Science, Assessments and Data Availability Related to Anticipated Climate and Hydrologic Changes in Inland Freshwaters of the Prairies Region (Lake Winnipeg Drainage Basin)

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ABSTRACT

This report is a review of scientific studies of expected changes to the climate and water cycle of the Canadian Prairies under climate change. Because climate change has been underway for decades, this work reviews both historical trends and future projections. A large section of this review examines studies of surface water levels and geographically of the Saskatchewan River Basin (SRB) because of the large number of available scientific studies. The SRB is the watershed that is most vulnerable to drought given the semiarid climate, large population and extent of agricultural land. The review also includes the Assiniboine, Red, and Winnipeg River Basins, although relatively fewer studies were available. This report is based on the review of almost 100 studies. The majority of these are analyses of historical trends in climate and water variables.

RÉSUMÉ

Le présent rapport est un examen des études scientifiques menées au sujet des changements anticipés du cycle climatologique et hydrologique dans les Prairies canadiennes en raison du changement climatique. Étant donné que des changements climatiques se produisent depuis des dizaines d'années, cet examen se penche à la fois sur les tendances historiques et sur les projections futures. Une grande partie des travaux est consacrée à l'examen des études menées sur les niveaux d'eau de surface et la géographie du bassin de la rivière Saskatchewan en raison des nombreuses études scientifiques dont il a fait l'objet. Le bassin hydrographique de la rivière Saskatchewan est celui qui est le plus vulnérable aux sécheresses, compte tenu du climat semi-aride, du nombre important d'habitants et de l'étendue des terres agricoles. Cet examen se penche également sur les bassins des rivières Assiniboine, Red et Winnipeg, même si relativement peu d'études sont disponibles à leur sujet. Le présent rapport est fondé sur l'examen de près de 100 études, qui sont pour la plupart des analyses des tendances historiques des variables climatiques et hydrologiques.

EXECUTIVE SUMMARY

This report reviews a wide range of scientific studies of recent and expected changes to the climate and water cycle of the Canadian Prairies under global warming. Because global warming has been underway for decades, the studies reviewed include analyses of both historical trends and future projections. The literature on climate and water in the Prairie Provinces is dominated topically by studies of surface water levels and geographically by an emphasis on the Saskatchewan River Basin (SRB). A focus on water quantity is plausible given the historical social, economic and environmental consequences of drought. The SRB is the watershed that is most vulnerable to drought given the semiarid climate, large population and extent of agricultural land. The content of this report reflects this topical and geographic bias in the existing information; however, we also review the relatively fewer studies of the Assiniboine, Red, and Winnipeg River Basins, and the recent research concerning the status of Lake Winnipeg.

This report is based on the review of almost 100 studies. The majority of these are analyses of historical trends in climate and water variables. Through this review it is evident that there are some inconsistent, even contradicting results. This inconsistency generally does not represent disagreement among the scientists, but rather the variability and complexity of the climate and water regimes of western Canada. As a result of this complexity, the monitoring and analysis of climate and water variables can reveal different trends for different time periods and watersheds. Dry climates, like in the Canadian Prairies, have amongst the world's most variable climate and runoff from year to year. Water levels also vary at other time scales, from years to multiple decades. In western Canada, this low-frequency variability in the hydroclimate has been linked to oscillations in sea surface temperature in the Pacific Ocean. The dominant teleconnections are the Pacific Decadal Oscillation (PDO) and El Niño Southern Oscillation (ENSO). The resulting wet and dry cycles can produce what appears to be conflicting trends in water levels, because the analysis and interpretation of water level trends can depend very much on the length of gauge records and the period of observation. The results also depend on the methods of trend detection and statistical analysis. This report notes these differences in methodology and identifies what we consider to be the most robust methods and most reliable results. Despite the complex behaviour of the regional climate and hydrology, and the various data sources and types of analyses, there are some common tendencies in the response of prairie climate to global warming and of prairie water resources to regional climate change. Among the more consistent trends and future scenarios is the shift in precipitation and runoff from late spring and early summer to winter and early spring. Less surface and soil moisture can be expected in the mid-to-later stages of the longer and warmer summers. Rainfall will be more concentrated in time, with larger amounts in fewer storms. As a result, we can expect some unusually wet conditions, but also long dry spells between the less frequent rainstorms. The net result of these hydrological changes is potentially greater risk of more extreme events and more variability in the distribution of precipitation, affecting ecosystems and human needs. These more extreme conditions, and a wider range of water levels and moisture conditions, likely will determine much of the impact of climate change in the Prairie Provinces. Adaptation to avoid the most adverse impacts on aquatic ecosystems and inland freshwater resources must include integrated and adaptive water resource planning and policy to manage a range of variability and extremes that exceed our past experience.

Another consistent tendency among the many trend analyses and climate projections was a contrast between the most western and eastern regions of the Lake Winnipeg Watershed. The Saskatchewan River basin, and runoff from the Rocky Mountains, is characterized by declining streamflow and lake levels in response to wasting glaciers, earlier spring runoff, a shorter cold season and a longer warm season; most climate models project decreased summer precipitation. In the eastern Prairies, on the other hand, there are rising streamflows and lake levels, and most climate models project increased precipitation in all seasons. This geographic discrepancy is highlighted by the contrast between significant decreases in historical and projected flows in the South Saskatchewan River basin and a dramatic increase in the discharge of the Winnipeg River. The greatest risk from climate change to the Red and Winnipeg Rivers may be an increase in flood potential, in contrast to the potential for sustained and devastating drought to the west.

The documented trends and projected climates have significant implications for the freshwater resources of the Lake Winnipeg Basin. The impacts include altered runoff quantity and seasonality, higher water temperatures, longer ice-free season, higher nutrient loading, enhanced algal growth and altered ecosystems evolved for cooler temperatures. The combined effects of changes to water quantity and quality will require changes to land and water management practices. Currently accepted best management practices may no longer fully address the expected changes from a future climate. With increasing water demands, reduced streamflows could routinely lead to deficits for ecological services (environmental flows). Warmer and longer summers will not only increase water demand for agricultural and native ecosystems, but also result in more frequent forest and grass fires, with the associated effects on water quality.

A consistent trend throughout the studies was that summer surface water temperatures will increase in proportion to rising air temperatures. The ice-free season could be nearly a month longer by the end of the 21st century. As air temperatures have risen across the Northern Hemisphere, spring break up has occurred earlier and, to a lesser degree, autumn freeze up has occurred later. Less lake-ice cover will lead to changes in temperature, light levels, UV radiation exposure and water circulation patterns, and consequently to changes in biological diversity and productivity. Variations in light and nutrient availability, water circulation patterns, and layering of warm and cold water during the ice-off period are of particular concern.

Much of the variability in measured water levels, including emerging trends, can be linked to the influence of large-scale ocean-atmosphere circulation patterns. At the same time, there are significant trends in some gauge records that span shifts in the phases of these teleconnections. These consistent trends most likely represent a fundamental change in hydrologic regime in response to regional climate and land use change. The various scales of variability in the regional runoff and hydroclimate require different management practices and adaptation strategies to ensure the efficient and sustainable supply and use of water resources. Current water resource management practices deal relatively well with the large intra-annual variability and the short cycles driven in part by the ENSO. Longer cycles, and associated severe drought and excessive moisture, exceed the length of most instrumental records and water supply planning horizons. Because scientific understanding of this lower-frequency variability, and the drivers (*e.g.,* the PDO), is relatively recent, and the adverse consequences occur less frequent than less severe hydrologic events, there are fewer options for dealing with sustained severe drought or excessive moisture. Besides this natural variability, there are the long-term trends in water levels that are consistent with a warmer climate and loss of permanent land cover. These changes require yet another mode of adaptation involving fundamental institutional and systemic changes in water allocation and use. Detecting these long-term trends, and separating them from transient trends that are artifacts of low-frequency periodic variability, will inform decision making to achieve adaptation to climate change.

While the Canadian Prairies have relatively abundant data and scientific expertise in the realms of climate and water, our review of the state of knowledge revealed some significant gaps in research and information. First, regarding water temperature data, even though they are collected by government agencies, we could find no analyses of historical trends. Similarly, the only projections of future changes in water temperature are for Lake Winnipeg. The other information gap is a current and consistent set of climate change scenarios. For each the many studies of the impacts of future climate change on water quantity and quality, the researchers used projections of changes in climate variables, mostly temperature and precipitation. These projected climate changes vary over a large range of values, because the researchers chose to use different climate models and emissions scenarios. The most comprehensive analyses of future climate are the scenarios developed by the Canadian Forest Service and the Prairie Adaption Research Collaborative. These projects, however, are based on climate models that already have been superseded by a new generation of models. The other shortcoming of the available climate change scenarios is the emphasis on shifts in mean conditions and the relatively few projections of climate and hydrologic variability and extremes. In general, freshwater systems are impacted by and managed for extreme conditions (drought and excessive water levels) rather than for average conditions.

INTRODUCTION

In sub-humid regions like the Canadian Prairies, water is a critical natural resource and vital to the functioning of terrestrial and aquatic ecosystems. In western Canada, water resources are sensitive to fluctuations in climate; some of the major societal stresses have been extremes in hydroclimate impacting every sector of society. Drought is Canada's most costly weather event (Bonsal *et al*., 2011). As the global atmosphere changes, our water resources will come under increasing stress. The Prairie Provinces' water resources have already been extensively modified by human activities (McGee *et al*., 2012).

Most of the population and irrigated agriculture in the Prairie Provinces depends on water from the Rocky Mountains. Deep accumulations of snow shed runoff into the Saskatchewan-Nelson River system in the southern half of the Prairie Provinces and the Peace and Athabasca Rivers flow north to the Arctic Ocean. The Saskatchewan River system drains the southern Rocky Mountains and flows into the north basin of Lake Winnipeg. Other major rivers that flow into Lake Winnipeg include the Red River draining northward into Manitoba from the Dakotas and Minnesota, the Winnipeg River that drains off the Precambrian Shield of Ontario and northern Minnesota, and the Assiniboine River that flows out of southern Saskatchewan. The Nelson River flows from the north end of Lake Winnipeg, north to Hudson Bay. These major watersheds include countless small tributaries and, in many cases, closed sub-basins that never contribute to a water body beyond their own borders.

A shift in the distribution of water resources between seasons, years and watersheds is the major risk from climate change in the Prairies region (Sauchyn and Kulshreshtha 2008). Adaptation to avoid or reduce adverse impacts on communities, economies, and managed ecosystems requires knowledge of past and future trends and variability in surface and soil water balances. Nearly all of the existing information on future climate and water supplies is in the form of change scenarios, that is, the expected shift in mean conditions from the recent past (usually 1961-90) to a future 30-year period, typically 2040-69. The impacts of climate change also include a change in the frequency and severity of climate extremes and departures from average conditions; in particular, excessive moisture and drought. Without knowledge of the future tendencies in the distribution of water among years, decades and watersheds, most decision makers will have limited technical capacity to address adaptive management practices and appropriate policy for planned adaptation to climate change.

In this report we review a wide range of scientific literature that has reported historical observations and expected changes to the climate and water cycle under global climate warming. Our focus is the anticipated climate and hydrologic changes in inland freshwaters of the Prairies region (Lake Winnipeg drainage basin – Figure 1). The discussion of the various climate warming impacts on the water cycle includes the effects of changing precipitation and temperature, the consequences for rivers and watersheds, extreme weather events, changes to water quality, and adaptation of water management to accommodate the response of water resources to climate change. This report places an emphasis on the western part of the Lake Winnipeg basin. This simply reflects a bias in the literature. Notwithstanding a major recent report on the status of Lake Winnipeg (Environment Canada and Manitoba Water Stewardship 2011) and even more recent Special Issue on “Lake Winnipeg - The Forgotten Great Lake” in the Journal of Great Lakes Research (2012), there has been far more research on the Saskatchewan River Basin (SRB) than other parts of the Lake Winnipeg Basin (LWB). This bias is understandable given that 1) the SRB is the largest part of the LWB, 2) it has most of the population, 3) the SSRB is the most stressed river basin in Canada, and the only river basin in Canada to be classified as stressed according to international assessments, 4) it is the source of most of the agricultural chemicals that have upset the nutrient balance of Lake Winnipeg, and 5) there has been considerable research on the impact of a warming climate on recent and projected runoff from the mountain snowpack and glaciers that are the main source of the Saskatchewan River.

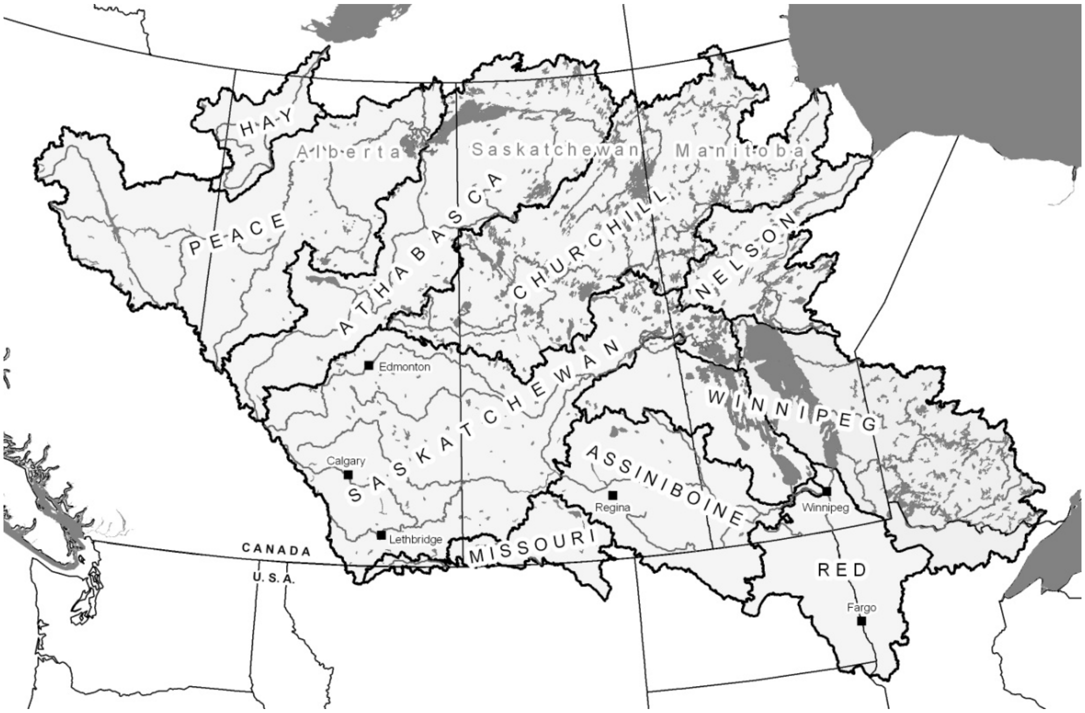

Figure 1: Map of the drainage basins of the Prairie Provinces. The Saskatchewan, Winnipeg, Assiniboine and Red Rivers drain into Lake Winnipeg. (Byrne et al. 2010)

CLIMATE AND WATER

Prairie water levels and processes have marked seasonality. Cold weather processes, including snow accumulation and melt, frozen soils and glacier runoff, influence the hydrology of Western Canada (Pomeroy *et al.* 2007; Toth *et al*. 2009). During the fall and winter, water is mostly stored as snow and ice. In early spring, the rapid release of water from melting snowpacks lying over frozen ground produces high surface runoff. Snow is about a third of the annual precipitation, but accounts for about 80% of the runoff and most of the water that fills lakes, sloughs, dugouts and reservoirs, and recharges soil moisture and groundwater storage. In late spring and summer, most water is stored as soil moisture, and very little rainfall ever runs off. Plant water use rapidly depletes soil water and dry soils absorb most summer rains, leading to little runoff. The exceptions are intense summer convective storms over narrow swaths of land. Generally, the least rainfall falls during the period from mid-summer to fall and, therefore, soil moisture, actual evaporation, and runoff reach an annual minimum.

The water balance defines the nature and distribution of the ecosystems of the Prairie Provinces. A balance of precipitation to water loss by evapotranspiration separates the forested area from the grassland (Hogg 1994). Over much of the northern half of the Prairie Provinces, short cool summers and long cold winters, combined with more precipitation than in the grasslands, support boreal forest. Here, runoff occurs in all seasons; there are extensive wetlands that store snowmelt and rainfall and release it slowly. Evapotranspiration usually is close to rainfall in warmer years.

In the Prairie Ecozone, snowmelt and rainwater are consumed in most years by evapotranspiration, and only upland areas with island forests generate runoff. Runoff is highly variable with a large snowmelt streamflow pulse in the spring. In the rainshadow of the Rocky Mountains, low annual precipitation in the range of 300-400 mm generates very little runoff. In this dry landscape of glacial landforms; the drainage is poorly developed and therefore there are large areas of internal drainage that do not contribute to the major river systems. Numerous small, closed depressions (sloughs and wetlands) tend to be disconnected from the stream network, but can be important local recharge for shallow groundwater aquifers. Local prairie water resources are limited and very sensitive to changes in climate and land cover. Management of these limited and variable water supplies is challenging in periods of extreme drought. Thus, few prairie streams can be managed for substantial water consumption or irrigation, and groundwater and mountain-fed rivers are the most reliable water supplies (Pomeroy, et al. 2007).

