to irrigation or adequate soil moisture early in the season to enable germination and emergence of the crop. The impacts of a water deficit will therefore depend almost entirely on how much it lasts beyond one season—the "more" in "a season or more." In recent years, droughts have only rarely persisted for more than several seasons or at most two to three years. These droughts were recorded by water and weather gauges and thus both perceived and defined meteorologically as the "normal" maximum duration. As a result, droughts of longer duration would conceivably exceed the adaptive capacity of Prairie agricultural communities. This chapter explores the question of whether droughts recorded and experienced by agrarian communities in western Canadian are as bad as they can get or whether we can expect droughts of greater intensity and longer duration based on our knowledge of past droughts. Thus, this chapter puts our recent experience with drought in a paleoclimatic context. Prairie drought is a recurring theme in paleo-environmental research (Sauchyn and Bonsal 2013; Bonsal et al. 2012; Lapp et al. 2012; St. George et al. 2009; Sauchyn et al. 2002, 2003). This chapter provides an overview of this research and presents a case study of paleodrought based on the reconstruction of the annual flow of Swift Current Creek (Saskatchewan) over the past four centuries.

Future climate will be a combination of natural climate cycles and the effects of anthropogenic climate change. Because the period of weather observations, since the 1880s, is short relative to some natural climate cycles and the return period of rare severe events, knowledge of pre-instrumental climate is required to determine the full range of variability and extremes in the regional climate and hydrology. Longer proxy hydroclimate records provide water resource managers and engineers with a historical context to evaluate 1) baseline conditions and water allocations, 2) worst-case scenarios in terms of severity and duration of drought, 3) long-term probability of hydroclimate conditions exceeding specific thresholds, 4) scenarios of water supply under climate change, 5) variability of water levels to assess reliability of water supply systems under a wider range of flows than recorded by a gauge, and 6) geographic extent of multi-year periods of low-and-high flows, including the synchronicity of droughts in adjacent watersheds (St. George and Sauchyn 2006).

Drought Proxies

The climate of the past, or paleoclimate, is preserved in biological and geological archives. Ecosystems and soil landscapes evolve under a certain range and seasonality of heat and moisture, and thus they correspond to regional climate regimes. But climate is not static, and as it varies, ecosystems and sediments preserve the climate changes and variability; they act as recorders of environmental change enabling the reconstruction of past climate variability on seasonal, yearly, and century-long time scales. This reconstruction of environmental history, irrespective of the proxy, is based on an understanding of the natural systems and their relationship to the current climate: "the present is the key to the past." Thus, the interpretation of proxy data is only as good as the contemporary ecological, hydrological, meteorological, and geological data used to calibrate and interpret the proxy. There must be an appropriate measure of drought if environmental history is to be reconstructed.

Any systematic analysis of the intensity, duration, timing, frequency, and spatial extent of drought, including the inference of these characteristics from biological and geological archives, requires an operational definition based on one or more drought-related variables (Zargar et al. 2011). Among the quantitative expressions of drought, the most popular has been the Palmer Drought Severity Index (PDSI), which is based on precipitation, temperature (evapotranspiration), and soil water recharge rates. One complaint about the PDSI is that scaling of the index is sensitive to the soil moisture balance component. As McKee et al. (1993) pointed out, all measures of drought frequency, duration, and intensity are a function of implicitly or explicitly established time scales. They introduced the Standardized Precipitation Index (SPI) and demonstrated its applicability over intervals of 3 to 48 months. McKee et al. (1993: section 3.0) found a maximum correlation between the PDSI and SPI at 12 months, "suggesting that the PDSI does indeed have an inherent time scale even though it is not explicitly defined." Vicente-Serrano et al. (2010) added a temperature term to the SPI to create the Standardized Precipitation-Evapotranspiration Index (SPEI). They concluded that "the PDSI is not a reliable index for identifying either the shortest or the longest time-scale droughts, which can have greater effects on ecological and hydrological systems than droughts at the intermediate time scales . . . only hydrological and economic systems that respond to water deficits at time scales of 9–18 months can be monitored using the PDSI" (2010: 9).

No common index or definition is available for paleodrought. The PDSI is the basis for most previous studies of recent and past prairie drought (Bonsal et al. 2012; Lapp et al. 2012; Sauchyn and Skinner 2001) and for the *North American Drought Atlas*, a continent-wide reconstruction of past drought from thousands of tree-ring chronologies (Cook et al. 2007). Use of the SPI or SPEI is likely to yield similar results as the PDSI, but at least these indices have the advantage of explicit time scales over which the applicability of the index is consistent (Vicente-Serrano et al. 2010; McKee et al. 1993). When the SPI is averaged over periods of up to 48 months, drought occurs with decreasing frequency, although these infrequent droughts of long duration represent the integration of series of water deficit events, with intervening periods of precipitation that are insufficient to overcome the accumulating water deficit. This statistical averaging is analogous to the integration of weather events, and the smoothing of short-term hydroclimatic variability, by drought proxies, whether annual tree growth or the gradual accumulation of plant and animal remains at the bottom of a lake. The higher the resolution of a proxy, the closer it comes to capturing a discrete drought event.

Drought indices were developed for analyzing instrumental meteorological and hydrometric time series and expressing the frequency and severity (intensity and duration) of water deficits. Their use for calibrating drought proxies is a unique application. Normally the use of a drought index, and particularly the choice of an averaging period, depends on the sensitivity of a system to water deficits of varying duration and intensity (Maliva and Missimer 2012). With drought proxies, however, that "averaging period" is a function of the sampling of the ecological or geological archive. The use of numerical drought indices is best suited for proxies, such as laminated sediments and tree rings, where the temporal resolution is high (years) and consistent, and the proxy is a measured physical or chemical property of the natural archive. Where the temporal resolution is low (decadal), and the indicator is simply the relative abundance of a climate proxy (e.g., plant pollen), inferred drought is typically described as an interval of dry climate or low water levels. Long paleo-environmental records encompass changes in climate, including shifts in aridity, which is a permanent water deficit as opposed to the temporary weather condition of drought (Maliva and Missimer 2012).

Each climate proxy represents a unique response of natural systems and processes to environmental change. Therefore, there is no universal definition of paleodrought in terms of duration and intensity, and human impacts are not considered unless there is an archaeological component to a paleoclimate study. Each proxy is a signal of a particular scale and aspect of climate, from the response of terrestrial (upland) vegetation to regional temperature and precipitation over multiple years, to the sensitivity of aquatic organisms to lake salinity, and carbonate mineralogy to lake water chemistry and temperature. The use and interpretation of climate proxies are subject to the following universal limitations and factors.

Location and timing: The sensitivity of natural systems to climate change and variability fluctuates over time and space. On the margins of regional ecosystems, species are at the limits of their ranges and thus are climatically sensitive. Island forests and permanent wetlands in the Prairie Ecozone provide a valuable source of information on environmental change, because they exist in an otherwise semiarid region and thus the terrestrial and aquatic species in these forest and wetlands are living on the margins climatically. The availability of indications of environmental change also varies over time. For example, lake sediments can yield detailed information about climate during dry periods (i.e., when lakes are low and sensitive), but during wet periods, lake sediments tend to yield less information about climate, because high water levels buffer the effects of fluctuations in temperature and precipitation. For 21 lakes in central Saskatchewan, Pham et al. (2008) found a coherent response to climatic variability in dry years but a lack of synchrony in wet years. Similarly, where heat, light, moisture, and nutrients are sufficient, tree growth is complacent—the rings have consistent width and no signal of inter-annual climate variability.

Resolution: Temporal resolution varies among proxy records according to the time span represented by individual samples and measurements. For example, in shallow and dry prairie lake basins, a single sample of lake sediment can represent material accumulated over decades, because sediments are re-suspended in the water on windy days and also lakes can periodically disappear. Some unusually deep freshwater lakes, on the other hand, contain continuous, undisturbed, and in some cases, annually laminated sediments (St. Jacques et al. 2015).