One of the most unique characteristics of the climate of Canada's western interior is the large year to year variation. The climate tends to flip between wet and dry at regular intervals. These wet-dry cycles are associated with atmospheric circulation patterns and feedback between the atmosphere and surface conditions (snow and ice cover, vegetation, soil moisture, and sea-surface temperatures (SSTs)) that force the land surface through variations in their optical and thermal properties (Maybank *et al*. 1995). Droughts result from anomalous circulation patterns in the mid to upper atmosphere. They tend to be intensified by high temperatures and evapotranspiration (Bonsal *et al*. 1999; Shabbar *et al*. 2011; Sauchyn and Bonsal in press). They also can be initiated and/or amplified in winter by persistent mid-tropospheric circulation patterns (Shabbar *et al*. 1997). The linkages between regional climate and large-scale atmospheric circulation is known as teleconnections. Studies of teleconnections and the climate of North America have linked the El Niño/Southern Oscillation (ENSO) with winter/spring temperature and precipitation; El Niño is generally associated with warmer/drier winters and La Niña with colder/wetter winters (Shabbar and Khandekar 1996; Shabbar *et al*. 1997). Other teleconnections, the Pacific Decadal Oscillation (PDO) and the North Atlantic Oscillation (NAO), also have an affect mainly during the winter season (Bonsal *et al*. 2001).

Climate controls the thermal regime of lakes, the growth and decay of winter ice cover, and the warming and stratification of the water column through the spring and early summer, with cooling and turnover through autumn. Primary productivity, in particular cyanobacterial productivity, and eutrophication in general, are positively correlated with summer temperature (Park *et al*. 2004; Hamilton *et al*. 2005; Milius *et al*. 2005). Surface blooms of phytoplankton tend to be larger and more intense in warmer years if nutrient concentrations are sufficiently high. McCullough and Levesque (2011) suggested that "if greater summer warming leads to more frequent stratification, then dissolved oxygen concentration in bottom waters may be reduced, possibly to the point of anoxia in the hypolimnion or surface sediments and internal nutrient loading may be increased". In a new paper, McCullough *et al*. (2012) concluded that higher flows in the Red River have caused a sudden doubling of total phosphorus and a shift to a cyanobacteria-dominated plankton population in Lake Winnipeg.

RECENT TRENDS IN CLIMATE AND FRESHWATER RESOURCES

TEMPERATURE

Recent trends in the climate of Canada, including the Lake Winnipeg Basin, have been the subject of various studies (Gan 1998; Akinremi *et al.* 1999; Beaubien and Freeland 2000; Zhang *et al*. 2000; Bonsal *et al*. 2001; Zhang *et al*. 2001; Shabbar and Bonsal 2003; Bonsal and Regier 2007; Dibike *et al*. 2012). The trends identified over Western Canada include significant decreases in cold spell frequencies and extreme low temperature during 1900–1998. There are also trends toward more days with extreme high temperature in winter and spring, but these are not as pronounced as the decreases to extreme low values. The number of frost days over most of Alberta and Saskatchewan have decreased, with a few minimal increases scattered throughout the provinces. The frost-free season is longer mostly due to an earlier start and similar ending date. Warmer winter/spring temperatures are correlated with earlier spring flowering in central Alberta; eight days earlier at Edmonton over the last six decades (Beaubien and Freeland 2000). The blooming of aspen poplar is almost a month earlier than a century ago.

The temperature time series in Figure 2, for 12 communities spanning the Prairie Provinces, illustrates that average annual temperatures have been rising since weather stations were first established in the 1880s; although there is considerable variability from year to year. In fact, the Prairies have Canada's most variable climate and are among the most variable climates in the world. Trends in the frequency of extreme daily temperatures, and analyses of annual and seasonal temperature trends, strongly suggest that Western Canada is not getting hotter, but rather less cold. There has been a greater increase in daily minimum (as opposed to maximum) temperatures, and the largest warming has occurred during winter and early spring. Increases during summer have only been observed for minimum temperature. This observed warming has beneficial effects that include a longer frost-free period and more growing degree days. However, changes to the timing of temperature-related hydrological events (*e.g.* spring runoff) could ultimately have adverse effects on mid- to late-summer water supplies (Qian *et al*. 2010; Zhang *et al*., 2000).

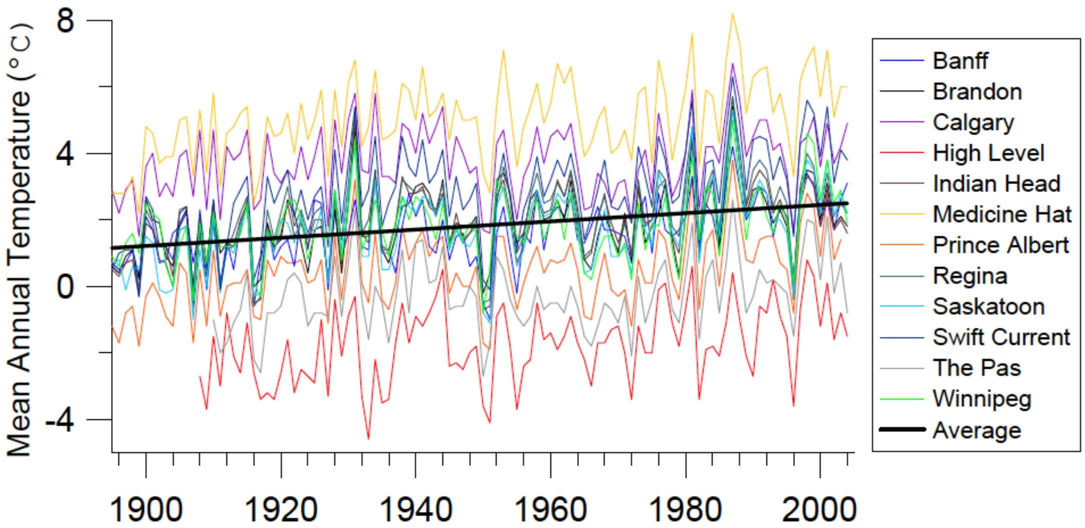

Figure 2: Mean annual temperature records from across the Prairie Provinces for the period 1895-2005. For these 12 long records, there was an average increase of 1.6 degrees from a low of 0.9 at Calgary to 2.67 at Swift Current. (Sauchyn 2010)

Over southern Canada (south of 60°N) mean annual air temperature increased by an average of 0.9°C from 1900 to 1998, with greatest warming in the west during winter and spring (Zhang *et al*. 2000). For 10 climate stations in the Prairie Provinces, Schindler and Donahue (2006) reported increases in mean annual temperatures of 1.0 to over 4.0 °C since the early 20th century. Zhang *et al*. (2000) reported a spring warming trend in Manitoba and Northern British Columbia. Gan (1998) determined that, in the past 50 years, the Prairies were experiencing an extensive warming and relatively significant drying trend. He detected a significant warming in January, March, April, and June, and concluded that the statistical results were strong enough to suggest that the temperature trends in the Prairies is likely attributed to global warming. Gameda *et al*. (2007) found that mid-June to July maximum temperatures have declined in the cultivated regions of the Prairies. This very specific midsummer cooling is attributed to strong regional influences of large-scale declines in summer fallow land management practices. However, analyses by Millett *et al*. (2009) of temperature trends for a series of climate stations located across the entire southern Prairies and into the Dakotas reported average daily air temperatures have risen about 1°C in 95 years compared to about 0.6° C of global warming in the same period. Millett *et al*. (2009) also report greater winter warming overall due to substantial increases in minimum temperatures.

The data reported by Gameda *et al*. (2007) suggest that the general warming trend observed over the Prairies has been mitigated by cooling in summer associated with changes in agriculture summer fallow practice. Regional warming may be greater than reported by Gan (1998) and Millett *et al*. (2009), as land-use changes may be mitigating overall global warming effects. Any cooling benefits due to the reduction in summer fallow have likely been negated because summer fallow is no longer a widespread practice; so continued warming of the Prairies is likely. Overall, the literature discussed above supports the contention that warming of the Prairie Provinces will exceed the global average, exacerbating our global warming challenges.

The most recent analysis of climate trends in the Lake Winnipeg Watershed (LWW) was completed by Dibike *et al*. (2012). They used the daily 10-km Gridded Climate Dataset for Canada (GCDC), that includes high resolution gridded daily maximum and minimum air temperature (°C) south of 60° N for the period 1961–2003(Hutchinson *et al*. 2009). They applied the non-parametric Mann–Kendall test of significance to trends in annual and seasonal mean values. The trends in seasonal mean maximum (Tmax) and minimum (Tmin) temperatures are mapped in Figure 3. With the exception of southwestern Alberta and southern Saskatchewan, that is much South Saskatchewan River Basin, there has been a significant ($p < 0.05$) increase in winter Tmax but not in the other three seasons. Tmin, on the other hand, has increased significantly across the LWW, other than southern Alberta, and in all seasons, except autumn. In all seasons, daily Tmin has risen at a faster rate than the daily Tmax.

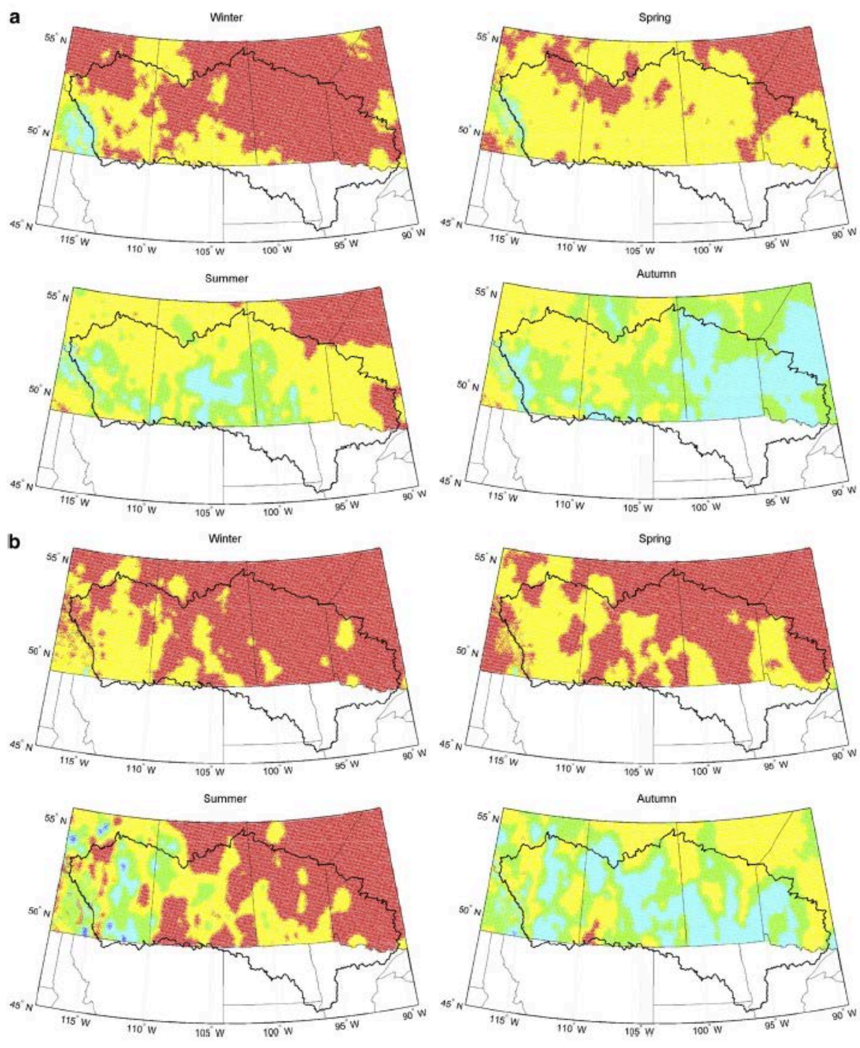

Figure 3: Trends in seasonal mean maximum temperature (a) and minimum temperature (b) during 1961–2003 in the Lake Winnipeg Watershed at the 5% significance level. Red — significantly increasing; Yellow — increasing but not significant; Dark Blue — significantly decreasing; Blue — decreasing but not significant; Green — no trend. (Dibike et al. 2012)

PRECIPITATION

Changes in precipitation in the historical record are difficult to define due to the extreme variability. In Figure 4, total annual precipitation recorded at Medicine Hat is plotted as positive (blue) and negative (red) departures from the annual average. While the mean value is 384.5 mm, precipitation has ranged from 185.5 mm in 2001 to 689.3 mm in 1927. Precipitation swings from large deficits to large surpluses between years (*e.g.* 2001 to 2002) and decades (*e.g.* 1917-24 versus the 1950s). An often used measure of variability is the ratio of the standard deviation for a set of statistics to their mean value. When Longley (1952) determined this coefficient of variation (CV) for precipitation records from across Canada, the highest values (largest inter-annual variation) occurred in the Prairies over an area roughly corresponding to the Saskatchewan River Basin (SRB), Canada's largest dryland watershed. The CV in this region exceeds 25%; at Medicine Hat, it is 28.5%.

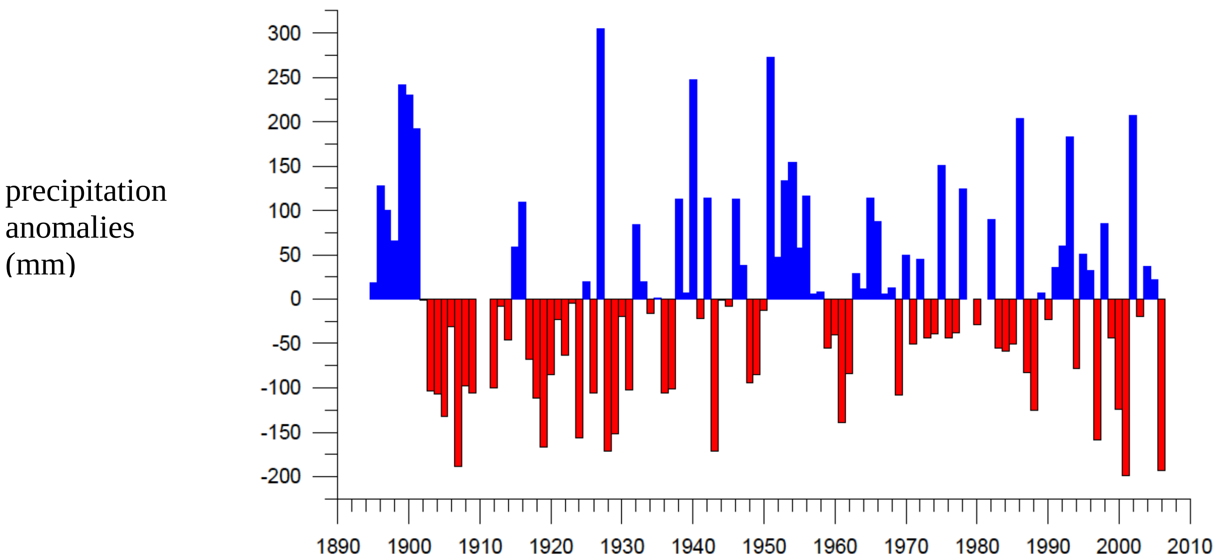

Figure 4. Positive (blue) and negative (red) departures from mean annual precipitation (mm), Medicine Hat, Alberta, 1895-2006. (mean= 384.5mm) (Sauchyn 2010)

In general, annual precipitation has increased over most of southern Canada with the exception of southern Alberta and Saskatchewan, where drought and its consequences are most severe. While historical declines in mean annual precipitation have occurred for the western part of the Prairie Provinces, the opposite may be happening for eastern regions. Millett *et al*. (2009) examined twentieth-century precipitation trends and found that annual precipitation is declining in some parts of Alberta, but an opposite trend was detected for stations in southeastern Saskatchewan and Manitoba. Schindler and Donahue (2006) reported declines in annual precipitation of 14 to 27 % since early in the 20th century at six western prairie province climate stations with reliable long term records. Older work by Gan (1998), using the period 1949-89, suggests that the southern half of the Prairie Provinces had become somewhat drier. Gan's work uses more western than eastern climate stations, which may explain a bias towards drying.

Precipitation trends include changes in storm behaviour. Akinremi *et al.* (1999) determined that the total number of precipitation events in the Canadian Prairies increased from 1920-1995. Over half of the days with precipitation in that time frame had recorded depths of less than 5 mm; precipitation increased in the period 1956-1995 due to a higher frequency of low-intensity events. Small precipitation events are captured in the vegetation, resulting in more water being lost by evapotranspiration, and less water reaching the soil, rivers, lakes, wetlands, and the water table. Other more recent studies, show recent trends and model projections of increasingly intense precipitation (Stone *et al.* 2000; Kharin *et al*. 2007). If precipitation is delivered in fewer and more extreme events, the intervening weather will tend to be drier and, thus, both drought and unusually wet conditions are expected to be more common with climate change.

The Mann–Kendall test of trends in gridded climate data by Dibike *et al*. (2012) revealed that over a large part of the LWW winter precipitation declined significantly over the period 1961–2003 (Figure 5). This decline was especially pronounced in western Ontario, Alberta and western Saskatchewan. Otherwise the only significant trend is increasing summer precipitation in parts of Manitoba. It should be noted that Dibike *et al*. (2012) did not account for low-frequency variability which is characteristic of western Canadian precipitation, especially in winter. Thus, for example, the decreasing trends detected by Dibike *et al*. (2012) could be attributable in part to a step change between generally higher precipitation in the 1950s through mid-1970s and the drier decades of the 1980s through early 2010s (St. Jacques *et al*. 2010).

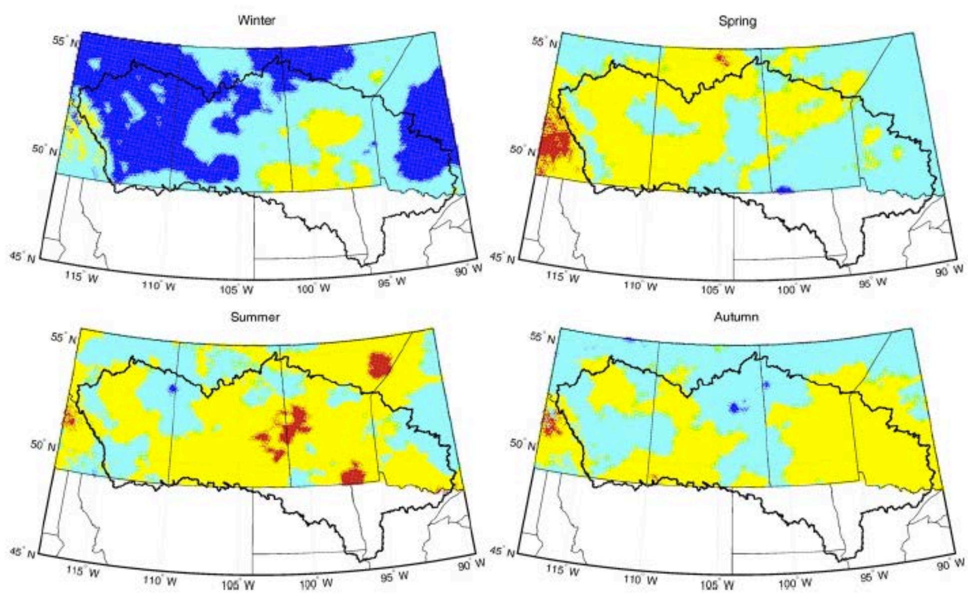

Figure 5: Trends in seasonal precipitation (1961–2003) in the LWW at the 5% significance level. Red — significantly increasing; Yellow — increasing but not significant; Dark Blue — significantly decreasing; Blue — decreasing but not significant; Green — no trend. (Dibike et al. 2012)

Whereas precipitation is the measure of the delivery of water from the atmosphere, effective precipitation is the water that is actually available to ecosystems and for human use. Two popular measures of effective precipitation are the climate moisture index (CMI = precipitation (P) – potential evapotranspiration (PET))and the Palmer Drought Severity Index (PDSI), which like the CMI is a function of P and PET but also has a soil moisture storage term (Hogg 1994). Historical trends in the summer CMI suggest drier conditions of 1-2 mm/yr in southwest and west-central Alberta and an even larger deficit of 1-4 mm/yr in southern Saskatchewan. This drying trend throughout west-central and southern regions of the Prairies is in contrast to increased CMI (*i.e.* less dry conditions) along the Rocky Mountains and in northwestern Alberta. A recent drying trend reflects the extent and severity of the 2001-2002 drought following an absence of dry years; 2001 and 2002 were the worst drought years since 1961, and the worst two-year drought since 1929–1930. Millett *et al*. (2009) reported that historical trends in the Palmer Drought Severity Index (PDSI) reflected a wetter water balance for the far southeastern Prairies, but a general drying trend in the western Canadian Prairies. There has been a decreasing PDSI trend (*i.e.* more drought) over most of the Canada from 1950-2002; with significant positive trends (from 1895-2007) in growing season and annual standardized precipitation index (SPI) values (Qian *et al*. 2010). A general increase in precipitation has been offset by an increase in temperature, creating more evaporative demand. Using the SPI and PDSI as drought indicators, Bonsal and Regier (2007) showed that the worst and most prolonged Canadian Prairie-wide droughts during the period 1915 to 2002 occurred in the early part of the 20th century (1920s and 1930s). Figure 6 provides an example of 20th century PDSI time series for Saskatoon. The series shows considerable decadal-scale variability and anomalously negative PDSI values (*i.e.* drought conditions) during the late 1990s to early 2000s.

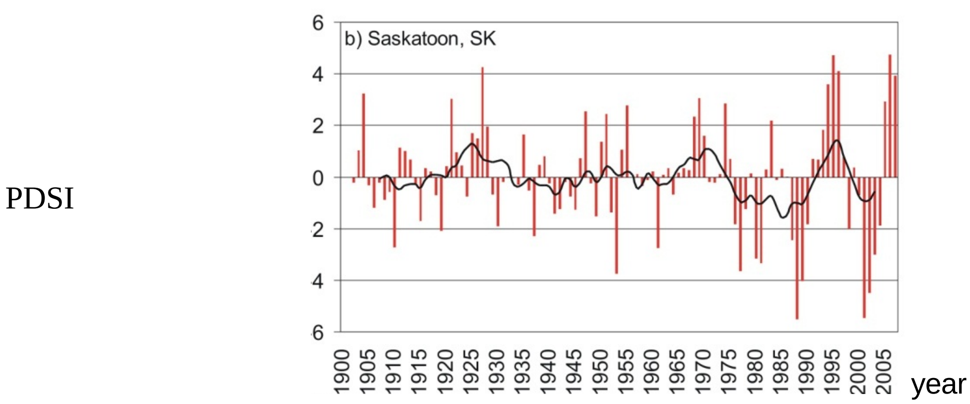

Figure 6: Annual Palmer Drought Severity Index from 1900 to 2007 for Saskatoon, SK. Solid lines represent 10-year running means (Sauchyn and Bonsal in press).

SURFACE WATER

Over the last 30 to 50 years, mean stream flow has decreased in many parts of Canada with significant reductions in the south (Zhang *et al*. 2001). Over south central Alberta and Saskatchewan, water levels of most closed-basin lakes have declined throughout the 20th century (van der Kamp *et al*. 2008). The lake level time series in Figure 7 show, until recently, general declines in four Saskatchewan lakes, but rising levels of Devil's Lake, North Dakota (van der Kamp *et al*. 2008). These contrasting lake level data reflect the previously noted difference between drying trends in the western prairies versus increasing precipitation to the east.

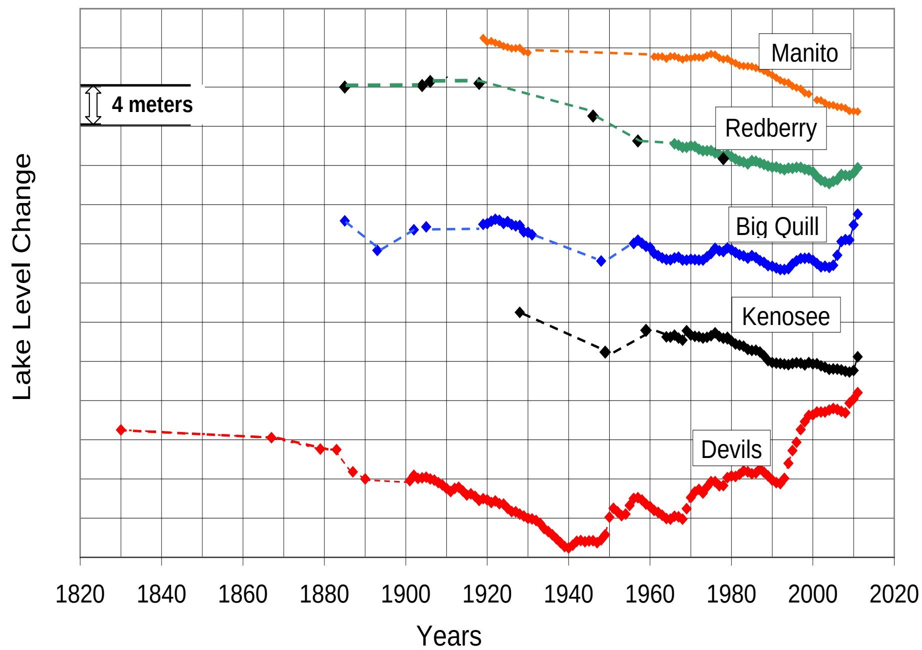

Figure 7: Prairie lakes 1820 – 2011: Devil's Lake (North Dakota) is rising since 1940 while nearby Canadian prairie lakes (Kenosee) were falling (lake level change (m)), until recently (van der Kamp et al. 2008)

The strongest surface water trends are in the large rivers emanating from the western mountains. Declining summer streamflow is largely temperature driven in response to retreating glaciers and early melt of the winter snowpack. Demuth and Pietroniro (2003) concluded, "*The reliability of water flow from the glaciated headwater basins of the upper North Saskatchewan River Basin has declined since the mid-1900s. Hydrologic and ecological regimes dependent on the timing and magnitude of glacier-derived meltwater may already be experiencing the medium-long-term impacts of climate change discussed by the IPCC."* Whereas wasting glaciers are a symbol of global warming, the attention they receive gives the impression that, with the loss of glaciers, we are losing our water supply. However, snow not glacier ice is the source of most of our water. At Edmonton and Calgary, the contribution of glacier melt to the North and South Saskatchewan rivers, respectively, is less than 3% of annual regulated flow; although glacier meltwater can represent up to 10% of annual flow for many headwater streams in the Rocky Mountains (Comeau *et al.* 2009). Glaciers also represents a significant proportion of the late summer flow of the mountain rivers, especially in dry and/or hot years when the snow pack disappears early in the year. Thus, the demise of the Rocky Mountain glaciers will have adverse impacts by eliminating natural storage in the driest years. The loss of the mountain glaciers is an indicator of the combined impacts of declining winter snow accumulations and longer melting periods. Coincident with large increases in winter/spring temperature, reductions in snow-cover extent and duration have occurred in the latter half of the snow season and especially in April (Brown 2000; Dery and Brown 2007; Brown and Mote 2009).

Low stream flows have been observed with increasing frequency on the Canadian Prairies, and low flow magnitude declined during the period 1912-1993 (Yulianti and Burn 1998). Burn (1994) investigated the spring snowmelt and subsequent runoff events as indicators of climate change in 84 unregulated river basins across Western Canada. He found that rivers located at higher latitudes experienced greater advances in the timing of the peak spring runoff event. Thirty percent of the unregulated rivers showed a statistically significant change to earlier spring runoff. This earlier runoff will result in a decline in late season streamflow, as more heat units associated with longer warmer summers increase evapotranspiration potential, effectively transpiring soil water and increasing potential soil water storage. Zhang *et al*. (2001) found that mean annual streamflow in Canada decreased in the latter 50 years of the last century. Mote (2006) found consistent declining trends for 1950-97 snowpacks for much of western North America, including the Rocky Mountains of Montana and Alberta. Trend analysis studies reveal prominent streamflow declines in Alberta and adjacent states and provinces (Rood *et al*. 2005). Overall, rivers draining from the triple continental divide in northern Montana displayed a reduction in discharge of 0.22% per year for the period of available records. From further trend analysis work on the historical streamflow record, Rood *et al*. (2008) concluded that winter flows (especially March) were increasing slightly, spring run-off and peak flows are occurring earlier in the year, and summer and early autumn flows (July–October) were considerably reduced. This trend is indicative of the expected shift of the hydrological balance under climate warming scenarios (Zhang *et al*., 2001). The increase in March streamflow may be attributed to an increase in spring precipitation as rain, combined with an earlier snowmelt (Burn 1994; Gan 1998; Leith and Whitfield 1998; Zhang *et al*. 2001).

St. George (2007) analyzed nine long-term gauge records in the Winnipeg River Basin, looking at historical trends and links to climate variability. Figure 8 illustrates that mean annual flows of the Winnipeg River at the Slave Falls gauging station increased significantly from 1924 to 2003. By 2003 annual flows had increased by 58% relative to mean flows in 1924. Most of this increase in discharge has occurred during November to April, with increases ranging from 60% to 110%. This trend of higher winter flows also applies to the gauges upstream from Slave Falls. There are no significant trends in summer flows. Some of the increasing trend could be attributable to flow regulation and diversion, however, these trends occur consistently among gauges in the upstream reaches of the WRB.

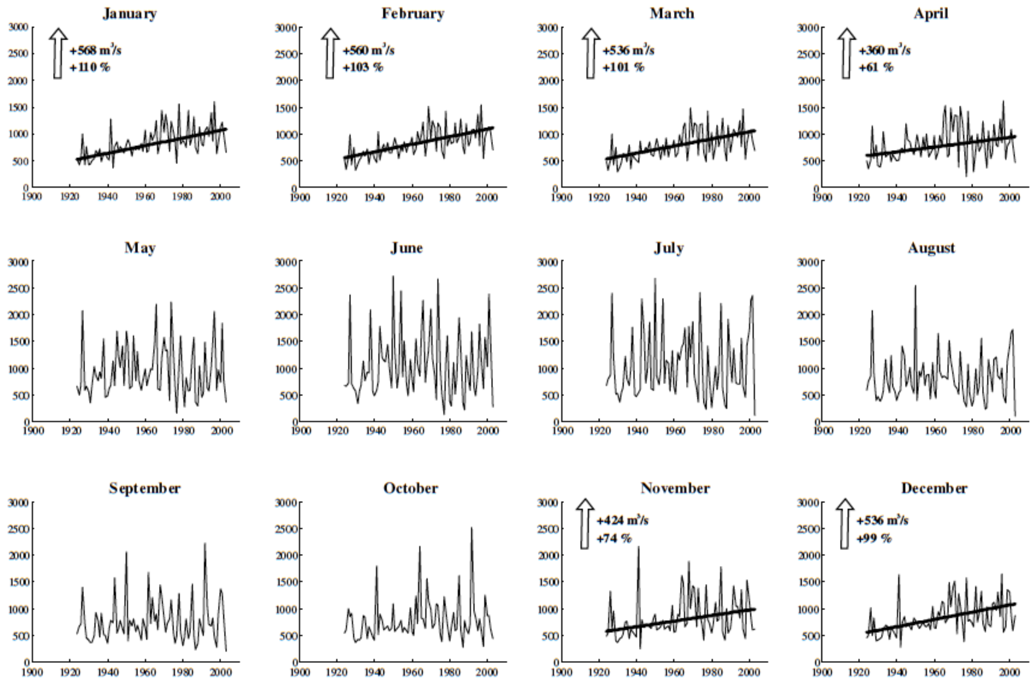

Figure 8: Linear trends in monthly streamflow (m3/sec) for the Winnipeg River at Slave Falls from 1924 to 2003. Statistically significant increases in flow are highlighted with a heavy line. Total and percent changes are expressed relative to the beginning of the trend line. Annual discharge is expressed in m3/s. (St. George 2007)

St. George (2007) provided the following interpretation of these water level trends in the WRB:

> *"Rising winter discharge across the basin has coincided with increasing annual and seasonal precipitation. Total annual (October–September) precipitation at Kenora, increased by approximately 108 mm (15.5%) since 1924. This change largely reflects increases in summer (May–July) and autumn (August–October) precipitation, as no significant trends were observed for winter (November to January) precipitation, and precipitation during spring (February to April) decreased by 25%. No significant trends were identified in annual, monthly or seasonalised temperature records from Kenora. The changes observed at Kenora are part of a general increase in precipitation across much of northwestern Ontario. Summer precipitation has risen from between 20% to 60% in the eastern sector of the English River basin, the north end of Lake of the Woods, and in the Whitemouth basin of southeastern Manitoba. Autumn precipitation has increased over a much more extensive area, with changes of +40 to +60% occurring over most of the north-central and northeastern part of the Winnipeg River basin."*

The results obtained by St. George (2007) for the Winnipeg River differ significantly from the tendencies for other rivers in Canada including other basins in the Lake Winnipeg Watershed (Rood *et al*. 2005; Lapp *et al*. 2009; St. Jacques *et al*. 2010; Kienzle *et al*. 2011). The more common tendency is towards declining annual and summer flows. In this respect, the situation for the Winnipeg River may be more similar to hydroclimatic conditions in the upper US Midwest. The rise in winter streamflow by 60 to 110% occurs throughout the WRB, at both regulated and unregulated gauges, suggesting climate factors are the underlying cause of the higher flows. This implies that future flows derived from climate models may differ from the streamflow projections for other basins in the LWW. From climate model projections, increases in runoff of 20 to 30% are anticipated for northern and central Manitoba by mid-21st century (St. George 2007). "These projections, and the observation of increasing flows in the WRB, suggests that it seems likely that the potential threats to water supply faced by the Canadian Prairie provinces over the next few decades will not include decreasing streamflow in the Winnipeg River basin." (St. George 2007).

The various trend detection studies reviewed in this report have not necessarily used the most robust methods; transient trends can be an artifact of short record length and low-frequency variability. There are many problems with analyzing the instrumental streamflow records simplistically using methods such as ordinary least squares regression techniques. These records can be discontinuous, and short, for instance, in Saskatchewan having periods of record of ~35-50 years with a few exceptions. The naturally-flowing streams in the southern Prairies can have years of no flow, but also outlier years of exceptionally high flows, i.e, extremely flashy flows with a very non-normal distribution. There is frequent positive autocorrelation in many river discharge time series, which results in the overestimation of the effective sample size of the residuals in classical linear regression and Mann-Kendall non-parametric methods (Kulkarni and von Storch 1995; Zheng *et al*. 1997; Cryer and Chan 2008). Therefore, these methods will disproportionately reject a null hypothesis of no trend (Zheng *et al*. 1997; Zhang *et al*. 2001; Burn and Hag Elnur 2002; Yue *et al*. 2002a). Lastly, there is heavy human impact from water consumption, diversion and storage, especially in the larger rivers of the southern Prairies, which overlays and obscures the natural hydrology. Any analysis of the Canadian Prairie hydroclimatology must work within the limitations of the streamflow datasets available through the Water Survey of Canada and various provincial government agencies. Saskatchewan hydrological records are the shortest, with a mean period of record of 48 years, followed by those from Manitoba (average length 51 years) and Alberta (53 years).