Non-climatic controls: Significant variations in proxy data can reflect the response of natural systems to internal thresholds or to events that are indirectly or not related to climate. Forests expand and become denser, and lakes fill with sediment and evolve chemically; proxy data from these systems can contain a signature of these processes. Land-use change also has a strong influence on the pollen and chemical record from prairie lakes (Pham et al. 2008).

Chronological control: Establishing the timing of climatic changes and resolving climatic variability depend entirely on chronological control, typically based on radiometric dating of organic and mineral carbon. Only tree rings and varves (annually laminated sediments) can be assigned to individual calendar years. Even these often represent floating chronologies, which must be dated by other means or correlated (cross-dated) with modern samples or strata to obtain absolute dates.

In the northern Great Plains of North America, changes in climate are recorded in the shifting of vegetation, fluctuations in the level and salinity of lakes, patterns of tree rings, and the age and mobility of sand dunes. In this dry environment, where lake water levels and chemistry, prairie vegetation, and rates of runoff and erosion reflect the soil and surface water balance, most proxies record fluctuations in hydroclimate, including periods of water deficits. Prairie paleodrought is identified mainly from studies of sediments, archival documents, and tree rings.

Lake and Terrestrial Sediments

Soils and sediments are ubiquitous climate proxies. They provide paleoclimate records that span the geologic history of a surface or sediment sink, although the age and origin of sediments usually can be resolved only to within decades (with the rare exception of annually laminated sediments). The sediments in permanent lakes represent a continuous accumulation of mineral and biological proxies. Although lakes are less common in semi-arid environments, they are important climate archives where drought is frequent and has ecological consequences. Pham et al. (2009) determined that the long-term chemical characteristics of prairie lakes were regulated mainly by changes in winter precipitation or groundwater flux. This finding has important implications for the hydro-climatic interpretation of the abundance of type of organisms found in lake sediments.

The postglacial climate history of the Canadian Prairies is known mostly from the analysis and interpretation of the type and abundance of fossil plants and aquatic organisms found in lake sediments. The analysis of bulk samples representing multiple decades limits the inference of hydroclimate to indications of relative aridity rather than drought. More recently, the continuous sampling and precise dating of lake sediments at fine intervals has yielded time series of higher resolution. The fine sampling of diatom assemblages from prairie lakes has revealed droughts embedded in multi-centennial shifts in moisture regimes (Michels et al. 2007; Laird et al. 2003). Using paleo-environmental information from the Peace–Athabasca Delta (PAD), Wolfe et al. (2008) determined that the levels of Lake Athabasca have fluctuated systematically over the past millennium. The lowest levels were during the eleventh century, whereas the highest lake levels coincided with maximum glacier extent during the Little Ice Age (sixteenth to nineteenth centuries). This important work has demonstrated that recent water level fluctuations on the PAD are within the range of long-term natural variability and therefore are very unlikely to be caused by the impoundment of water upstream (Wolfe, Hall, et al. 2012).

The frequency and duration of droughts also has been inferred from the age and origin of sand dune deposits (Wolfe, Hugenholtz, et al. 2012). Dry periods lasting years to decades will trigger the reactivation of a dune field; but the most severe droughts may not be detectable if continuous and extensive sand dune activity prevents the preservation of biological or geological evidence. From the precise optical dating of quartz grains, Wolfe et al. (2001) identified widespread reactivation of sand dunes in southwestern Saskatchewan about 200 years ago and correlated this geomorphic activity with tree-ring records of prolonged drought during the mid-to-late eighteenth century. A lag occurred between peak dryness around 1800 and the onset of dune activity at about 1810. Dune stabilization has occurred since 1890. The droughts of the 1930s and 1980s were insufficient to reactivate dunes.

Historical (Archival) Records

The Euro-Canadian (non-Aboriginal) history of the northern plains is several centuries longer than the instrumental observation of weather that began with agrarian settlement. Explorers and fur traders reported extreme weather and related events (e.g., fires, floods, ice cover). These documents are archived in libraries, museums, government repositories, and notably in the Hudson's Bay Company Archives in Winnipeg. This archival information is valuable for verifying paleoclimate data from other sources (Rannie 2006; Blair and Rannie 1994). Severe, and at times prolonged, drought in the late eighteenth and mid-nineteenth centuries, evident in tree-ring and sand-dune chronologies, are described by explorers and fur traders. The archives of the Hudson's Bay Company contain this report:

> At Edmonton House, a large fire burned "all around us" on April 27th (1796) and burned on both sides of the river. On May 7th, light canoes arrived at from Buckingham House damaged from the shallow water. Timber intended to be used at Edmonton House could not be sent to the post "for want of water" in the North Saskatchewan River. On May 2nd, William Tomison wrote to James Swain that furs could not be moved as *"there being no water in the river."* (Johnson 1967: 33–39, 58)

At the end of this dry decade, reports from Fort Edmonton House describe poor trade with both the Slave and Southern Indians due to "*the amazing warmness of the winter*" (Johnson 1967: 33-39, 58) diminishing both the bison hunt and creating a "*want of beaver.*" There were reports of smoke that almost obscured the sun and remarks like "*the country all round is on fire.*" The "*amazing shallowness of the water*" prevented the shipment of considerable goods from York Factory (the headquarters of the Hudson's Bay Company on Hudson Bay).

In the 1850s, Captain John Palliser was dispatched from London by the Royal Geographical Society to evaluate the potential for British settlement of western Canada. He concluded that

> this large belt of country embraces districts, some of which are valuable for the purposes of the agriculturalist, while others *will forever be comparatively useless*. . . . The least valuable portion of the prairie country has an extent of about 80,000 square miles, and is that lying along the southern branch of the Saskatchewan, and southward from thence to the boundary line [the US border]. (Palliser 1862: n.p.)

Palliser filed these remarks in 1860 in the midst of a 25-year drought. Despite his warning, settlers were drawn from Europe, eastern Canada, and the United States. The railroad and communities like Medicine Hat, Alberta, were built. In the very first edition of the *Medicine Hat Times*, dated 5 February 1891, an editorial entitled "Our True Immigration Policy" stated, "It would be almost criminal to bring settlers here to try to make a living out of straight farming" (Jones 2002: 18). As it turned out, the next several decades were relatively wet, settlers flooded in, and the populations of Saskatchewan and Alberta increased by nearly 500% in one decade. Certainly they were not aware of decadal-scale climatic variability and the fact the climate would later flip again and bring the devastating droughts of the 1920s and "Dirty 30s."

Tree Rings

Tree rings provide a source of hydroclimatic data, such as data on available water and heat, and a chronology with absolute annual resolution spanning centuries to millennia. During the summer growing season in

Canada's western interior, there is usually more than enough light and heat. In this dry continental climate, soil moisture is the most limited determinant of tree growth. Therefore, the increment of annual growth is a proxy of hydrological or agricultural drought; dry years consistently produce narrow rings. Tree rings from living and dead trees that were growing at the same time for at least a few decades can be cross-dated, and calendar years can be transferred from the living to the dead trees. This process has produced tree-ring chronologies spanning the past millennium in western Canada. The mathematical relationship between standardized tree-ring widths and hydroclimatic data from nearby gauges is applied to the tree-ring data to reconstruct the relative moisture levels each year for the entire tree-ring record. Because the soil moisture that supports tree growth is derived mainly from melting snow and early-season rain, and because winter precipitation is strongly linked to large-scale climate oscillations, tree rings capture these teleconnections and the associated inter-annual to multi-decadal climatic variability, including periodic severe and prolonged drought.