Declining runoff trends should be interpreted with care in Alberta and southwestern Saskatchewan as streamflow is strongly affected by the Pacific Decadal Oscillation (PDO). The ~60 year low frequency cycle of the PDO can potentially generate a declining linear trend in short instrumental streamflow records. Many gauge records begin in the 1950s or 1960s (a period of strongly negative PDO, hence high prairie streamflow), or omit the 1930s and 1940s (periods of high positive PDO, hence low prairie streamflow). Therefore, any trend line fit between this initial high flow period followed by the subsequent low flow period of the 1980s-2000s (positive PDO) shows a declining trend. If this influence of the PDO is not taken into account in an analysis of prairie instrumental hydroclimatic records could produce declines that could be attributed to climate change, while they are actually artifacts of the sampling period and the PDO phase changes (Chen and Grasby 2009). Very few western streamflow trend analyses have considered the issue of PDO phase (Rood et al. 2005; Luce and Holden 2009; St. Jacques et al. 2010 are exceptions). One solution is to weigh more heavily records spanning more than one PDO cycle in length. The six declining gauge records in the southwest Prairies are among the longest streamflow records, with five beginning in the 1910s or 1930s, spanning more than one PDO cycle; therefore, the declines are less likely to be artifacts of the PDO phase. Zhang *et al.* (2001), using the MK test on pre-whitened data, found similar declining annual mean streamflow at naturally flowing gauges in the southwest Prairies over an earlier period of record. Rood *et al.* (2005; 2008) and St. Jacques *et al.* (2010) also detected declining trends in southern Alberta naturally-flowing stream gauge records. St Jacques *et al*. (2010) analyzed trends and variability in the observed and naturalized flow of the major streams in southern and central Alberta. A Generalized Least Squares (GLS) regression model was derived for each gauge using, as predictors, trend plus natural large-scale climatic drivers of hydroclimatic variability: the Pacific Decadal Oscillation (PDO), El Niño Southern Oscillation (ENSO) and North Atlantic Oscillation (NAO). Results for the North Saskatchewan River at Edmonton are plotted in Figure 9. The black curves are the recorded (top) and naturalized (bottom) annual flow from 1912 to 2007 and the blue curves are the flows predicted by the GLS models. The regression models capture 54% of the variability in both recorded and reconstructed flow. Also shown as a solid red line are declining trends in recorded and naturalized flow of 0.14% and 0.10% per year, respectively, over the length of the record. This decline has been documented previously and attributed to a loss of glacier mass in the upper reaches of the watershed, resulting in significant declines in mid-summer and autumn flows (Demuth and Pietroniro 2003).

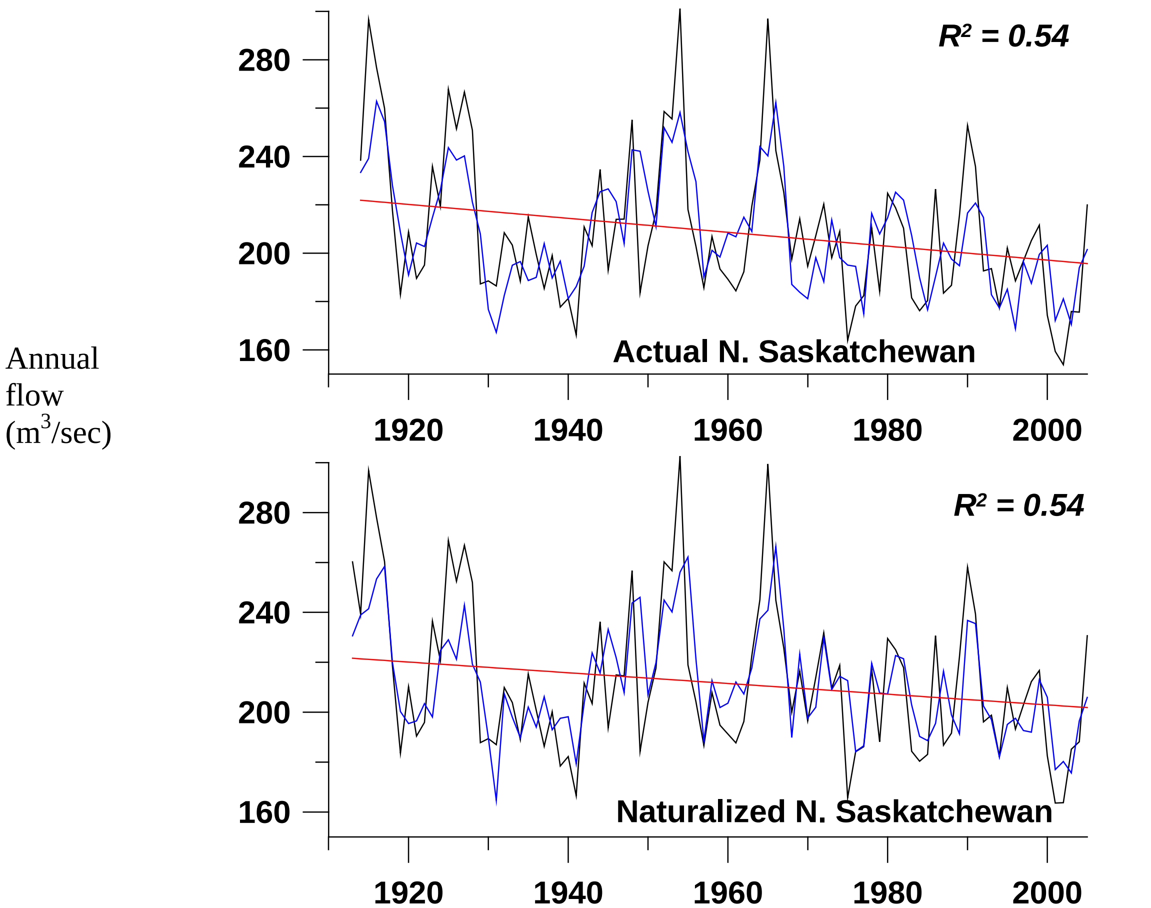

Figure 9: The recorded (top) and naturalized (bottom) annual flow (black curve) of the North Saskatchewan River at Edmonton, 1912-2007 (Alberta Environment, 2003). A regression model (blue curve) based on natural drivers (PDO, ENSO, NAO) of hydroclimatic variability captures 54% of the variability of the flow (St Jacques et al. 2010). In addition to this inter-annual to inter-decadal variability there is significant declining trend over the length of the record as shown with solid red line.

While the hydroclimatology of southern Alberta has been well-studied recently (*e.g.*, Stewart *et al*. 2005; Gobena and Gan 2006; Gobena and Gan 2009; Fleming *et al*. 2007; St. Jacques *et al*. 2010), northern Alberta, Saskatchewan and Manitoba has been examined much less and less recently (*e.g.*, Gan 1998; Zhang *et al*. 2001; Woo and Thorne 2003; Burn *et al*. 2008). Because trend analyses of Prairie rivers annual discharges are either not based upon recent data (*e.g.*, Westmacott and Burn 1997; Gan 1998; Yulianti and Burn 1998; Zhang *et al*. 2001) and/or do not deal with the problem of autocorrelation biasing the trend test (Burn *et al.* 2008; Khaliq *et al*. 2009), St. Jacques *et al*. (In press) examined streamflow records from through-out the Prairie Provinces. They extracted the streamflow records from the Water Survey of Canada (HYDAT; www.wsc.ec.gc.ca) database, augmented by internal data from Saskatchewan Watershed Authority, Alberta Environment and Manitoba Hydro (Figure 10). In total, 86 stream discharge records were analyzed: 37 in Alberta and environs, 27 in Saskatchewan, and 22 in Manitoba; most had active gauges. Mean daily flow records were averaged over January-December or March-October. Trends in annual (or warm season, as appropriate) mean daily flow (m^3/s) for the 86 Prairie records were assessed by the non-parametric Mann-Kendall (MK) statistical test (Mann 1945; Kendall 1975). Significance levels of $p \leq 0.05$ and $0.05 < p \leq 0.10$ were used in trend detection following standard hydrological practice (Smith *et al*., 2007). The results obtained by St. Jacques *et al*. (In press) are plotted in Figure 10 and tabulated in Appendix A.

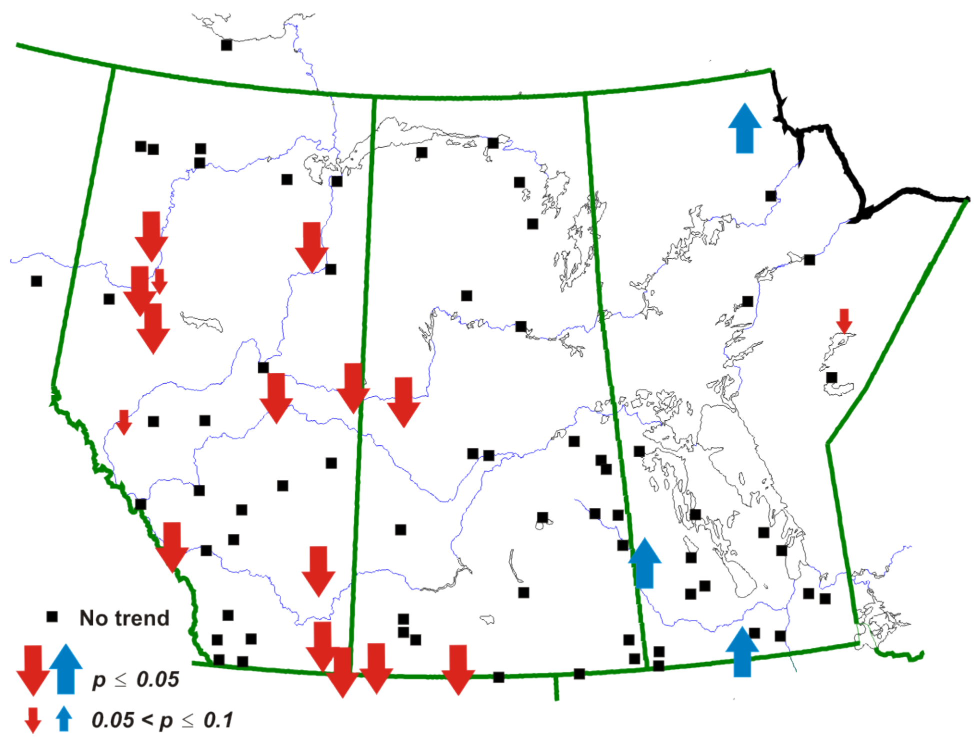

Figure 10: Trends in prairie streamflow at 85 unregulated gauges. Red/blue arrows indicate downward/upward trends. (St. Jacques et al. In press)

The modified Mann-Kendall trend tests demonstrated a distinct geographical pattern with significant declines in the west and significant increases in the east (Figure 10). There are 12 declining trends (10 significant at the $p \leq 0.05$ level) throughout

Alberta, which extend into western Saskatchewan as three further declining trends (all significant at the $p \leq 0.05$ level). On the other hand, there are three highly significant increasing trends in southern Manitoba, and one increasing trend (significant at the $p \leq 0.05$ level) at Seal River, and one decreasing trend at Gods River, both in northern Manitoba. There are declines in annual mean daily flow in the naturally-flowing streams throughout Alberta and southwest Saskatchewan, no significant trends in the central region and increased flows in Manitoba in both the far north and south (Figure 7). If these trends have occurred by chance, with a 5% significance level, one would expect ~4 of the 85 naturally-flowing streams to show a significant trend; there would be no geographical pattern in the trends, and no geographical consistency of trend sign. Therefore, these patterns are most likely real. The non-parametric Mann-Kendall test used in the analysis is a relatively low-powered test, *i.e.,* a large change must have taken place before the MK test is able to detect it (Sokal and Rohlf 1995; Yue *et al*. 2002b). There could be further declines or increases present that a more powerful test could detect. Zhang *et al*. (2000) provide a climatological context for these trend results. In their analysis of Adjusted Historical Canadian Climate Data, they showed that the Prairie Provinces have become significantly warmer over the past century, as well as wetter (significantly wetter in the Rocky Mountains, in the far north and in eastern Manitoba).

Composite analyses based upon Monte Carlo permutation *t*-tests show that the Pacific Decadal Oscillation (PDO), North Pacific Index (NPI) and Pacific North American Index (PNA) have a clear impact on Prairie annual mean daily discharge, with higher annual discharges occurring during negative PDO, high NPI and negative PNA years, and lower flows during the positive PDO, low NPI and positive PNA years throughout most of the Prairie Provinces (St. Jacques *et al*. In press). Composite analyses also show the weaker impact of ENSO, and the weaker still effect of the AO, again with usually higher flows during La Niña and the negative AO years throughout the region, and usually lower flows during El Niño and the positive AO years. The phase relationships are reversed in the very far north for the Pacific-based climate patterns, where discharges were higher during the positive PDO, low NPI, positive PNA, and El Niño years or conversely where discharges were lower during negative PDO, high NPI, negative PNA, and La Niña years. Unlike the Pacific-based climate oscillations, the AO's fingerprint on streamflow is weakest in the west and strongest in the east and shows a negative relationship in the central Prairies, which reverses in the periphery. As expected, patterns of streamflow variation according to climate oscillation phases closely followed the patterns of precipitation variation according to climate oscillation phases. An examination of the effect of PDO phase on the probability of two years of successive least (or highest) quartile flows of Saskatchewan River tributaries confirms the above fingerprint of the PDO, with higher flows occurring during the negative phase and lower flows occurring in the positive phase. The mean probability of two years of successive least quartile flows is 0.149 during the positive phase of the PDO; this probability drops to a negligible 0.015 during the negative phase of the PDO. Conversely, the mean probability of two years of successive highest quartile flows is a small 0.043 during the positive phase of the PDO; this probability increases to 0.135 during the negative phase of the PDO.

The St. Jacques *et al*. (In press) study is the most comprehensive in terms of prairie-wide geography and numbers of gauges and climate oscillations, demonstrating relationships between the climate oscillations and Prairie Provinces' streamflow. Burn *et al*. (2008) undertook a similar study on small prairie streams and found that no such relationships existed. However, their study included only a quarter of the streamflow gauges examined in St. Jacques *et al*. (In press), was based upon shorter streamflow and climate oscillation records, used a lower threshold of climate oscillation events, and was based upon a regular *t*-test with its normality assumptions that are inappropriate for small streams (Gobena and Gan 2006). Using the non-parametric Mann-Whitney test, Gobena and Gan (2006) found that river discharge is higher during negative PDO, La Niña and negative PNA years, and lower in the positive phase years in their collection of streamflow records concentrated in British Columbia and southern Alberta mountain headwaters. They did not demarcate the eastern extent of the climate oscillations' influences since they included only three gauge records each from Saskatchewan and Manitoba. Woo and Thorne (2003) demonstrated significant relationships between western Canadian annual and spring peak flows and the SOI and PNA, using 1968-1998 data.

Significant declines in the regulated flows of the South Saskatchewan River Basin are in accord with previous Alberta-focused studies (Rood *et al.* 2005; Rood *et al.*2008; Schindler and Donahue 2006; St. Jacques *et al.* 2010). St. Jacques *et al.* (2010) showed that the basin declines were due to both direct human impact and climatic changes, with both effects being approximately equal in magnitude. The worst of the decline is in the southern Oldman and Bow River Basins, as the downstream gauge at Medicine Hat shows a very significant decline, and not in the northern Red Deer River Basin, which shows a non-significant decline. This decline propagates all the way downstream to the gauge at Le Pas, Manitoba, which shows a highly significant decline. In southern Alberta, there is an unfortunate pattern of a drying climate (which results in less river discharge) triggering more water use for irrigation, which results in further reductions of discharge.

In the central Prairie region, annual naturally-flowing hydrological series show no significant trends. Previous studies, Gan (1998) and Burn *et al*. (2008), based on less recent data also showed little significant change in annual or warm-season discharge in Saskatchewan. Since Zhang *et al*. (2000) showed that Saskatchewan's climate has become significantly warmer over the past century, as well as wetter. Either increased evaporation from higher temperatures is balanced by increased precipitation throughout much of the province, or emerging trends in the short hydrological time series are still below the threshold of detection of the weak MK test. In response to a warming climate, Burn *et al.* (2008) and Rood *et al.* (2008) detected seasonal shifts towards earlier peak flow from snowmelt across the prairies, particularly in western Alberta.

Southern Manitoba exhibits increasing flows in mean annual discharge, similar to emerging trends in adjacent North Dakota (*pers. com.* R.W. Dudley, United States Geological Service). It is uncertain whether this is due to climatological changes and/or to landscape changes (*i.e.*, increased tile drainage of fields). Immediately to the north of the Prairie provinces, rivers in the Northwest Territories are showing increases in annual discharge and winter baseflow due to hydrological cycle intensification and decaying permafrost from anthropogenic global warming (Smith *et al*. 2007; St. Jacques and Sauchyn 2009). The increased flow in the Seal River in northern Manitoba, where sporadic permafrost is present, is likely also due to permafrost decay. There has been a significant 37.1% increase in winter baseflow (estimated by January-March average daily flow) over the 56 years of record (St Jacques et al. (In Press)).

St. Jacques *et al*. (In press) detected the fingerprints of the PDO, the NPI and the PNA on annual discharge in Canadian Prairie provinces streams and rivers, with increased flows during the negative phases of the PDO and the PNA, and decreases flows during the positive phases. A lesser fingerprint of ENSO and the AO are also detected. Because of the ~60-year cycle of the PDO, this has important implications in the detection of emerging trends in streamflow in response to global climate change. Separation of emerging trend from PDO phase artifact is greatly facilitated in streamflow time series that span at least one PDO cycle, preferably one and a half cycles, especially in the small prairie streams where parametric statistical methods are inappropriate. This highlights the continued importance of the stream gauge monitoring programs maintained by the Water Survey of Canada and the various provincial water authorities. A modified MK trend analysis of Prairie provinces rivers and streams shows decreasing flows in Alberta and in southwestern Saskatchewan, no significant trends in the naturally-flowing streams in the central region and increased mean annual flows in Manitoba.

LONGER-TERM SURFACE WATER TRENDS

Water level gauges are the principal source of data for analyses of hydrologic trends and variability. Streamflow and lake levels integrate the effective precipitation across a watershed and over days to months. There is a relatively dense network of water level gauges in the southern Prairies since precipitation and the raw surface water supply is a limiting factor for agriculture and most other economic activities. This network was originally established in the early 20th century, but not for the scientific 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, 2011). Therefore just a few gauges have operated continuously for more than 50 years. Because weather station and water level records are from the period affected by anthropogenic global warming, and because they are short relative to some climate cycles, this report briefly examines the proxy record of the prairie climate of the past millennium to reveal the natural climate variability that underlies the trends imposed by global warming. Long-term trends, gradual regional responses to global climate changes, rare abrupt climate change, and long climate cycles are evident only in paleoclimatic records derived from geological and biological archives. Temperatures inferred from boreholes on the Canadian Plains and from tree rings at high elevations in the Rocky Mountains show that the warmest climate of the past two millennia is during the 20th century (Majorowicz *et al.* 2002; Luckman and Wilson 2005).

An understanding of long-term surface water variability requires information about pre-instrumental (paleo) hydrology. High-resolution lake sediment records have been obtained with the continuous sampling of sediment cores at fine intervals. The diatom assemblages from Saskatchewan lakes have revealed multi-centennial shifts in moisture regime (Laird *et al*. 2003; Michels *et al*. 2007). A marked shift to moister conditions occurred about 800 years ago at Chauvin Lake and about 670 years ago at Humbolt Lake, *i.e.* near the end of the Medieval Climate Anomaly (MCA) and the onset of the Little Ice Age. 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 11th century, while the highest lake levels coincided with maximum glacier extent during the Little Ice Age. This important work has revealed that recent water level fluctuations on the PAD are within the range of long-term natural variability and therefore are very likely not caused by impoundment of water upstream (Wolfe *et al*., 2012).

Tree-rings are the source of both hydroclimatic data, such as annual fluctuations in water levels, and a chronology with absolute annual resolution spanning centuries to millennia (Meko and Woodhouse 2010). They are an especially good indicator of drought; dry years consistently produce narrow rings (St. George et al., 2009). Reconstructions of water levels are possible because both tree growth and stream flow respond to precipitation, capturing a regional moisture signal (Sauchyn *et al*. 2003; Axelson *et al*. 2009; Perez-Valdivia and Sauchyn 2010; Sauchyn *et al*. 2011*b*). Tree-ring and archival records from Manitoba have highlighted the recurrence of wet years and flooding, and point to a contrast in climate between the western and eastern Prairies (Blair and Rannie 1994; St. George and Nielsen 2002; Ferguson and St. George 2003; St. George and Nielsen 2003; Rannie 2006).

In the dry climate of the western Prairies, tree growth is limited each year by available soil moisture and, therefore, tree rings are a proxy of precipitation, streamflow and drought (e.g., Sauchyn *et al*. 2011*b,* St. George et al., 2009). Figure 11 is a reconstruction of the annual flow of the North Saskatchewan River at Edmonton from 1063 to 2007. The streamflow was inferred from tree-ring width chronologies at seven sites in the upper runoff-generating region of the NSRB (Sauchyn *et al*. 2011*b*). This plot reveals intervals of decades or longer of above average moisture (blue years) including the early part of the 20th century, when the western prairies were settled and the landscape was transformed from grassland and parkland to agricultural and use. The most extensive and severe droughts (red bars in Figure 11), for example of the mid 19th and late 16th centuries, pre-date the agrarian settlement of the region and water allocation and apportionment agreements. Thus the tree rings, and other climate proxies, suggest that the climate of the 20th century lacked the sustained droughts of preceding centuries that affected sand dune activity, the fur trade, and the health of Aboriginal people (Sauchyn *et al*. 2002; Sauchyn *et al.* 2003). The short duration of drought since the 1930s may be linked to multi-decadal climate variability, more so than to climate change, which is expected to cause increased aridity and more frequent drought (Wetherald and Manabe 1999; Kharin and Zwiers 2000). Much of this variability can be attributed to shifts and characteristic cycles in the large-scale climate forcing discussed above. For example, there is a significant difference in the likelihood of drought between the cold and warm phases of the Pacific Decadal Oscillation (PDO) (Lapp *et al*. in press). Recent observations and experience are not good indicators of future drought, since as the data in Figure 11 show, they do not represent the full range of drought variability, but furthermore the oceans and atmosphere are currently warming at unprecedented rates.

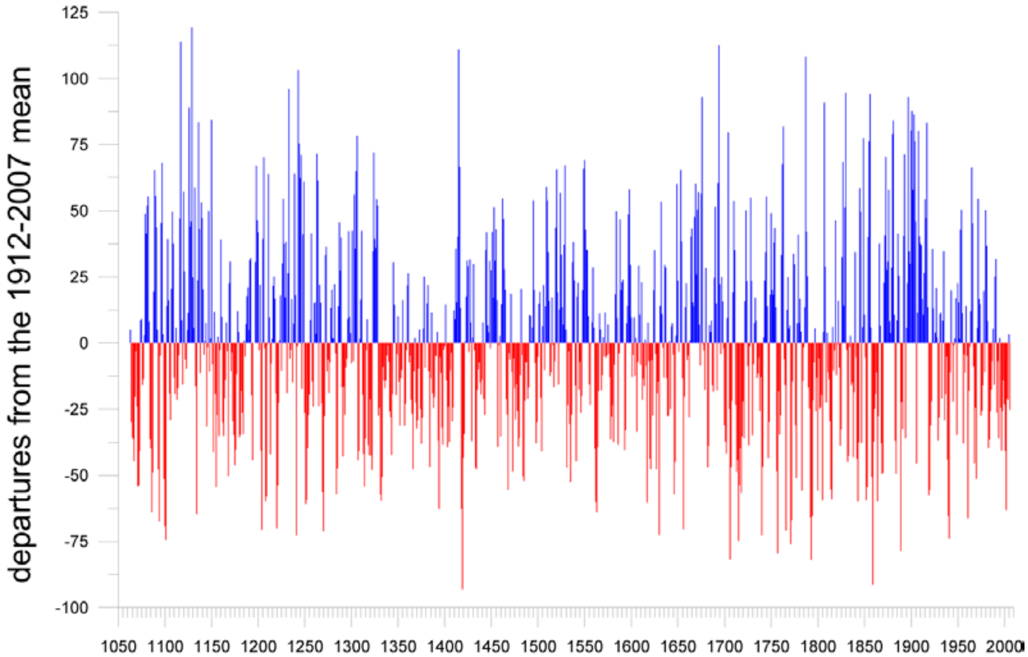

Figure 11: A tree-ring reconstruction of the annual flow of the North Saskatchewan River at Edmonton, AB. The flow is plotted as positive (blue) and negative (red) departures from the mean annual flow (m3/sec) for the period 1912-2007. (Sauchyn et al. 2011b)

FUTURE CLIMATE AND HYDROLOGY

The many studies reviewed on the preceding pages clearly document significant variations in the climate and hydrology of the Prairie Provinces over past decades to centuries. While these studies inform our understanding of present climate changes, these historical trends and variability cannot be simply extrapolated to provide estimates of future climate change. The climate in not stationary, it does vary in a consistent and predictable manner, especially with the human modification of the climate system. The only reliable sources of future projections are climate models that simulate the response of ocean-atmosphere circulation to external drivers, including increasing concentrations of greenhouse gases.

General Circulation Models (GCMs) are numerical models that represent mathematically the physical dynamics of the climate system and feedbacks between the atmosphere, ocean, cryosphere and land surface. Typically GCMs have a horizontal resolution of between 250 and 600 km. This resolution is too coarse to model directly some of the smaller-scale processes, such as cloud and precipitation processes; these are parameterized, that is, averaged over larger scales, or related to other variables that are explicitly modeled. The most advanced GCMs are coupled atmosphere-ocean models, in which three-dimensional models of the atmosphere are linked dynamically with three-dimensional models of the ocean. These transient response models are able to simulate the time-dependent response of climate to changes in atmospheric composition, including concentrations of greenhouse gases (GHGs). Future emissions of greenhouse gases into the atmosphere depend very much on social and economic factors such as population and economic growth and energy use. For its Third and Fourth Assessment Reports (IPCC 2001, IPCC 2007) the IPCC developed six SRES (Special Report on Emissions Scenarios) marker scenarios for the period 2000 to 2100 (Nakicenovic *et al*. 2000). Many climate-modeling centers (Table 1) have undertaken experiments with some or all of these emissions scenarios (see, for example, data available from the IPCC Data Distribution Centre: www.ipcc-data.org).

Table 1: Global Climate Modelling Centres (Barrow 2010)

GCM	Modelling Centre(s)
BCCR-BCM2.0	Bjerknes Centre for Climate Research, Norway
CGCM3.1(T47) CGCM3.1(T63)	Canadian Centre for Climate Modelling and Analysis, Canada
CNRM-CM3	Météo-France/Centre National de Recherches Météorologiques, France
CSIRO-MK3.0 CSIRO-MK3.5	Commonwealth Scientific and Industrial Research Organisation (CSIRO) Atmospheric Research, Australia
ECHAM5/MPI-OM	Max Planck Institute for Meteorology, Germany
ECHO-G	Meteorological Institute of the University of Bonn, Meteorological Research Institute of the Korea Meteorological Administration (KMA), and Model and Data Group, Germany/Korea
FGOALS-g1.0	National Key Laboratory of Numerical Modeling for Atmospheric Sciences and Geophysical Fluid Dynamics (LASG)/Institute of Atmospheric Physics, China
GFDL-CM2.0 GFDL-CM2.1	U.S. Department of Commerce/National Oceanic and Atmospheric Administration (NOAA)/Geophysical Fluid Dynamics Laboratory (GFDL), USA

GISS-AOM GISS-EH GISS-ER	National Aeronautics and Space Administration (NASA)/Goddard Institute for Space Studies (GISS), USA
INGV-SXG	National Institute of Geophysics and Volcanology, Italy
INM-CM3.0	Institute for Numerical Mathematics, Russia
IPSL-CM4	Institut Pierre Simon Laplace, France
MIROC3.2(hires), MIROC3.2(medres),	Center for Climate System Research (University of Tokyo), National Institute for Environmental Studies, and Frontier Research Center for Global Change (JAMSTEC), Japan
NCAR (CCSM3) NCAR (PCM)	National Center for Atmospheric Research, USA
UKMO (HadCM3) UKMO (HadGEM1)	UK Meteorological Office, Hadley Centre for Climate Prediction and Research, UK

Despite the advances in computing technology and the resolution of GCMs, model simulations are still not sufficiently accurate, in terms of absolute values at regional scales, to be used directly in studies of climate change impacts. Instead, mean differences are computed between the model's representation of current climate (the common baseline period is 1961-1990) and some future 30-year period. The conventional approach is to use the future time horizons 2010-2039 (the '2020s'), 2040-2069 (the '2050s'), and 2070-2099 (the '2080s'). Changes in temperature are expressed as differences (future climate minus baseline climate) and ratios (future climate/baseline climate) are used for other variables such as precipitation and wind speed. The climate change scenarios represent "coherent, internally consistent and plausible descriptions of a possible future state of the world" (IPCC 2001).

CLIMATE CHANGE SCENARIOS

Most assessments of the impacts of climate change rely on the use of climate change scenarios. Thus the many studies of climate change impacts on prairie ecosystems, water, economic activities and communities have required outputs from climate models, which are available from the climate modeling centers (Table 1; Sauchyn *et al*. 2010; Barrow, 2010). Few studies have attempted, however, to produce a comprehensive set of climate scenarios that encompass the Prairie Provinces, a range of climate variables, and the 21st century. These few exceptions are the climate models projections produced by the Canadian Forest Service (Price *et al*. 2011) and a series of climate change scenarios created at the Prairie Adaptation Research Collaborative (PARC) for the purpose of provincial and national climate change impact assessments (Barrow and Yu 2005; Barrow 2007; Sauchyn *et al*. 2007; Sauchyn and Kulshreshtha 2009; Sauchyn *et al*. 2009; Barrow 2010; Barrow 2011).

Price *et al*. (2011) developed climate projections for Canada using output from four well-established general circulation models (GCMs) forced by each of three SRES greenhouse gas (GHG) emission scenarios recommended by the IPCC: scenarios A2, A1B, and B1 (See Nakicenovic *et al*. 2000 for a description of the three emission scenarios). They produced scenario data for monthly mean daily maximum and minimum temperatures, precipitation, solar radiation, wind speed, and vapor pressure. All variables were expressed as changes relative to the simulated monthly means for 1961–1990. The downscaling procedure used the ANUSPLIN software package to fit a two-dimensional spline function to each month's change data for each climate variable at a spatial resolution of 5 arcminutes (0.0833º) longitude and latitude. The resulting scenarios show consistent changes in response to differing GHG forcing and model simulations. The largest differences were between emission scenarios; A2 generated the greatest warming by 2100, and the B1 scenario the least. The largest regional increases in temperature and precipitation are in Canada's far north. The least are in the southeast and west coastal regions, with intermediate warming in western interior. All models projected increases in precipitation in conjunction with the projected increases in temperature, although with more spatial and seasonal variability. Gridded scenario data sets are available to researchers and others needing high-resolution data for studies of the impacts of climate change.

Given the coarse spatial resolution of GCMs, the model outputs are nearly always downscaled for application to regional climate impact studies. There are two broad approaches: statistical, as with Price *et al*. (2011), and dynamical, by running a Regional Climate Model (RCM) at higher spatial resolution (typically 50 km) within the larger spatial domain of a Global Climate Model (GCM). A wealth of GCM output is now available mainly from the IPCC Data Distribution Centre (IPCC-DDC; www.ippc-data.org) and the Coupled Model Intercomparison Project (CMIP3; www-pcmdi.llnl.gov/ipcc/about_ipcc.php; Meehl and Stocker 2007). RCM data are becoming available through the North American Regional Climate Change Assessment Program (NARCCAP; www.narccap.ucar.edu) and the Canadian Centre for Climate Modelling and Analysis (CCCma; www.cccma.ec.gc.ca). PaiMazumder et al. (2012) derived future projections of prairie drought frequency and severity from the Canadian Regional Climate Model. Barrow (2010) produced a set of climate change scenarios for the Prairie Provinces using output from RCM experiments for western Canada (see Table 2). The following RCM-based climate change scenarios are from the Barrow (2010) report.

Table 2: Regional – Global Climate Model Combinations available from NARCCAP. Check marks indicate experiments that are currently available. (Barrow 2010)

Driving GCM / RCM	GFDL	CGCM3	HadCM3	CCSM	NCEP
CRCM		✓		✓	✓
ECPC	✓		✓		✓
HRM3	✓		✓		✓
MM5I			✓	✓	✓
RCM3	✓	✓			✓
WRFP		✓		✓	✓

The maps in Figures 12 and 13 show the distribution of temperature across the southern prairies for the baseline period 1971-2000 and the future period 2040-71. In both figures, the map in the upper right corner is derived using data from the Canadian GCM. Thus, this map has much coarser resolution than those constructed using output from the RCMs. These maps show increased annual temperatures throughout the Prairies, with a general increase of at least two degrees. The pattern of precipitation is shown in Figures 14 and 15 for the baseline period 1971-2000 and the future period 2040-71. Comparing the two sets of maps reveals generally increased precipitation in most areas, but especially in the eastern Prairies.

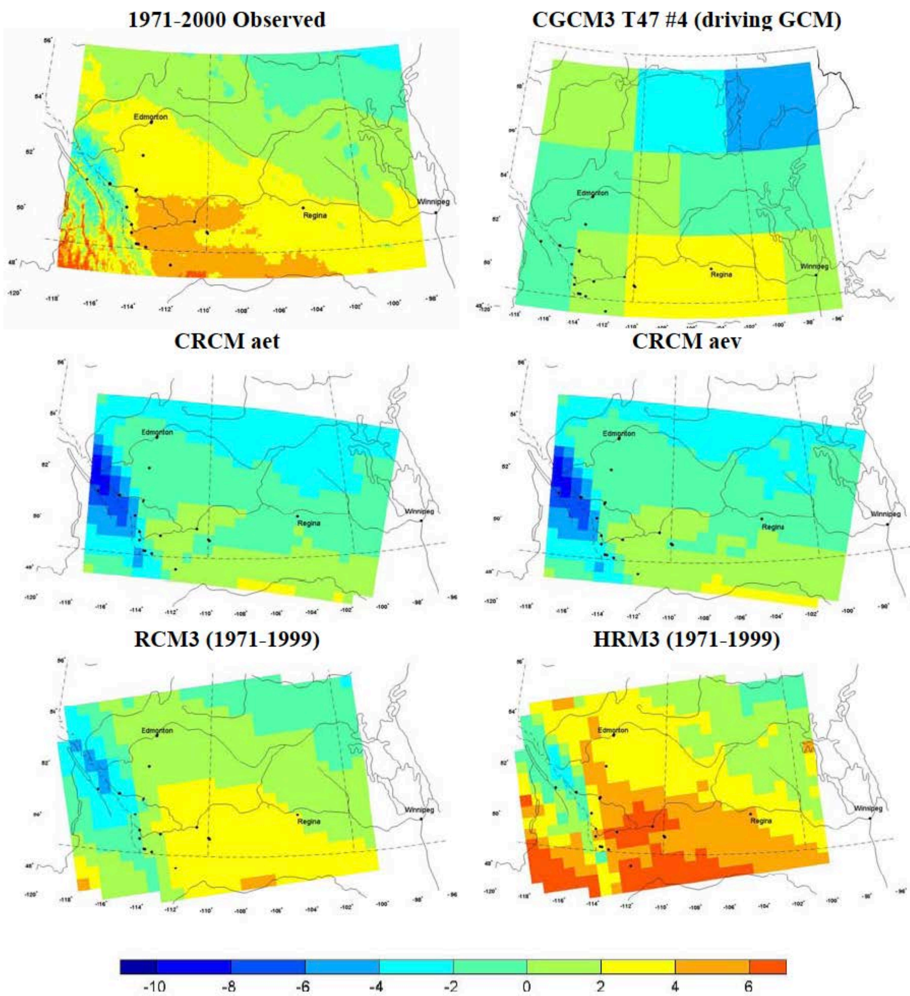

Figure 12: Maps of mean annual temperature (°C) for the baseline period 1971-1999. The top two maps are of observed temperature and simulated by the Canadian Global Climate Model. The other four maps are derived from output from Regional Climate Models (Barrow 2010).