Over the past 25 years, researchers in the Tree-Ring Lab at the University of Regina have collected more than 8,000 samples from old trees at more than 170 sites in the boreal, montane, and island forests of the Rocky Mountains and northern Great Plains. This network of tree-ring sites encompasses the semi-arid Prairie Ecozone. Because the tree rings were collected at dry sites (south- and west-facing slopes, sandy soils, ridge crests), where tree growth is moisture-sensitive, a strong correlation exists between the ring-width chronologies and drought and moisture indices. These tree-ring data have been the basis for a series of studies of Prairie drought (e.g., Bonsal et al. 2012; Lapp et al. 2012; St. George et al. 2009; Sauchyn et al. 2002, 2003; Sauchyn and Skinner 2001), including recent research by Kerr (2013), which is the source of the following case study.

A Tree-Ring Reconstruction of Hydrological Drought

Throughout the world, agriculture is the dominant use of water, and the major impacts of drought are directly or indirectly related to food production. Therefore, most indices of agricultural drought are expressions of the soil moisture balance, which unlike precipitation is not routinely measured. The best index of hydrological drought is streamflow; it is extensively monitored and integrates the net precipitation (in excess of evapotranspiration) over time (days to seasons) and watersheds. There is a relatively dense network of water-level gauges in the southern Prairies, since there is a strong demand for a limited surface water supply. This hydrometric network was originally established in the early twentieth century—not for the study of hydrology or climate, but rather to identify supplies of water initially for steam locomotives and irrigation (Greg McCullough, Water Survey of Canada, personal communication, June 2011). Therefore, just a few gauges have operated continuously for more than 50 years, recording only a few periods of sustained low water levels.

Tree rings are an effective streamflow proxy; they record the timing and duration of high and low water levels, and they have a similar muted response to episodic inputs of precipitation. When watersheds are wet (dry), streams rise (fall) and tree growth is enhanced (suppressed). Tree rings usually underestimate hydrological peaks, because there is a maximum positive biological response to available moisture; other factors constrain growth when soil moisture is not lacking. Thus, tree-ring data from moisture-sensitive ring-width chronologies are a better proxy of drought than of excess moisture.

Recently, Kerr (2013) completed a study of paleohydrology in the dry core of the northern Great Plains. Much of this region, at the junction of Alberta, Saskatchewan, and Montana (Figure 1), receives less than 330 mm of annual precipitation. Wetter conditions prevail in the uplands, so they contain island forests and the headwaters of all local rivers and streams. Kerr (2013) augmented and updated a network of tree-ring chronologies derived from lodgepole pine (*Pinus contorta*) and white spruce (*Picea glauca*) in the Cypress Hills (Alberta and Saskatchewan) and from Douglas fir (*Pseudotsuga menziesii*) and ponderosa pine (*Pinus ponderosa*) in the Sweet Grass Hills and Bears Paw Mountains of north-central Montana. Statistical tree-ring models explained 40%–55% of the recorded summer and annual flow of the Frenchman River, Battle Creek, and Swift Current Creek in southwestern Saskatchewan. The water-year (October–September) data from a gauge on Swift Current Creek are plotted in Figure 2 along with the flow predicted by a statistical tree-ring model for the same period (1979–2009). The two curves match in terms of the timing of high and low flows, although the tree rings underestimate the magnitude of the highest flows. Thus, they are a better proxy of drought than excess water.

Figure 1. Tree-ring sites (triangles) and streamflow gauges (squares) for a study of paleohydrology in the dry core of the northern Great Plains
(Source: Kerr 2013)

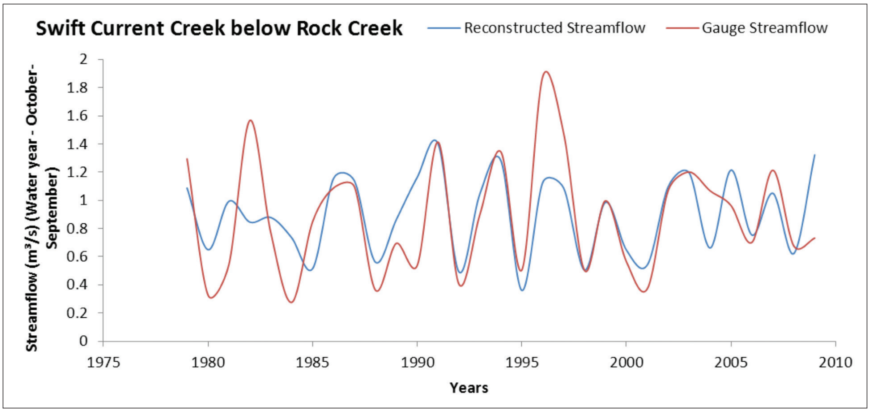

Figure 2. A plot of water-year (October–September) streamflow (m3/sec), from 1979 to 2009, as recorded at the gauge on Swift Current Creek below Rock Creek and reconstructed using tree rings.

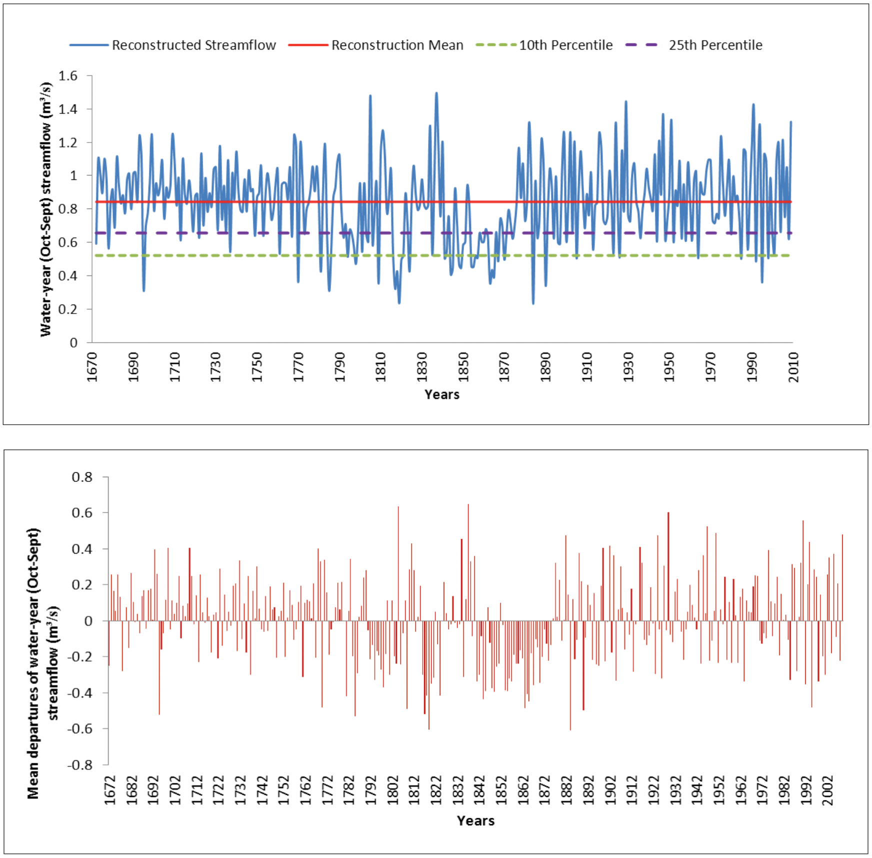

Figure 3. A tree-ring reconstruction of the flow of Swift Current Creek since 1672. Top plot: Water-year (October–September) streamflow (m^3/sec) showing the mean flow and 10th and 25th percentiles. Bottom: Water-year (October–September) streamflow (m^3/sec) plotted as departures from the mean reconstructed value. (Source: Kerr 2013)

By applying the statistical tree-ring model of streamflow to the entire length of the tree-ring chronologies, water-year flow from 1672 to 2009 was reconstructed. Two versions of this paleo-flow time series are plotted in Figure 3. The top plot shows the inferred annual flow, mean flow, and two thresholds of low flow—the 10th and 25th percentiles. In the bottom plot, departures from the reconstructed mean flow highlight the inter-annual variability and inter-decadal pattern, with extended periods of low flow evident in the 1790s to early 1800s and the late 1840s through 1870s.

Table 1. Hydrological droughts (<25th percentile) with severe droughts (<10th percentile) indicated in bold for average water-year flows at Swift Current Creek, below Rock Creek (1670–2009). Red text indicates five or more consecutive years of drought.

Single-year event	Two or more consecutive-year events
1672, 1678, **1695**	
1713, 1722, 1737, 1749, 1753, 1761, 1767, **1770**, 1773, **1781**, 1792, **1794**	1784, **1785**, 1786, 1796, 1797, **1798**
1801, 1806, **1809**, **1824**, 1835, **1867**, 1874, **1884**, 1886, **1890**, 1894	1803, 1804, 1816, **1817, 1818, 1819, 1820**, 1821, **1841**, 1842, **1844**, **1845**, **1848**, **1849**, 1850, 1851, **1854, 1855**, 1856, **1857**, 1858, 1859, 1860, 1862, **1863**, **1864**, **1865**, **1870**, 1871, 1896, 1897
1900, **1905**, 1913, 1923, 1926, 1936, 1944, 1948, 1952, 1956, 1958, 1961, **1964**, 1980, **1985**, 1988, **1992**, **1995**, 1998	
2008	2000, 2001

Because much of the unexplained variance in the calibration period (1979–2009; Figure 2) can be attributed to the underestimation of high flows, more confidence can be applied to the interpretation of low flows, which consistently correspond to narrow tree-rings, capturing the timing and duration of drought. The late eighteenth through mid-nineteenth centuries have the most sustained low flows. Severe hydrological droughts occurred from 1794 to 1798, 1816 to 1821, and 1854 to 1860 (Table 1). The repetitive nature of moisture surpluses and deficits in the streamflow reconstruction suggests some quasi-cyclical behaviour in the hydroclimatic regime. Spectral analyses provided evidence of this periodic hydroclimatic variability at the inter-annual (~2–6 years) and multi-decadal (~20–30 years) scales corresponding to the dominant frequencies of the El Niño–Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO).

Hydrologic droughts in the Swift Current Creek paleohydrology coincide with low flows and below-average precipitation in other paleoclimate records from western North America. The early to mid-1700s was a period of prolonged drought documented by paleoclimatic investigations across western North America (Cook et al. 1999; Woodhouse and Overpeck 1998; Laird et al. 1996; Stockton and Meko 1983). Various paleoclimatic studies emphasize the sustained nature of drought during the mid-nineteenth century, with very little relief in a few scattered wet years. This intense, long-lasting drought is well documented as occurring from the 1840s through mid-1860s throughout the western United States, Canada, and Mexico (Stahle and Dean 2011; Stahle and Cleaveland 1988; Fritts 1983; Stockton and Meko 1983; Hardman and Reil 1936).

This case study of the paleohydrology of southwestern Saskatchewan demonstrates tree rings are an effective proxy of annual streamflow. The proxy record for Swift Current Creek reveals periods of sustained low flow, including pre-settlement droughts that exceed in intensity and duration the worst conditions that have affected modern agriculture on the northern plains. Water deficits of this severity will reoccur in the future in a climate of rising temperatures.

Conclusion

Seasonal, and sometimes prolonged, moisture deficits are so characteristic of the climate of the Canadian Prairies that they define the region ecologically and ultimately limit forest and farmland productivity. Severe drought of high intensity and/or long duration, with serious consequences, is relatively infrequent. Thus over the past 13 decades, since Euro-Canadians first came to ranch and farm, people have experienced and recorded relatively few severe droughts. Although the meteorology and socio-economic impacts of these relatively few severe droughts have been studied extensively (e.g., Bonsal et al. 2011; Wheaton et al. 2008), the sample size is too small to analyze the frequency of these events in relation to regional climate variability and change. Thus, in this chapter, we examined the paleoclimate record of drought extending back over the past millennium.

A robust conclusion of the paleoclimate research on the Prairies is that the climate of the instrumental period is representative of the longer-term frequency of one- to two-year droughts but does not capture the full range of intensity and duration. The dry periods of greatest severity and duration occurred before the Prairies were settled. These include the intense drought years of the late eighteenth century (and the sand dune activity described above) and the sustained drought of the 1840–60s. Thus, the proxies suggest that the climate of the twentieth century (especially since the 1930s) was relatively favourable for the settlement of the Prairies, because the region has lacked the sustained droughts of preceding centuries. While the twentieth-century droughts may have been characterized by relatively modest precipitation deficits compared to earlier events, they have been hotter droughts than the cooler moisture-deficient periods of preceding centuries. This finding has important implications for studying and projecting future drought in a period of rapid global warming. The most serious impact of a warming climate in this region would be realized if the droughts of the 1790s or 1850s, and associated natural forcing, were to reoccur in the much warmer greenhouse gas climate of the twenty-first century.

The paleoclimatic records capture the tempo of natural climate variability, including the near-regularity of wet and dry cycles at certain frequencies. They show that the hydroclimatic regime periodically shifts from predominantly interannual variation to intervals with extended wet and dry spells and that there is a significant difference in the likelihood of drought according to phase of ocean-atmosphere oscillations (ENSO and PDO). This knowledge of long-term climate variability contributes to our understanding of the climate system at scales that exceed the length of instrumental records. The longest and most intense droughts, and the factors that cause them, reoccur so infrequently that a pre-instrumental paleoclimate perspective is required to validate the modelling and prediction of these events.

Our capacity to withstand and prepare for water scarcity has developed in response to the droughts that have occurred since the Prairies were first settled for agriculture, which have been shown to be much less intense than those that occurred before the Prairies were settled (i.e., those in the paleoclimate record presented here). Greater adaptive capacity will be required if future drought conditions are more intense or prolonged than those previously experienced. Significant adaptations may be required, particularly to water management practices and policies, starting with a scientific knowledge base that extends beyond instrumental records and the scale at which water supplies seem relatively secure and stationary, and then encompassing the longer view provided by paleoclimate records and model projections of future climate. Communities and governments are investing effort and resources in adaptation planning, in large part to mitigate the potential impacts of a warmer and more extreme climate. To inform this process, and be perceived as a credible source of information on exposure to drought, reconstructions of long-term climatic variability must be based on definitions of drought that are applicable to agriculture and water resource management.

The characteristics of drought detected using natural and historical archives must be related to droughts of recent experience and to the nearest modern analogues. To communicate the severity of paleodroughts, an example might be given of a situation in which one intense recent drought is followed immediately by another similarly intense drought. In this way, the characteristics of the megadroughts in the paleoclimate record can be translated into terms that are used and understood by other natural and social scientists, and by engineers and resource managers responsible for monitoring and managing drought.

Acknowledgments

Funding for the case study was provided by the Rural Community Adaptation to Drought project through the Social Sciences and Humanities Research Council and by the Prairie Adaptation Research Collaborative. Jessica Vanstone, Cesar Perez-Valdivia, Ben Brodie, and Tiffany Vass assisted Samantha Kerr with field and laboratory work.

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CHAPTER 3

FUTURE POSSIBLE DROUGHTS

Elaine Wheaton, David Sauchyn, and Barrie Bonsal

Background and Rationale

Nothing is definite in the future, but drought is certain to play a role, as it is a part of the climate of the Canadian Prairies. Droughts can be casually defined as a worrisome lack of water or more formally defined as a prolonged period of abnormally dry weather that depletes water resources for human and environmental needs (Meteorological Service of Canada 1986). Droughts occur in many regions of North America and the world, but the agricultural region of the Canadian Prairie provinces of Alberta, Saskatchewan, and Manitoba is among the most susceptible to droughts and is the focus of this chapter.