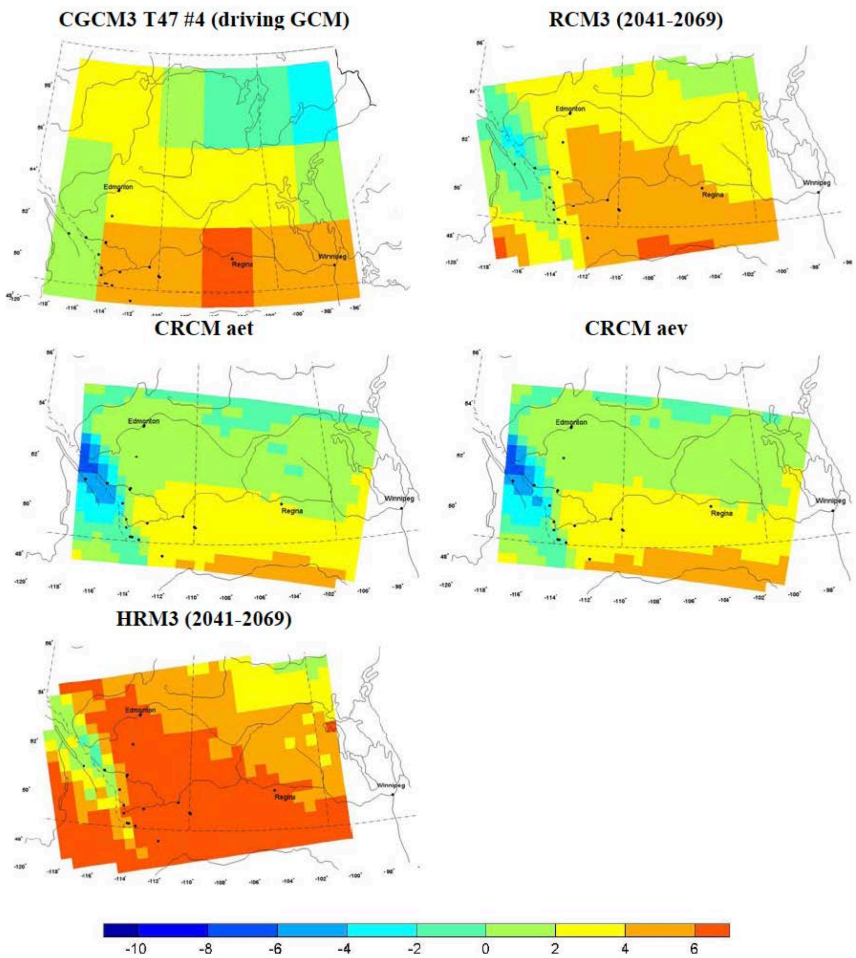

Figure 13: Maps of mean annual temperature (°C) for the future period 2040-71. The top two maps are of observed temperature and simulated by the Canadian Global Climate Model. The other four maps are derived from output from Regional Climate Models (Barrow 2010).

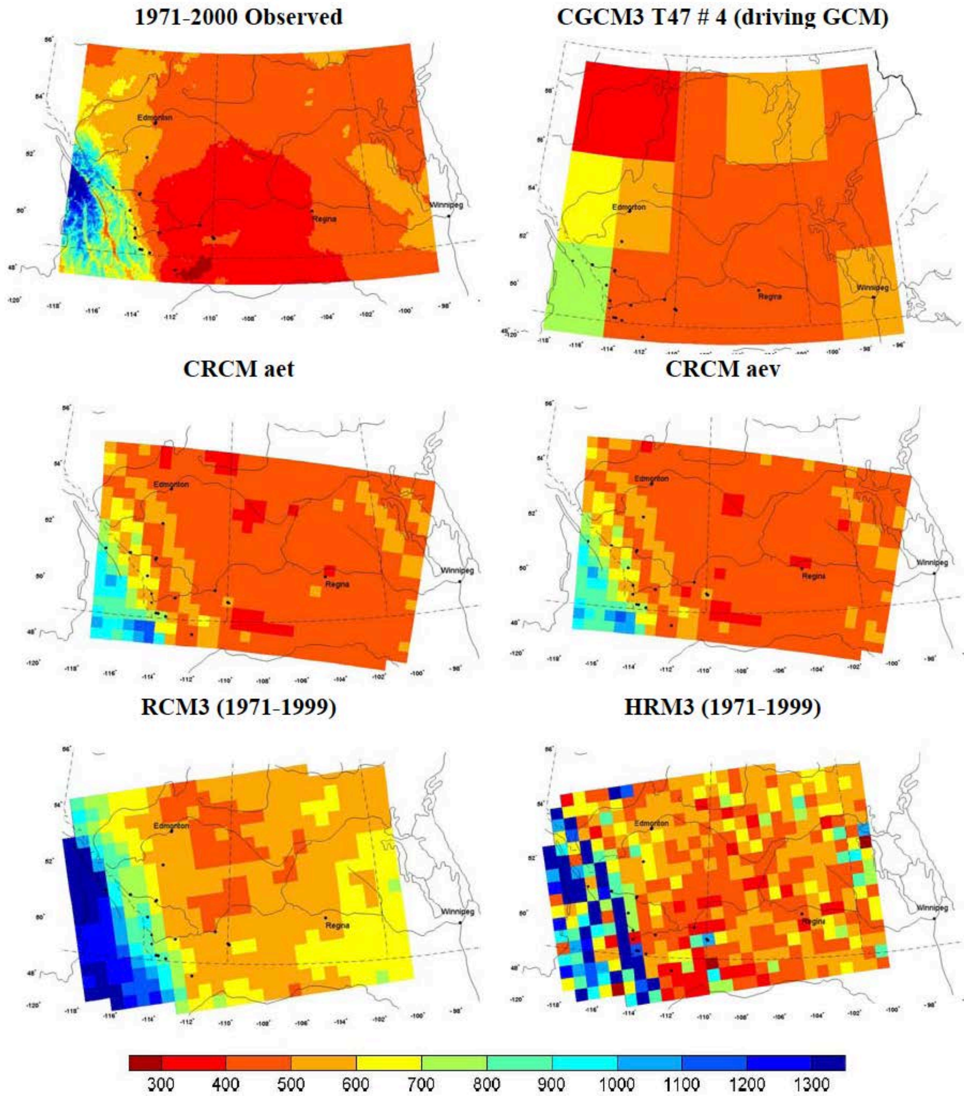

Figure 14: Maps of mean annual precipitation (mm) for the baseline period 1971-1999. The top two maps are of observed temperature and simulated by the Canadian Global Climate Model. The other four maps are derived from output from Regional Climate Models (Barrow 2010).

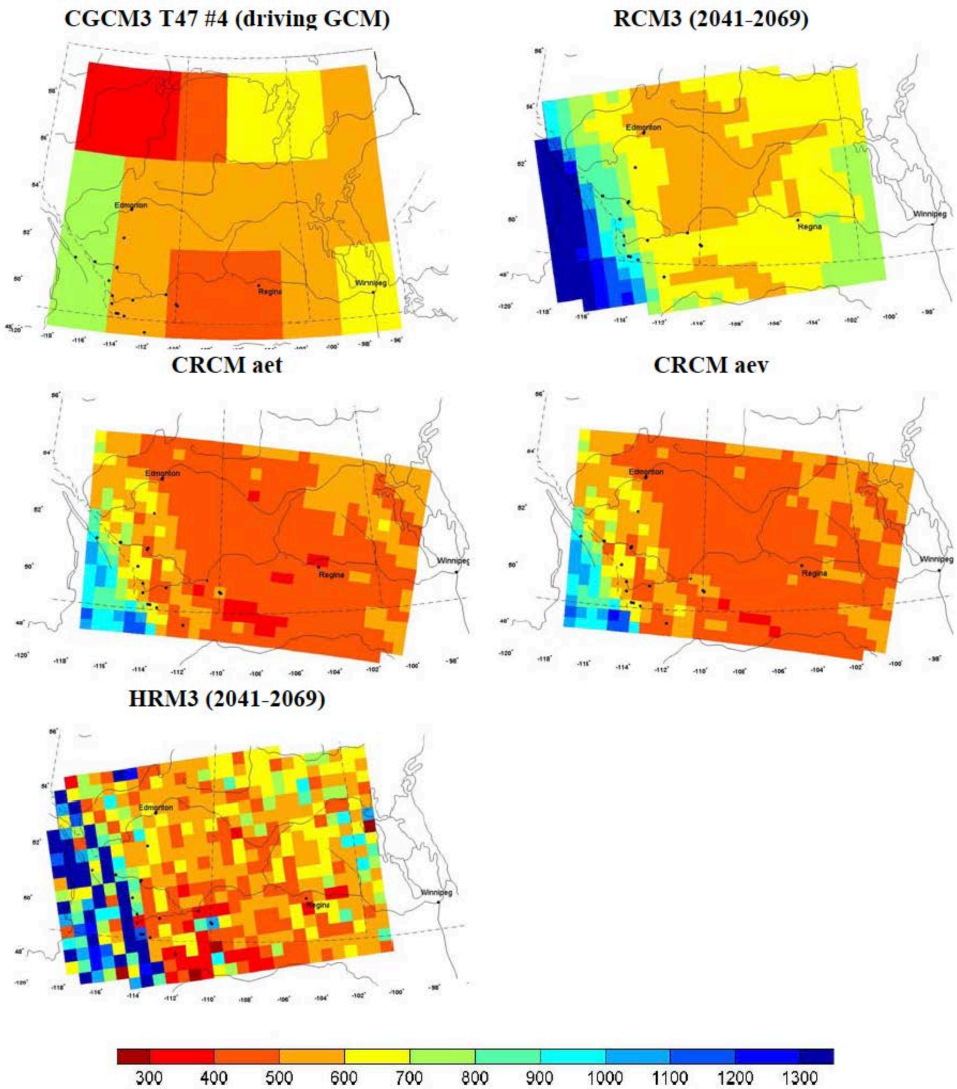

Figure 15: Maps of mean annual precipitation (mm) for the future period 2040-71. The top two maps are of observed temperature and simulated by the Canadian Global Climate Model. The other four maps are derived from output from Regional Climate Models (Barrow 2010).

While temperature and precipitation are the most commonly measured and modeled climate variables, and are the principal climatic controls on raw surface water supplies, a more meaningful hydrological variable is the precipitation that is effective in restoring surface and soil water balances. Global Climate Models (GCMs), used for both Global Climate Model and Global Circulation Model, project future summer drying of continental interiors and associated increased risk of droughts (Meehl and Stocker 2007). Recent scientific research indicates that further global warming will amplify hydro-climatic extremes, with a concurrent increase in both precipitation intensity and the number of dry days (Ruiz - Barradas and Nigam 2010). Sheffield and Wood (2008) analyzed future changes in global drought occurrence (based on modelled soil moisture) using eight GCMs from the IPCC's Fourth Assessment. For the mid-latitudes of North

America, long-term (12+ months) droughts became more common but there was a large variation among the different emission scenarios. A recent study by Sushama *et al*. (2010) examined future dry spell characteristics over Canada using the Canadian Regional Climate Model (CRCM). Results indicated that by the end of this century, the southern region of the Prairies will experience an increase in both the number of dry days and dry spell duration during the critical April to September period. A first-order assessment of future (2041-2070) drought occurrences over southern Canada by Bonsal and Regier (2006) indicated small positive changes in the SPI for the majority of climate-change scenarios, reflecting a projected increase in future annual precipitation over most of southern Canada. The PDSI findings, however, revealed dramatic increases to the potential for future droughts particularly for warmer/drier scenarios.

The climate moisture index (CMI)is a relatively simple expression of a regional water balance (Hogg 1994; Hogg 1997). It is a measure of effective precipitation in excess of water loss by evapotranspiration, *i.e.*, P – PET. This index is meaningful biogeographically, with a CMI value of zero (*i.e.*, P = PET) defining the southern boundary of the boreal forest and a value of -15 corresponding to the aspen parkland –grassland boundary in western Canada (based on 1951-1980 climate data; Hogg 1994). Barrow (2010) calculated the CMI for the water year (October to the following September) and also over the three-month period May, June and July. There are a number of different methods for calculating potential evapotranspiration (PET), but the Thornthwaite method was used by Barrow (2010) for its relative simplicity and basic climate data requirements. The distribution of CMI across the southern prairies for the baseline period 1971-2000 and the future period 2040-71, mapped in Figures 16 and 17, demonstrate general drying with a shift to a more negative moisture balance throughout the region.

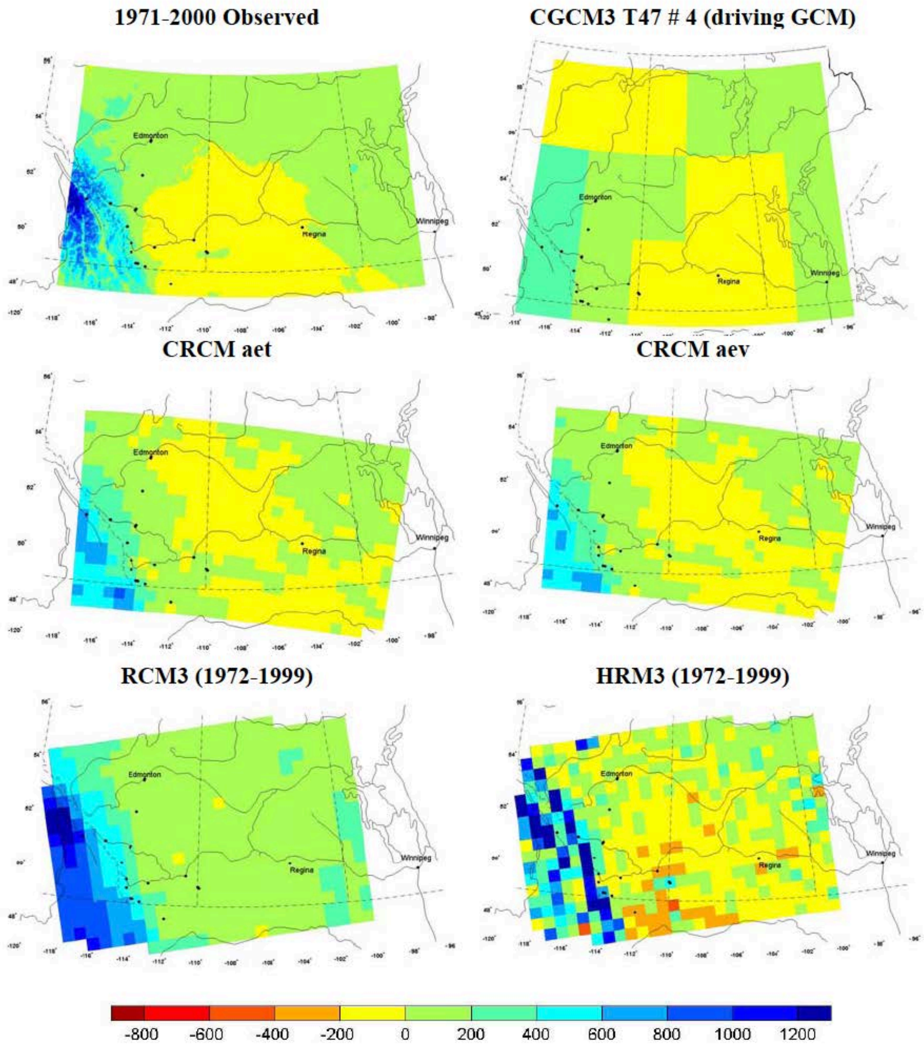

Figure 16: Maps of total water year (October – September) moisture deficit (mm) for the baseline period 1971-2000. Potential Evapotranspiration was calculated using the Thornthwaite method. (Barrow 2010)