Prairie people have considerable experience with climate extremes, such as drought and heat, but these extremes can still cause concern and damage. Drought is more costly than any other form of natural disaster (Wilhite 2000). This is especially true of the Canadian Prairies, where drought is very damaging to the economy, society, and the environment, even in recent years (e.g., Wheaton et al. 2008). Drought occurs in most years in some part of the Canadian Prairies, but it is the longer-duration and larger-area droughts that have the most severe impacts and provide the greatest challenges for adaptation. At least five major droughts have occurred in the Canadian Prairies during the past 120 years. These include multi-year droughts in the 1890s, 1910s, 1930s, and 1980s, and in 2000–2004 (Bonsal, Wheaton, Chipanshi, et al. 2011; Bonsal, Wheaton, Meinert, et al. 2011). During this last major drought, parts of the Prairies had some of the driest conditions in the historical record, and it was one of the first documented coast-to-coast droughts in Canada.

Each major drought on the Prairies appears to have several unique characteristics, including duration, area of coverage, intensity, and cause, but Bonsal, Wheaton, Meinert, et al. (2011) documented several similarities among the droughts, including their origin in the US northern plains and subsequent migration into the Canadian Prairies. The authors devised and used a six-stage drought classification system to compare the major droughts. A key difference of the 2000–2004 drought is that its peak in terms of area of severe drought was during winter, whereas the others peaked during the May-to-August growing season. Most of these major droughts lasted almost two years, but the 1928–32 drought lasted over 40 months.

More recently, a less severe and shorter drought occurred from 2008 to 2010 in the Canadian Prairies (Wittrock et al. 2010). A core of well-below-average rainfall appeared around Edmonton, Alberta, and northward in the summer of 2008. By that autumn, this core area had expanded westward to the British Columbia border and eastward into Saskatchewan. The drought intensified in the winter of 2008–9, and the most severe and largest dry area appeared in spring 2009. Rainfall eased the dryness by autumn 2009, but dryness continued in areas of Alberta. Spring rains in 2010 ended the meteorological drought for most areas, but effects lingered.

Reducing the negative impacts of drought requires considerable planning and preparation so that society can effectively adapt to future droughts. These activities require understanding the nature of future possible droughts, which is the rationale for work that projects important climate extremes, especially future drought. It is prudent and critical to advance knowledge of future possible droughts for effective adaptation, that is, to decrease these massive costs and to take advantage of any opportunities. Such opportunities can result from numerous benefits of drought, including increased quality of grain and hay, reduced levels of some insects and diseases, and fewer delays for construction of roads and buildings (Wheaton et al. 2011).

If the past were the only guide to the future, past information would suffice for estimating future droughts. However, the current risk of drought is changing, perhaps fairly rapidly, and research indicates that dry areas (such as the Prairies) are expected to become drier. The potential for future drought risk is increasing largely because of human-induced climate change (IPCC 2012).

Objectives and Methods

Information is needed regarding the nature of future droughts to facilitate adaptation and reduce vulnerability. Critical questions to address include: How will droughts change in terms of characteristics such as severity, duration, frequency, timing, cause, and area? The objective of this chapter is to address these questions by reviewing drought literature focused on the Canadian Prairies. Much work has emphasized the global scale, but considering that drought is an important hazard for the region, several papers have focused at the scale of the Prairie provinces. We attempt to emphasize the near future to about mid-century, but the relevant literature tends to use the following standard periods: the 2020s (2011–40), 2050s (2041–70), and the 2080s (2071–2100); some literature uses other scales, such as time-series results, for the period up to 2100.

For each study reviewed in this chapter, its methods are briefly described to help assess its results. More recent literature is used, where possible, with some reference to earlier literature for perspective. Generally, drought characteristics are measured using several indicators. The most common of these indicators are the moisture deficit (e.g., precipitation minus potential evapotranspiration), Palmer Drought Severity Index (PDSI), and Standardized Precipitation Index (SPI). Newer indices, such as the Standardized Precipitation Evapotranspiration Index (SPEI), are the subject of current research.

Future Possible Droughts of the Canadian Prairie Agricultural Region

A few studies have focused on the nature of future droughts in the Canadian Prairie provinces. Work at the global scale hints at future drought conditions on the Prairies, but focused assessments done at a finer resolution provide more detailed information. The reason for estimating future possible droughts is to improve adaptation as droughts have serious impacts and require considerable adaptation to reduce vulnerability (Kulshreshtha et al., this volume). In this section, we present methods and findings of recent work on future droughts in the Canadian Prairies and discuss this research within the context of earlier work.

One of the studies with findings for the Canadian Prairies is by Barrow (2010). She analyzed output from a set of regional climate models (RCMs) to determine characteristics of potential evapotranspiration (PET) and moisture deficit. PET was calculated using two methods for comparison: Thornthwaite and Penman-Monteith. RCMs were shown to simulate observed precipitation values better than global climate models (GCMs), as the RCMs have finer spatial resolution. All but one of the models used by Barrow (2010) showed increases in both intensity and area of moisture deficit (water-year October to September) for the 2041–70 period. Time-series analyses project increases in evaporative demand over time for all simulations driven by the projected temperature increases. For the Canadian Regional Climate Model (CRCM) results, annual moisture deficits for this future period range from about -400 mm in southwest Saskatchewan to -200 mm just north of about 50° North (Figure 1). These values are about double the annual moisture deficit for the 1971–2000 period. Also, the area with an annual moisture deficit of -200 to -400 mm expands considerably into the future, migrating from a narrow ribbon along the US border in southwestern Saskatchewan and southeastern to central Alberta to cover all of southern Saskatchewan past Regina.

Barrow's (2010) findings of future expansion of arid areas confirm earlier work. For example, Sauchyn et al. (2005) used the aridity index (ratio of annual precipitation to PET) for the Canadian Prairies, and found that the area of aridity (ratio less than 0.65) increased by 50% and expanded northward.

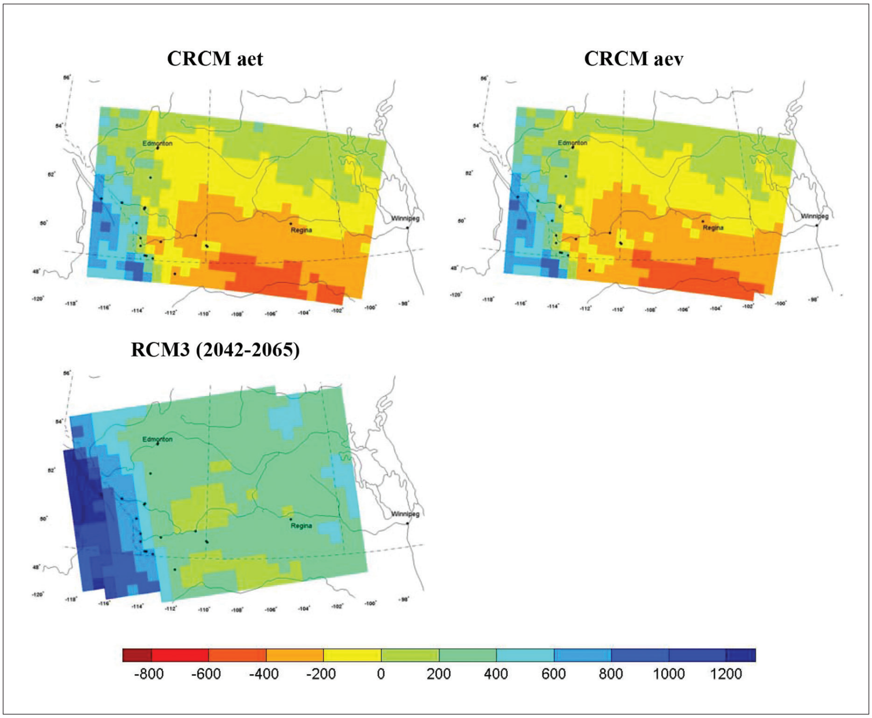

Figure 1. Spatial pattern of the future annual moisture deficit for the water-year of October to September (2041–70, precipitation minus potential evapotranspiration, mm). The two different experiment identifiers of the Canadian Regional Climate Model (CRCM) are labeled as aev and aet
(Source: Barrow 2010: 21)

Another study focusing on the Canadian Prairies by Thorpe (2011) used a range of climate change scenarios from several GCMs to estimate future PET for the Prairie Ecozone. He also found that PET increases in the future. The average Prairie Ecozone PET for Saskatchewan and Alberta is about 550 mm for the baseline climate of 1961–90, increases to about 600 mm at about 2020, reaches almost 700 mm by 2040, and increases even more rapidly thereafter for the warm scenario (Figure 2). Changes in annual precipitation are projected to vary from only small increases in the warm scenario to small decreases in the cooler scenario. The changes in precipitation are projected with much lower confidence than for temperature. These potential increases in precipitation are insufficient to compensate for the increased atmospheric water demand, producing the

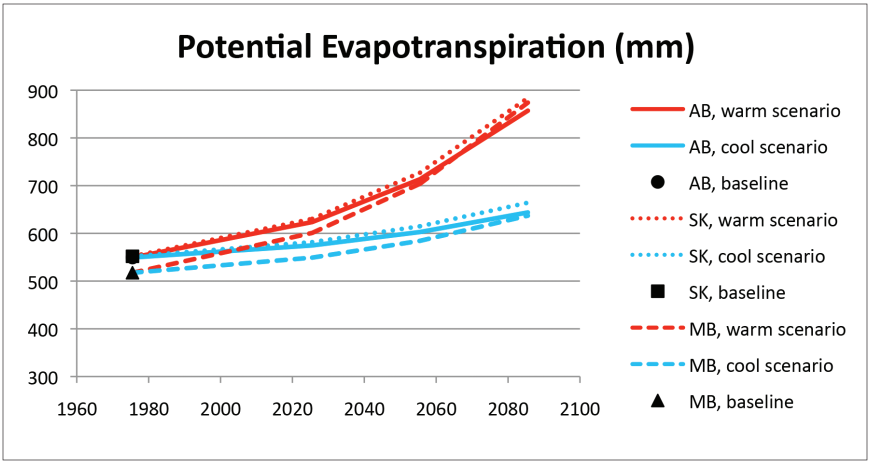

Figure 2. Average potential evapotranspiration for the Prairie Ecozone of Alberta (AB), Saskatchewan (SK), and Manitoba (MB) for the baseline climate (1961–90) and for two future scenarios
(Source: Thorpe 2011: 5)

greater moisture deficits as estimated by Barrow (2010), for example. Williams and Wheaton (1998) calculated that increased annual precipitation of about 7%–10% is needed to compensate for an increase in mean annual temperature of 3°C.

Sushama et al. (2010) used the CRCM and the number of dry spells or dry days with precipitation less than 2 mm (and other thresholds) to explore future drought characteristics. Results indicate that the number of dry days will increase by up to about five days in the 2050s for southern Saskatchewan. The 10- and 30-year return levels of maximum dry spell length are projected to increase during the 2050s and 2080s in the Canadian Prairies, especially in the south.

Price et al. (2011) developed high-resolution climate scenarios for Canada from several GCMs. Besides increases in temperature and only modest increases in precipitation, they project solar radiation levels will increase slightly during summer in the Canadian Prairies' semi-arid ecozone. These changes would contribute to increasing dryness. Vapour pressure levels are also projected to increase and would offset some of the effects of warming on evaporative demand, but overall evaporation rates are expected to increase. Generally, Price et al. (2011) estimate that temperature, precipitation, and solar radiation will increase, along with

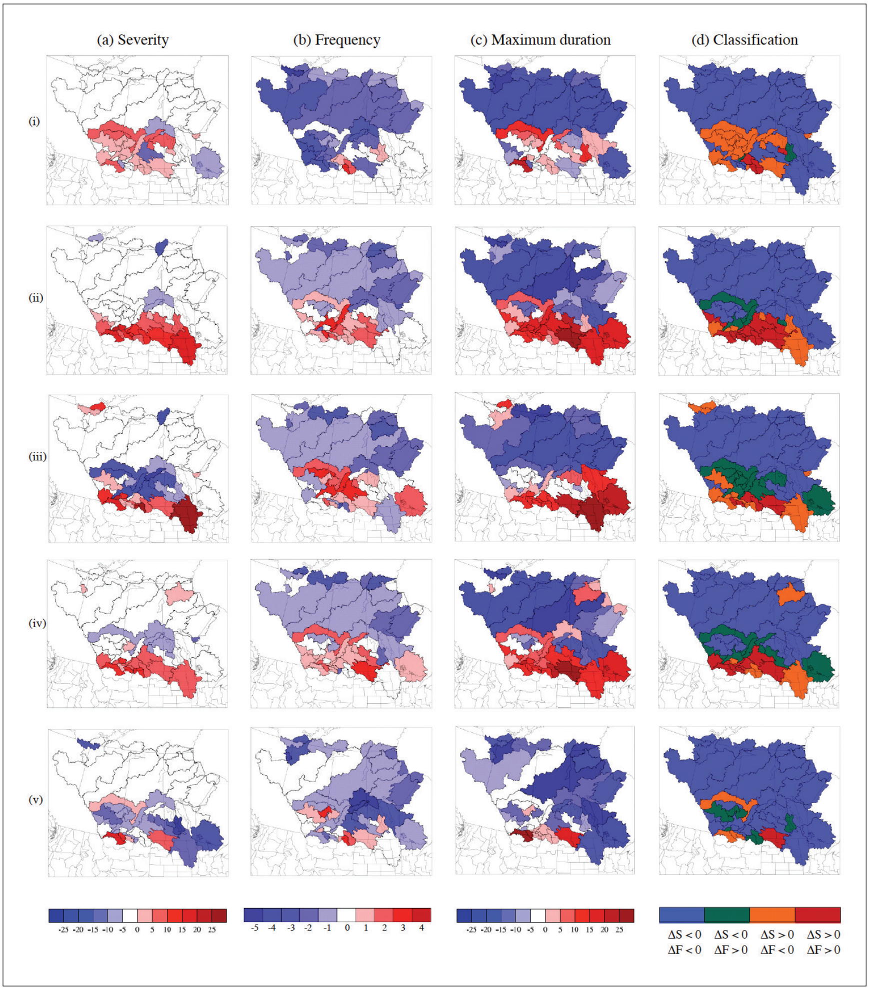

Figure 3. Projected changes to a) severity (%), b) frequency, and c) maximum duration (months) for 10-month drought events at the watershed scale, and d) classification of watersheds based on projected changes to the severity and frequency of 10-month events for the 47 watersheds in the Canadian Prairies for five pairs (i–v) of Canadian Regional Climate Model simulations
(Source: PaiMuzumber et al. 2012: Figure 12)

some increases in inter-annual variation, which indicate that multi-year droughts will become more common and more intense, especially with higher emission scenarios by 2100.

PaiMazumber et al. (2012) estimated future durations of drought severity; their results show that 6- and 10-month long droughts will become more severe over southern Saskatchewan and Manitoba in the 2050s compared with the 1971–2000 baseline. The 10-month droughts are expected to increase in frequency by as many as four events in the 2050s. Maximum durations of long-term droughts are projected to increase for a large part of the southern Prairies, and the largest increases are expected for droughts lasting 10 months or longer. The most vulnerable watersheds were found to have future possible increases in both severity and frequency of 10-month droughts for five pairs (GCM/RCM) of climate simulations for the 2050s (Figure 3). The CRCM and the high-emission scenario (A2) were used to develop climate scenarios, and monthly precipitation deficits were used to measure drought severity. Limitations of the research include the CRCM's ability to simulate precipitation, the use of only one model, and the use of precipitation alone to describe drought.