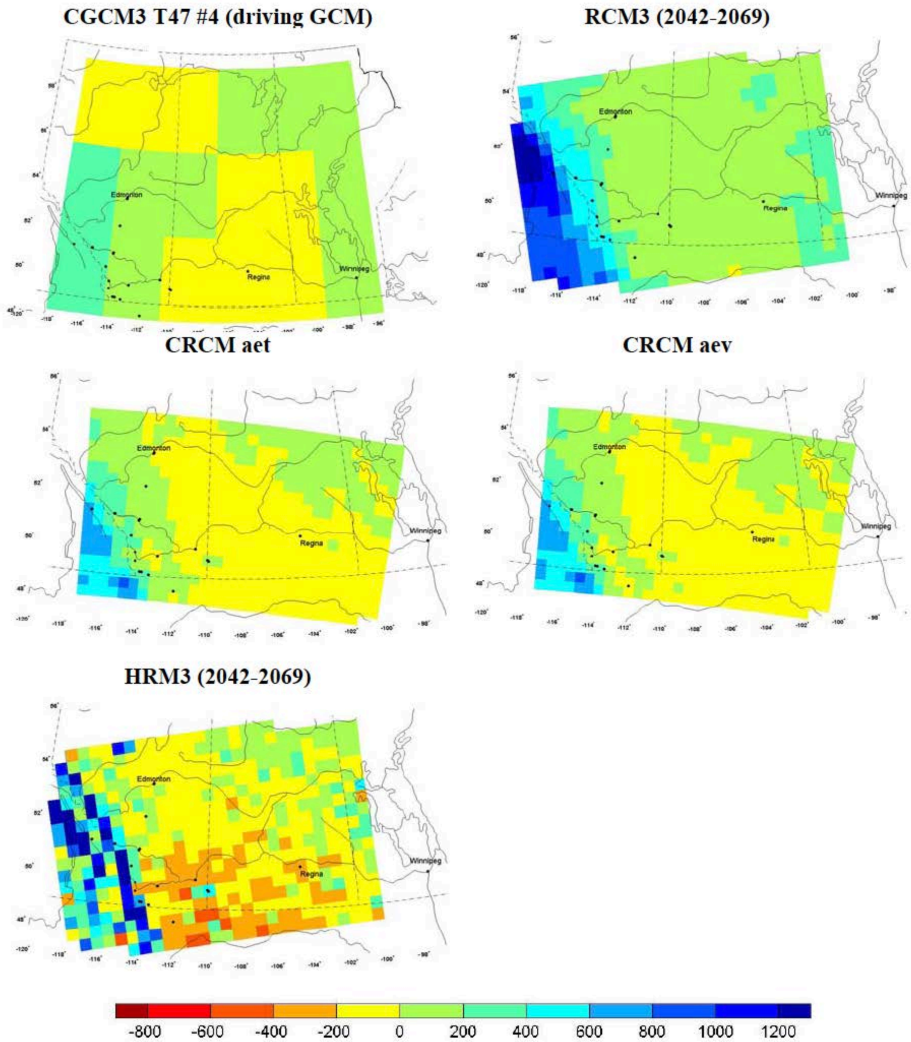

Figure 17: Maps of total water year (October – September) moisture deficit (mm) for the future period 2041-2070. Potential Evapotranspiration was calculated using the Thornthwaite method. (Barrow 2010)

In a recent paper, Dibike *et al*. (2012) presented projections of the future climate of the LWW using outputs from the North American Regional Climate Change Assessment Program (NARCCAP). The NARCCAP data base consists of output from regional climate models (RCMs) at a 50 km spatial resolution. The RCMs are nested within GCMs. The greenhouse gas (GHG) forcing is according to the SRES A2 emissions scenario, which represents a high rate of population growth and a slow rate or adaptation. Dibike *et al*. (2012) extracted daily precipitation and daily minimum and maximum air temperature (Tmax, Tmin) data from the NARCCAP database for three pairs of GCM/RCMs: CGCM3/CRCM, HadCM3/HRM3, and GFDL/RCM3. They constructed climate change scenarios for the LWW by determining the difference in mean monthly and seasonal values between the baseline period 1971–2000 and the future period 2041–2070 (Figures 18 and 19). Temperature projections were consistent among the models, with future increases in annual Tmax and Tmin of 2.5–2.8 °C and 2.8–2.9 °C, respectively, and largest increases (~2.7–3.8 °C) in winter and summer temperatures. The models projected an increase in annual precipitation of 6.5% over the LWW. The most consistent result was higher precipitation in winter and spring (11–15%). In general, higher precipitation is projected for the Winnipeg and Red River basins than for the Saskatchewan and Assiniboine River basins.

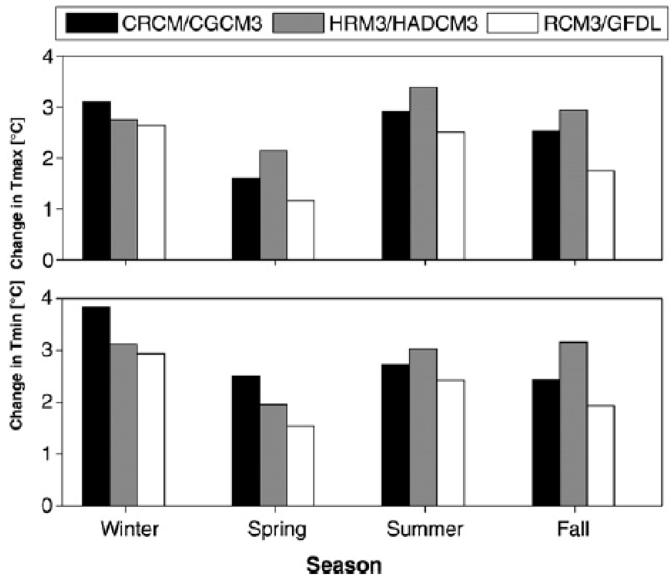

Figure 18: Comparison of projected changes in regional mean maximum temperature (Tmax) and minimum temperature (Tmin) in the Lake Winnipeg Watershed between the future (2042–2070) and baseline (1971–200) periods based on the three Global Climate Model/Regional Climate Model pairings. (Dibike et al. 2012)

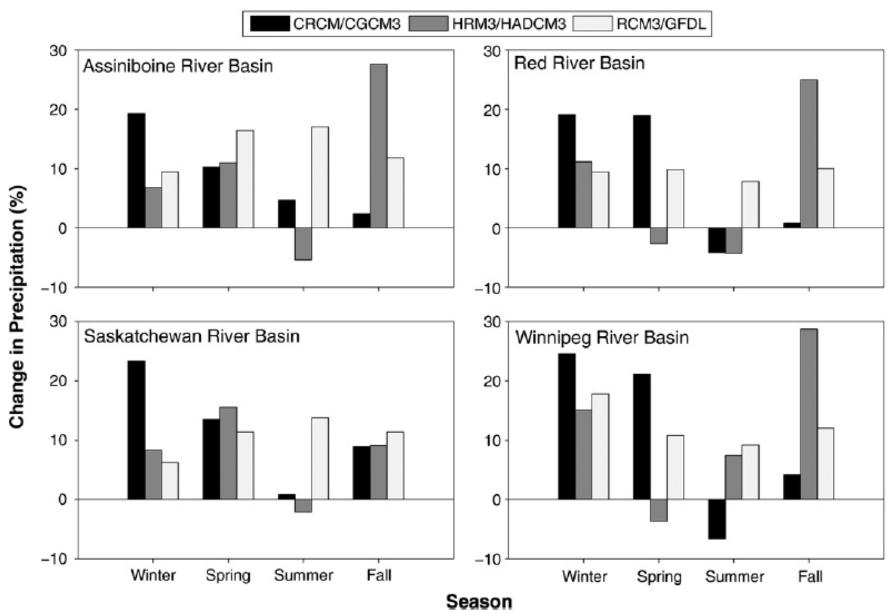

Figure 19: Comparison of changes in mean seasonal precipitation between the future (2040–2071) and baseline (1971–2000) periods in the major tributary river basins of the Lake Winnipeg Watershed between the future and baseline periods corresponding to each of the three Global Climate Model/Regional Climate Model projections. (Dibike et al. 2012)

STREAMFLOW

All scenarios of future hydroclimate and water supplies consistently project an earlier onset of the spring snowmelt, a tendency towards a more rainfall-dominated hydrograph, and reductions in the annual and spring flow volumes in the 2050s and 2080s. For the South Saskatchewan River Basin, reductions in annual flow, and a shift of the peak annual flow from summer to spring and winter, are projected for the major mountain tributaries (Lapp *et al*. 2009). The median scenario for the South Saskatchewan River at Medicine Hat is a reduction of 8.5% in mean annual flow by mid-21st century. Lapp *et al*. (2005) modeled historical and future snowpack for the Oldman Basin in southern Alberta, predicting shorter winters and declining snow accumulations in the low- and mid-mountain elevations. Their results suggested an average decline in spring snow runoff of around 40% for the period 2020-50. Merritt *et al*. (2006) found similar results for simulated runoff for the Okanagan Basin in southern British Columbia. Finally, MacDonald (2008) forecasted declines in spring snowpacks for the St. Mary River in northern Montana and southern Alberta under a range of climate scenarios. Larson (2008) predicted that hydroclimate and water supplies in the St. Mary headwaters would lead to substantial declines in spring runoff. However, the work of MacDonald (2008) included a scenario where GHG emissions were well controlled in this century. In that case, minimal declines in water supply were predicted.

The climate change scenarios for the Saskatchewan River basin suggest more precipitation in winter and spring, and less precipitation in summer and perhaps fall. Kienzle *et al*. (2011) simulated the impact of these regional climate changes on streamflow by coupling the climate change projections and a hydrological model. Figure 20 shows projected changes in streamflow for the 2050s for the upper North Saskatchewan River Basin (NSRB) for five climate change scenarios. Streamflow is plotted as the percentage change between the baseline of 1961-90 and the future thirty-year period 2049-60 (the ‘2050s’). These results clearly reflect the dominant climate change scenarios of a warming climate, especially in winter and spring, increased precipitation but mostly in winter, and decreasing effective precipitation in summer. In Figure 20, streamflow of 100% is equivalent to the1961-90 baseline and thus no change into the future. Flow in mid to late summer could fall by as much as 50%, with significantly higher runoff in winter.

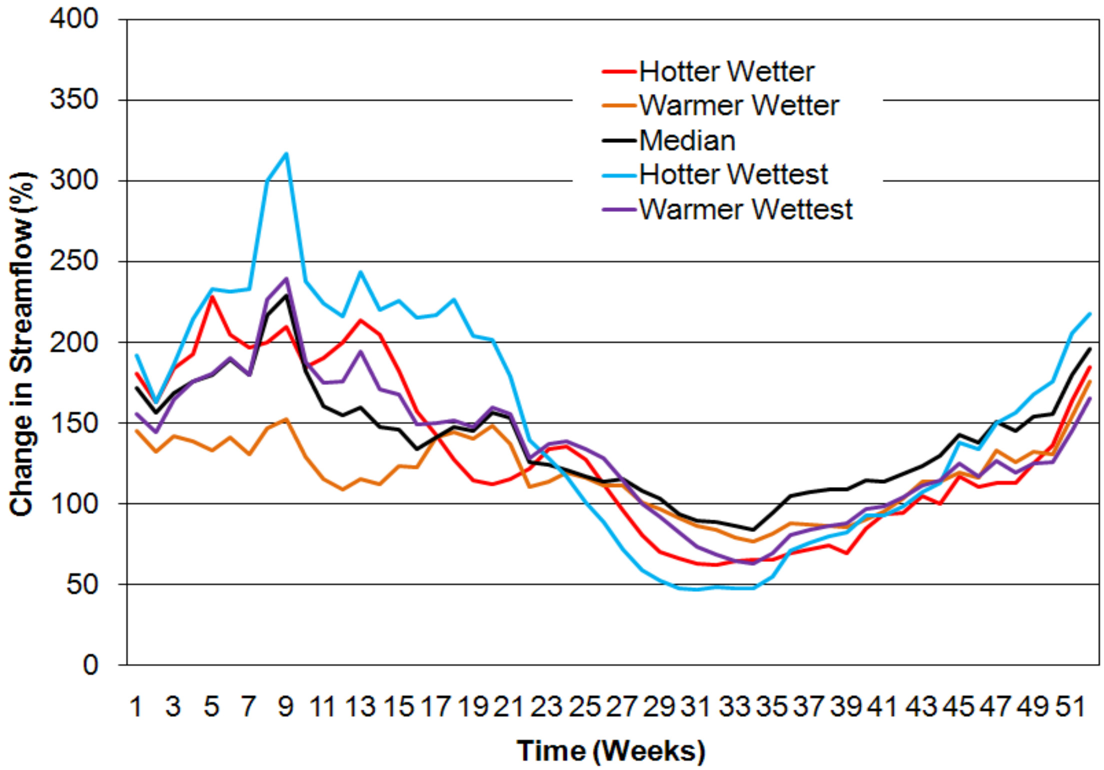

Figure 20: Simulated changes in streamflow for the 2050s for the upper North Saskatchewan River Basin for five climate change scenarios. Streamflow of 100% represents the 1961-90 baseline and thus no change into the future. Flow in mid to late summer could fall by as much as 50%, with significantly higher runoff in winter. (Sauchyn et al. 2011a)

A similar approach was used by Shrestha *et al*. (2011, 2012) to project future flows of the Winnipeg River. They modeled climate-induced hydrologic changes in two representative sub-catchments, the Red and Assiniboine basins. They used the hydrologic model, Soil and Water Assessment Tool (SWAT), and climate forcings derived from three RCMs to simulate a 21-year baseline (1980–2000) and future (2042–2062) flows. The effects of future changes in climatic variables, specifically precipitation and temperature, are clearly evident in the resulting snowmelt and runoff regimes. The most significant changes include higher total runoff, and earlier snowmelt and discharge peaks. Some of the results also revealed increases in peak discharge intensities. Such changes will have significant implications for water availability and nutrient transport regimes in the LWW.

Similarly, Slota *et al*. (2009) combined WATFLOOD, a physically-based mesoscale hydrological model, and a suite of GCM scenarios to study the effects of climate change on the flow regime in the Winnipeg River Basin (WRB). Projected changes in monthly averaged temperature and precipitation from these scenarios were used to modify the existing 92-year WRB historic record of weather events to produce synthetic climate scenarios as model forcing in WATFLOOD. Differences between streamflow from the perturbed climate and the historical flows, at the locations of Manitoba Hydro's hydroelectric generating stations, were used to determine the changes in power potential on the Winnipeg River.

Streamflow projections for the Assiniboine River Basin (ARB) were recently developed for Manitoba Conservation, Climate Change Branch by Stantec (2011). Output from the Canadian Regional Climate Model (CRCM) was used to drive a Hydrologic Model, the Danish Hydrologic Institute (DHI) MIKE-SHE. Results were compared between a baseline period and the future periods 2011-2040, 2041-2070, and 2071-2099. The MIKE-SHE hydrologic model was constructed for the ARB using data for topography, precipitation, temperature, storage, surface roughness, soil hydraulic conductivity, and soil field capacity. The Hydrologic Model was calibrated by using recorded historical unregulated streamflow for the period 1961 to 1990. The model runs were validated using historical unregulated stream flow data from 1991 to 2003. The CRCM simulated average monthly mean temperature and precipitation from 1960 to 2000 relatively well as compared to average historical monthly means. The CRCM projects increased temperature in all seasons for the ARB and increased precipitation for all seasons except summer, when a decrease is anticipated. Future flows, modeled with CRCM and MIKE-SHE, are within the range of historical variation and no trends were detected in annual flows. However, the variability may be limited by the use of only one run of one climate model. Increased temperature and evapotranspiration would generally be offset by increased annual precipitation, resulting in marginal change in runoff. The Stantec report (2011) makes the following conclusion regarding future flows in the ARB:

- *“10% probability of non-exceedence (low) annual flows is predicted to be similar in future. These flow years are generally not critical to summer water supply, given that the current method of water allocation is based upon the drought of record, which is a more severe (low) flow event.“*
- *“High probability of non-exceedence annual flows is predicted to be larger in future. Therefore, the risk of extreme spring floods may increase. This is due to predicted increases to fall, winter and spring precipitation, which could lead to higher flood flows if unusually high fall soil moisture is experienced.”*
- *“Average monthly flows showed no discernible trend in the future.”*
- *“An earlier spring melt is predicted to cause an earlier spring freshet.”*

There are some limitations to these standard practices for the modeling of future water supplies. Even though the hydrological models simulate very well the statistical characteristics of observed flow, this approach assumes stationary land cover and inter-annual variation. We know that the climate models do not simulate the climate oscillations (for example, El Niño – Southern Oscillation) that drive the inter-annual to decadal variability of precipitation and streamflow. Therefore mean monthly flows are projected for 30-year periods and more modeling and analysis would be necessary to develop scenarios of the inter-annual variability that will underlie the trends. These scenarios represent the shift in average water levels based on the difference in average daily temperature and precipitation for two 30-year periods. This so-called ‘delta approach’ does not account for change in the variability of the climate system; it assumes the variability of the baseline period 1961-90.

St. Jacques *et al*. (2012) departed from standard practices in hydrological engineering, to take a novel approach to projecting future flows in the Saskatchewan River Basin. They developed statistical models to simulate the historical flow series at each gauge, for example, as shown in Figure 9 above, under the topic streamflow trends. The predictors of streamflow in these models are climate indices, such as PDO and ENSO that represent the teleconnections between atmosphere-ocean circulation and the response of western Canadian hydrologic regimes. Then St. Jacques *et al*. (2012) ran these regression models using data from the GCMs that best simulate these large-scale atmosphere-ocean circulation patterns (Lapp *et al*. 2011). This approach to projecting future streamflows accommodates the non-stationarity of the climate system and inter-annual to decadal variability of the hydrologic regime. Thus these projections capture not only the changes in mean water levels but also the shifts in the distribution of extreme flows.

LAKE WINNIPEG

An assessment of the potential effects of climate change on Lake Winnipeg requires projections of future summer water temperatures and the length of the open water season. McCullough and Levesque (2011) developed a simple model of future thermal regimes of Lake Winnipeg based on empirical relationships between monthly air and water temperatures, spring ice melt/ break-up, and fall freeze-up for the North and south basins. This model was then run using air temperature projections from runs of the Canadian Global Climate Model (version 3; CGCM3) for each of the greenhouse gas emission scenarios: B1, A1B, and A2 (in order of increasing greenhouse gas concentrations). The air temperature scenarios are plotted in Figure 21. McCullough (2005) suggested conservative interpretation of projected changes for a small region, like the Lake Winnipeg area; global climate models operate on a coarse grid.