Bonsal et al. (2013) produced one of the most comprehensive descriptions of future possible drought for the Canadian Prairies and were the first to use three time periods—pre-instrumental period, instrumental (or observational) period, and future—spanning the years 1365–2100. Their study area was Alberta and western Saskatchewan from the US border north to past Edmonton (i.e., 54° North). They used five climate scenarios downscaled from two versions of the CGCM and the UK Hadley climate model (HadCM3), as well as the baseline period of 1961–90. Summer (June, July, August) self-calibrated PDSI and SPI values were averaged over the study area, and time series were produced from 1900 to 2100. They examined the time series of the areal averaged PDSI and SPI for the 1901–2099 period for the five GCMs, their means, and the nine-year running means (Figure 4).

Bonsal et al.'s (2013) results indicate that the pattern of the future mean PDSI values shows drying from the present to 2020, followed by a slight improvement with much variability to 2040. After 2040, persistently negative values occur with a downward trend, reflecting drier to drought conditions. The authors suggest this trend indicates a permanent regime shift to a more arid climate. In contrast, the SPI time series for the future period reveal no strong change compared with the instrumental period to about 2040; however, a higher persistence of multi-year droughts is found in the central and southern portion of the study area. This result occurs

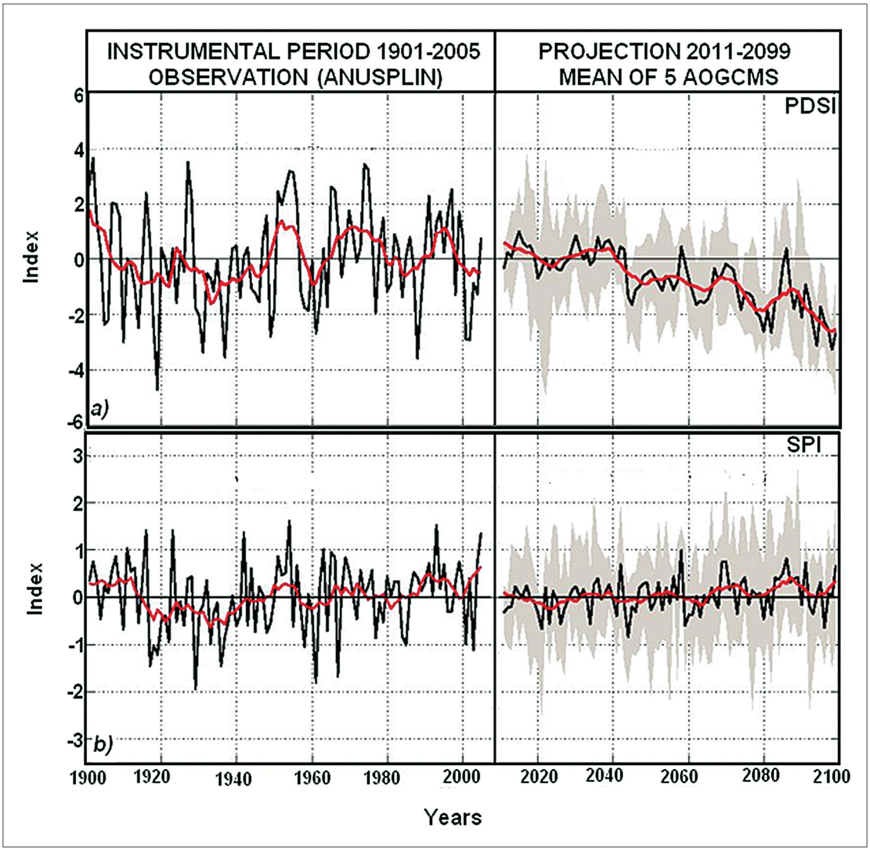

Figure 4. Summer a) Palmer Drought Severity Index (PDSI) and b) Standardized Precipitation Index (SPI) area-averaged values for the instrumental period (1901–2005) and the future (2011–2099). The black lines are the future ensemble-mean values from the five climate model runs, and the red lines are the nine-year running means. The minimum and maximum climate projections for each summer are shown in grey. (Source: Bonsal et al. 2013: Figure 9)

because SPI is calculated using only precipitation and not temperature. Drought indicators that consider precipitation alone are insufficient to determine future drought characteristics (e.g. Bonsal et al. 2013).

Drought area was also estimated by Bonsal et al. (2013); they found a substantial increase in the area and frequency of severe drought and worse (i.e., PDSI of -3 or less) in the area of the Canadian Prairies they studied. Even SPI shows that most future summers have severe drought conditions in some portion of the study area. These patterns suggest that severe droughts will become a more permanent feature in some areas of the southwestern Canadian Prairies in terms of characteristics such as occurrence, duration, and/or severity.

Multi-year droughts were also investigated by Bonsal et al. (2013) using the PDSI and found to be more frequent in the future period compared with the instrumental period (105 years). The length of a drought was considered to be the average number of consecutive summers with a negative value. Summer droughts of five years and longer have a frequency of 1.9 occurrences per 100 years during the instrumental period. This frequency is expected to more than double to 4.2 per 100 years in the future. The frequency of droughts of 10 years or longer increases to 3.1 per 100 years in the future. This result is even worse than the paleo record frequency of 3.0 per 100 years (see Chapter 2 by Sauchyn and Kerr in this volume). A worst-case situation is for increased frequency of drought of 10 years with consecutive summer droughts (i.e., negative PDSI values).

Although the general climate is projected to become drier, substantial variability could occur. The IPCC (2012) has identified areas of expected changes for the return period of intense daily rainfall events globally. For central North America, including the agricultural prairies, a decrease of 5 to 10 years is projected for the return period of a maximum 20-year rainfall event. This means that an extreme daily rainfall event could occur as much as twice as often as during 1981 to 2000. This result is for the middle 50% of models for the medium (A1B) to extreme (A2) emission scenarios. Dai (2010) also reports that the type of rainfall is expected to change with continued warming to more intense rainfall events and fewer light rainfalls. This pattern would tend to exacerbate drought, because intense rainfalls do not recharge soil moisture as well as more gentle rainfalls. Drier soils also tend to increase the risk of drought, because heating is used to warm soils to higher temperatures instead of evaporating water. This effect is similar to the cooling effect of water on one's skin as compared with dry skin that stays warmer.

Wheaton et al. (2013) reviewed projections of extreme precipitation globally and for the Canadian Prairies and found consistent estimates from several sources of increases in future extreme rainfall. Therefore, it seems that long periods of dry to drought conditions would be punctuated by periods of extreme rainfall. Some of the mechanisms behind this trend

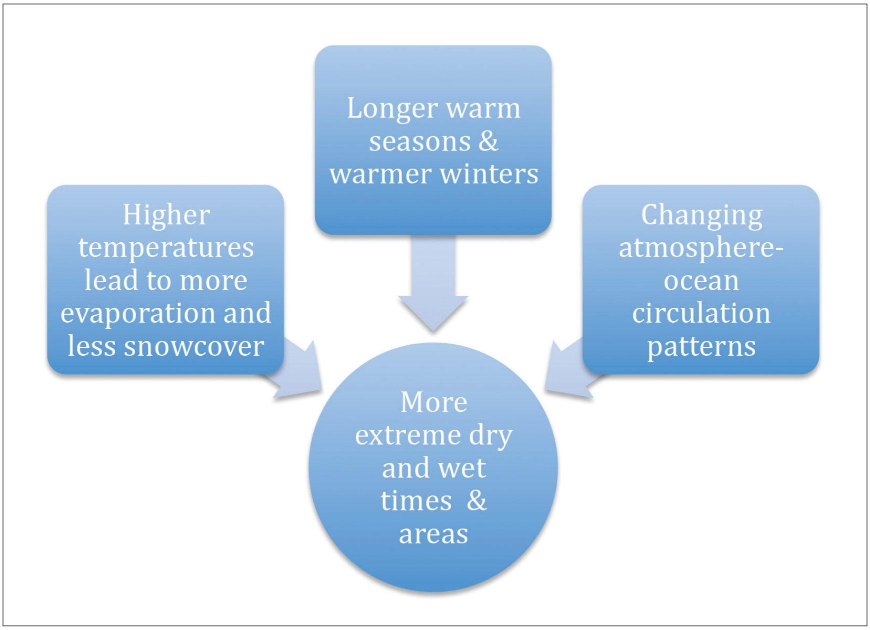

Figure 5. Dry times become drier and wet times become wetter (Source: Wheaton 2013)

include higher temperatures, shorter snow-cover seasons, longer warm seasons, and changing atmospheric and oceanic circulation patterns, as shown conceptually in Figure 5.

Based on research estimating future drought on a regional or global basis, there is a clear evidence for increasing risk of more common and persistent severe future droughts, including on the Canadian Prairies. A summary of projections of probable future drought characteristics emphasizes the consistency in projections of dry times and places becoming drier (Table 1). The Canadian Prairies will not be the only area facing more severe future drought. The IPCC (2012) states that drought will intensify in the twenty-first century in some seasons and areas. These regions include central North America, southern and central Europe, the Mediterranean, Central America and Mexico, northeastern Brazil, and southern Africa.

Table 1. Future possible drought characteristics, Canadian Prairie agricultural region

Drought indices	Projections	Time period	Spatial pattern	Climate models	Comments	References
P-PET	Decrease of about 200 mm and more farther south; driest area expands considerably	2050s mean annual water-year	Greater increase farther south, larger increase in SK	CRCM with CGCM3 HRM3	PET increases in intensity and area with time for all simulations; risk of moisture deficit becomes more severe.	Barrow 2010
AMI	Increase of about 1 degree- day/mm from current 3.5	2050s	Greater increase or dryness farther east	56 climate scenarios with range selected by AMI	Increased dryness occurs for all sites and time periods in the grassland region.	Barrow 2009
Precipitation deficits (monthly)	6- and 10-month droughts worsen	2050s	Southern SK and MB	CRCM with A2	The longer, 10-month drought adds about 4 events in the future.	PaiMazumber et al. 2012

PDSI negative for consecutive summers	Frequency of 3.1/100y for 10y+ droughts; more than 3× current rate	2080s		Statistically downscaled, 5 climate model runs	Frequency also increases for 5y+ droughts compared with instrumental and pre-instrumental.	Bonsal et al. 2013
Summer PDSI (areal average)	Permanent drought occurs after about 2040.	2011–2100 time series	Conditions are worse in the eastern Prairies.	Statistically downscaled with 5 climate model runs	Most statistics show worse droughts, including area, frequency, and intensity.	Bonsal et al. 2013
Multi-year droughts PDSI	Frequency more than doubles to 4.2/100y of 5y or longer droughts.	2011–2100 time series	Time series	Five scenarios ensemble-mean	Frequency of 10y+ droughts or longer triples.	Bonsal et al. 2013

Source: Wheaton et al. 2013.

Notes: PET = potential evapotranspiration; P = precipitation; PDSI = the Palmer Drought Severity Index; SK = Saskatchewan; MB = Manitoba; HRM3 = UK Hadley Regional Climate Model driven by HadCM3; CRCM = Canadian Regional Climate Model driven by CGCM 3 T47.

The annual moisture index (AMI) is GDD/P, the annual growing degree-days (base 5°C) divided by the total annual precipitation; multi-year drought mean duration is the average number of consecutive summers with a negative value of PDSI.

Lessons for the Future from Paleoclimates

At the end of this chapter, we conclude that current and past droughts may seem mild compared with future possible droughts. By "past" droughts we mean those that have affected the Canadian Prairies since agriculture was introduced, that is, those occurring after the settlement of the Prairies by Euro-Canadians. Also, nearly all planning and resource management that involves weather and water is based on direct observations and information collected from water gauges and weather instruments. This direct observation of weather and water began soon after the railroad was built and settlers arrived, so these records appear to be long, but they actually are very short compared to the age of the Prairie landscape and stream network that formed with the retreat of the continental ice sheet between 12,000 and 18,000 years ago. Climate varies over a large range of temporal scales, spanning seasons to climatic cycles that may last for tens of thousands of years. A weather record that spans decades to at most about 100 years will reveal only the shorter cycles. These short weather records are embedded in longer cycles that can be detected only from indirect study or inference of climate from geological and biological indicators (proxies) of climate variability and change.

The past climate or paleoclimate of the Canadian Prairies has been reconstructed from various climate proxies, including trees growing at the margins of Prairie grasslands and in island forests like the Cypress Hills, and the types and relative abundance of certain minerals, plant remains (e.g., pollen, spores, seeds), and aquatic organisms (e.g., diatoms, ostracodes) found in buried soils and lake sediments. The sampling and analysis of these remnants of prior ecosystems has revealed shifts in climate, in some cases abruptly, over the past 10,000–12,000 years of relative landscape stability. For example, the paleoecology of the Peace–Athabasca Delta (Wolfe et al. 2012) and the paleolimnology of Humboldt Lake, Saskatchewan (Michels et al. 2007) show systematic shifts in moisture regime, including extended dry periods (megadroughts) during the Medieval Climate Anomaly in the ninth to eleventh centuries. These past periods of higher temperature and aridity have been used as temporal analogues of the warmer climate emerging as a result of anthropogenic effects.

In Chapter 2, Sauchyn and Kerr look in detail at the nature of these various climate proxies and how they are used to infer past climate and water conditions. Here we are interested in what the paleoclimate of the Prairies can reveal about the climate to expect in coming decades. In the future, our climate will be increasingly influenced by human modifications of the atmosphere and Earth's surface. Anthropogenic emissions of greenhouse gases have been apparent only since the mid-nineteenth century and have become a major factor affecting climate only in recent decades. Knowledge of the regional climate regime is extremely important to detect an anthropogenic signal and to separate natural climate variation from what is human-induced. Future climate will be affected by both, although at some point the distinction between natural and anthropogenic will become irrelevant because the "natural" drives of climate (excluding volcanic eruptions), notably ocean-atmosphere circulation anomalies, are part of an increasingly artificial climate system. The paleoclimate record gives us a baseline; it shows the climate cycles as they exist in a mostly natural climate regime. Climate scientists expect that, for at least the next few decades, regional climate fluctuations will mostly consist of natural climate variability (Deser et al. 2012). This scenario applies, in particular, to regions like the Canadian Prairies that have a high degree of climate variability, and thus where the anthropogenic signal is more difficult to detect against the background of extreme inter-annual and decadal variability.

Based on the research above, we can expect that prolonged and severe droughts, similar to those that are evident in the paleoclimate record and discussed in the previous chapter, will reoccur in the coming decades. These droughts were of longer duration and, in some cases, greater severity than the worst droughts of the post-settlement period—those recorded by weather and water gauges. In the absence of global warming, we would expect unprecedented drought conditions. Global warming only amplifies the probability that future droughts will be more severe than those that have produced much of the adaptation of our communities and economy to a dry climate.

Summary and Conclusions

This chapter reviews recent literature regarding characteristics of future drought in the Canadian Prairies. Overall, research results, especially for the Prairies, indicate that dry times are expected to become much drier, and wet times wetter. Probable future droughts in the Canadian Prairies are likely to be drought types that, although perhaps not catastrophic, have the power to slowly erode adaptive capacity of both human and natural capital. Alternatively, the worst-case scenarios for future droughts may have low probability but could be catastrophic.

Current and past droughts may seem mild compared with future possible droughts, and the disruption of the climate by increasing greenhouse gases might result in some additional surprising effects on climate. The nature of future drought is particularly concerning because of insufficient water for increasing atmospheric demands and increasing (and even stable) societal demands. Much-improved adaptation to extremes, such as drought, is needed.

Estimating future droughts and extreme precipitation has several limitations, but projections using several different indicators, climate models, and emission scenarios provide compelling evidence of the risk of increased intensity, duration, frequency, and area of future droughts and extreme precipitation.

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