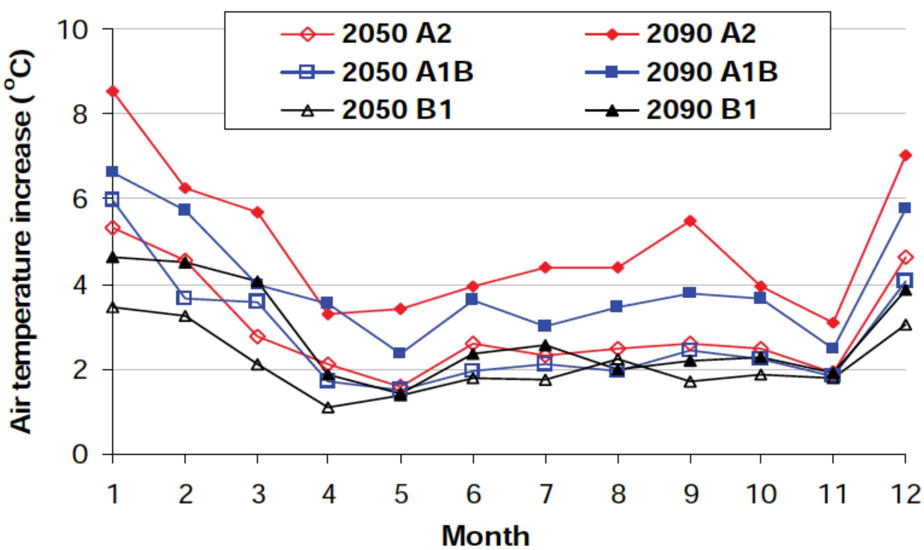

Figure 21: Increases in air temperature projected for the Lake Winnipeg region for 2040 to 2059 (labeled 2050) and 2080 to 2099 (labeled 2090) using CGCM3 with emission scenarios, B1, A1B, and A2. Each point is the mean of 100 predicted values, i.e. 5 model runs x 20 years. Predicted 21st century temperatures are compared to temperatures modeled using CGCM3 over the base period from 1970 to 1992. (McCullough and Levesque 2011)

The CGCM3 A2 (maximum GHG forcing) projection is a 2.4°C increase in mean midsummer air temperature over Lake Winnipeg during the first half of the 21st century and another 2.0°C during the second half (Figure 21). The B1 (minimum) projection is a 2.0°C increase in mean midsummer temperature in the first half of the 21st century, followed by a further rise of only 0.3°C in the second half. For the range of scenarios, the increases in winter (December, January, and February) temperature are 60 to 120 % greater than for the summer months. The projected air temperature changes are least in spring and late autumn (April, May, and November): increases of 1.1 to 2.1°C by mid-century, and another 0.1 to 1.8°C by the end of the century. Spring and autumn air temperatures are the main determinants of ice cover break-up and freeze-up.

By the mid-21st century, water temperatures are projected to rise by 1.9 to 2.5°C above average mid-summer surface water temperatures of 18.5°C in the north basin, and 21.0°C in the south basin over the period 1970 to 1992. Projections for the various GHG emission scenarios are plotted in Figure 22. Mid-summer surface water temperatures in Lake Winnipeg are highly variable, with standard deviations of 1.6°C in July and 2.0°C in August over the period 1970 to 1992 (estimated from the historical air temperature by McCullough and Levesque 2011). Therefore, mean mid-summer surface water temperature could be at least 1.6°C warmer than projected, with maximum mean monthly temperatures by the end of the 21st century that exceed record high observations for the past 60 years (McCullough and Levesque 2011). This greater heating of the surface water may lead to an increased tendency for water column stratification although McCullough and Levesque (2011) indicates this scenario has not been explored.

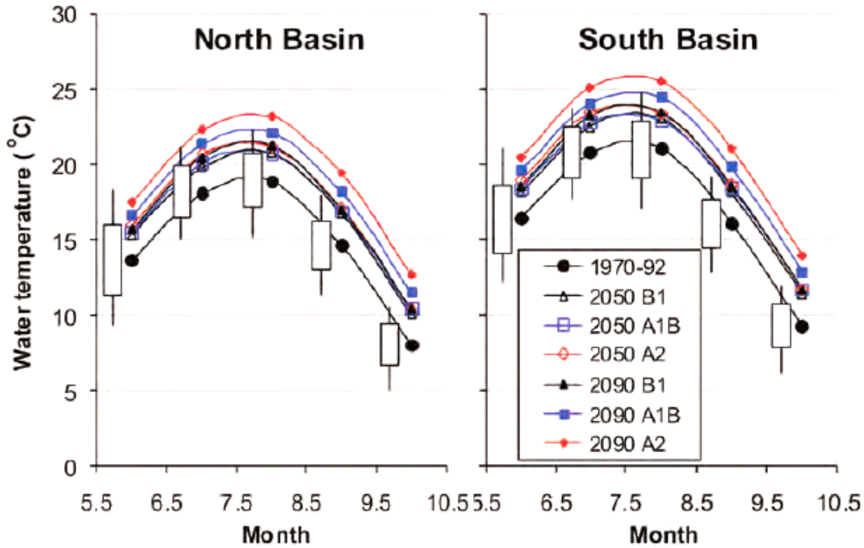

Figure 22: Historic and projected 20-year averages of open water season monthly mean surface water temperatures in the north and south basins of Lake Winnipeg. Offset box and whisker plots indicate one standard deviation and range of the 1970 to 1992 data. 2050 refers to the 20-year period 2040 to 2059; 2090 refers to 2080 to 2099. Air temperature data for 21st century periods were retrieved from CGCM3 model runs, with 3 forcing emissions scenarios: B1, A1B and A2. (McCullough and Levesque 2011)

IMPLICATIONS OF CLIMATE CHANGE FOR THE INLAND FRESHWATERS OF THE PRAIRIES REGION

The recent trends and future projections for the climate and water of the Prairies have significant implications for the state and management of inland freshwaters. In general, we can expect wetter and much warmer winters, warmer and drier summers, larger departures from average conditions and more frequent extreme events. Much of the western half of the continent is showing historical trends that suggest an increasing influence of the dry tropical climate of the USA Southwest. Consequently, we can expect negative impacts on all watersheds originating in the Rocky Mountains and on the western Prairies. The magnitude of the change in these watersheds is uncertain, but modeling results suggest it will be substantial. The fact that so many researchers have already identified statistically significant trends towards lower runoff supplies supports the contention that streamflow reductions will be significant.

SURFACE WATER QUANTITY AND QUALITY

Climate change impacts on the freshwaters of the Lake Winnipeg Basin may include altered runoff quantity and seasonality, and total nutrient loading (Schindler 2009). Longer warmer winters will reduce snowpack accumulations in the mountains and on the southern Prairies, leading to lower overall annual runoff in the major rivers, with the reductions more pronounced in the southwestern regions. Changes in streamflow timing will result from earlier melting of snow across the Prairie Provinces. More runoff will occur in March, April and May. This will reduce streamflow supplies in summer, fall, and into winter. Reduced streamflows and increased water demands will lead to routine supply deficits for ecosystems and communities.

Warmer and longer summers will increase water demand for agricultural and native ecosystems. Water use, including around 500,000 hectares of irrigation developments, has essentially fully allocated the Bow and Oldman Rivers in southern Alberta. Without further adaptation and management of water demand, reductions in streamflows could jeopardize the irrigation of tens to hundreds of thousands of hectares in those basins. It is estimated that a 10 to 20% expansion in irrigation in the Bow and Oldman basins is possible with water conservation (Alberta Environment 2003). Further north and east, rivers are not so heavily allocated, and some irrigation development may occur in response to warmer and drier conditions. Potential for significant increased human uses (including irrigation) exists in portions of the SSRB in Saskatchewan. The Brace Report (PFRA 2005) suggests that a 500% irrigation expansion is possible in Saskatchewan, with most of the water coming from the South Saskatchewan River. However, these adaptations are not likely to proceed without balancing the environmental, social and economic impacts.

A further impact that may alter both water supply and quality is the occurrence of extensive forest fires, such as those that have occurred in recent years over many regions of western North America. Large-scale forest fires create flashy runoff that erodes soils and degrades water quality. Various studies express concern over increasing forest fire risk due to climate change. Two prominent studies (Running 2006 and Westerling *et al*. 2006) explicitly link recent dramatic fire seasons in the western United Sates to climate change. The occurrence and impacts of forest fires are closely connected to climate and weather (Cary *et al*. 2006). More severe and persistent droughts will cause declining soil water in many years, which will likely increase forest fire extent and net areas burned (Sauchyn *et al.* 2003). Stocks *et al*. (1998) forecast large increases in the areal extent of extreme fire danger for boreal forest in Canada and Russia under a doubling of atmospheric CO_2. Flannigan *et al*. (2005) forecast the area burned in Canada will increase 74–118% by the end of this century in a 3 × CO2 scenario. In recent history, during extreme droughts, organic soils have dried and burned with forests, resulting in almost total loss of vegetation and soil cover and, subsequently, the ability to store water locally. Under these conditions, runoff events are less buffered, with subsequent instantaneous responses and the risk of causing flash floods. The drought of 2001 - 2004 extended much further north than expected, bringing drought and a bad fire season to the western boreal forest.

For the eastern Prairies, warmer temperatures are not likely to create drought stress in most years, as adequate additional precipitation may occur by virtue of humid air that dominates the eastern half of the continent. However, the boundary region between the wet and dry zones that lies over eastern Saskatchewan has shown significant shifts over the years. This region will likely endure much greater interannual variation between intensified wet and dry cycles. The greatest risk to the Red and Winnipeg Rivers due to climate change may be an increase in flood potential. The Red River has had several high flow years recently, and in April 2009, a cool winter with large snow accumulations and heavy ice cover once again caused severe flood stress for North Dakota and southern Manitoba. Extensive flooding again in 2010-11 likely represented mostly natural climate variability but it is consistent with projections of wetter climate and intense precipitation in the eastern Prairies.

Most of the research on climate change and prairie water resources, as described above, has focused on the large rivers that flow from the eastern slopes of the Rocky Mountains and supply most of the population of the Prairie Provinces with water. The smaller rivers and streams that flow from prairie uplands support important riparian ecosystems and are the water supply for much of the rural populations and some larger communities. The few studies of the climate and hydrology of these prairie-sourced streams include long-term research in central Saskatchewan (Pomeroy *et al.* 2007). Recent studies in these watersheds suggest that, in the near term, projected climate change could produce an increase in annual runoff (Fang and Pomeroy 2008). With further climate warming, however, annual runoff would begin to decline, as winter snow cover becomes discontinuous.

GROUNDWATER

In the Prairie region, groundwater is the dominant source of late season streamflow in the form of baseflow. If groundwater levels decline due to reduced recharge, prolonged drought or over-pumping, the baseflows will decline to levels where water supply and quality will be adversely affected. This occurred in central Alberta during the 2001-03 drought with dire consequences for some water users, such as a collapse of streamflow of the upper Battle River, resulting in severe water restrictions for domestic users, or the shutdown of power plants due to the lack of available cooling water (Kienzle 2006). Increased rainfall in early spring and late fall will enhance soil moisture and contribute to groundwater recharge when soil water levels are high. With a warmer climate imposing higher evapotranspiration rates, soil moisture will be utilized, and declining ground moisture retention will lead to a decrease in groundwater recharge and a slow but steady decline in the water table. Groundwater levels in shallow aquifers also is sensitive to inter-annual to decadal scale climate variability as a function of large-scale ocean-atmosphere oscisllations (Pérez-Valdivia and Sauchyn, 2012).

FLOATING FRESHWATER (LAKE AND RIVER) ICE

Floating freshwater ice is a critical component of aquatic habitats and control on biological diversity and productivity. It controls most major interactions between the atmosphere and aquatic systems, including solar radiation, thermal regimes and oxygen levels. With his many collaborators and graduate students, Dr. Terry Prowse is the authority on the floating freshwater (lake and river) ice of the Northern Hemisphere. Dr. Prowse and his co-authors produced a comprehensive overview in 2007 and have published many important papers on the changing distribution of lake and river ice and the relationship to climate variability and change (Prowse and Beltaos 2002; Bonsal and Prowse 2003; Prowse and Bonsal 2004; Dibike et al., 2011a, 2011b). Most of this work has concentrated on rivers and lakes of arctic, subarctic and alpine environments. This work can be applied, however, to the Lake Winnipeg basin and especially the colder northern and eastern regions. Further south and west, river and lake ice is present to a lesser extent. River ice break is a dramatic annual hydrologic event in cold regions producing flood stages that often exceed the highest flows during the open-water period (Prowse 2005). Whereas in the coldest regions, break up is typically a single spring event, in temperate climates, river ice can go through a series of freeze-up/break-up cycles throughout winter and early spring.

Data on freshwater ice in cold regions is limited by a lack of monitoring. Therefore most studies of historical changes have examined relatively simple properties of freshwater ice, such as maximum ice-cover thickness and the timing of spring break up and autumn freeze up. These studies have determined that across the Northern Hemisphere, as air temperatures have risen over the past 50 years, spring break up has occurred earlier and, to a lesser degree, autumn freeze up has occurred later. In a study of 27 records, spanning the Northern Hemisphere and about 150 years, freeze up was delayed by about six days per hundred years and break up advanced at a similar rate, resulting in an almost two-week per century reduction in the annual duration of ice cover (Magnuson, *et al*. 2000). In general, freeze up/ break up of river ice has delayed/ advanced by 10 to 15 days in response to long-term increases of 2–3°C in autumn and spring air temperatures (Prowse and Bonsal 2004). A data set of river and lake-ice thickness compiled for Canada over the last 50 years shows no obvious trends over the latter part of the 20th century (Lenormand *et al*. 2002; Lemke *et al*. 2007). The response of ice-cover duration to recent climate warming has varied regionally and is strongly related to the variability and shifts in the regimes of large-scale atmospheric and oceanic oscillations. In Canada, a shortening of the freshwater-ice season over much of the country is attributable mainly to earlier break ups, mimicking temporal (1966 to 1995) and spatial trends in autumn and spring 0°C isotherms (Bonsal and Prowse 2003). Figure 23 shows that trends toward earlier springs and earlier break-up dates are statistically significant over most of western Canada (Duguay *et al*. 2006).

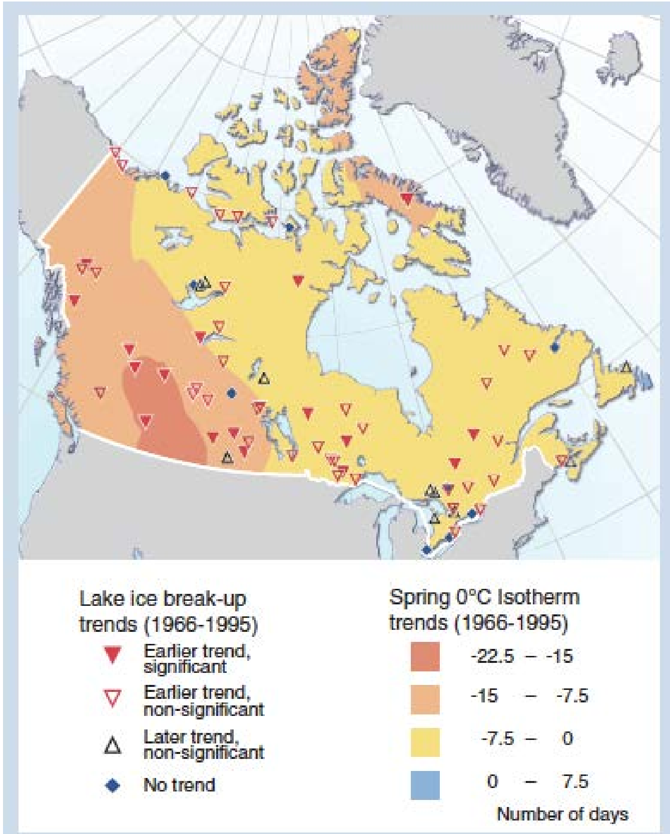

Figure 23: Trends in spring temperatures and in ice break-up dates in Canada. (Prowse et al. 2007a)

With climate change, decreased lake-ice cover will produce changes in biological diversity and productivity as a result of changes in temperature, light levels, UV radiation exposure, and water circulation patterns (Wrona *et al*. 2006). Variations in light and nutrient availability, water circulation patterns, and layering of warm and cold water during the ice-off period are of particular concern. The life cycles of most aquatic organisms are linked with ice cover and temperature, and the response to future climate changes is difficult to predict. Future projections of river and lake ice cover generally indicate further delays in freeze up and further advances in break up in proportion to the degree of warming that is forecasted (Prowse *et al*. 2007a). These projections are based on temperature-based relationships and do not include complicating effects such as snow cover (Prowse and Beltaos 2002; Duguay *et al*. 2003).

In an unpublished report, not cited by Prowse *et al*. (2007b), McCullough (2005) examined statistical relationships between monthly mean surface temperatures, and dates of ice break-up and freeze-up of the north and south basins of Lake Winnipeg. To model historic water temperature, and ice break-up and freeze-up, McCullough combined the air temperature records from Berens River about half way down the lake, and Pine Dock at the Narrows between the north and south basins. This composite record together spanned the period from 1909-2004. Using water temperature data from the Environment Canada weather buoys in Lake Winnipeg, he developed regression functions with air temperature as the predictor of June-October monthly mean surface water temperatures. Midsummer air temperature is strongly correlated with the maximum monthly mean temperature in Lake Winnipeg. The only significant long-term trends were an increase of 1.0^{o} C in September in the north basin, and an increase of 1.9^{o} C for August in the south basin.

McCullough (2005) estimated 21st century water temperatures using air temperature data from the Canadian Global Climate Model, Version 2 (CGCM2). The results are plotted in Figure 24. CGCM2 projects an approximately 2.0^{o}C rise in midsummer temperatures by the middle of the 21st century, and up to 4.5^{o}C more by the end of the century. There is a proportional increase in mean July and August surface water temperatures under the A2 or B2 greenhouse gas (GHG) emission scenarios. With A2 GHG forcing scenario, average midsummer temperatures in the north basin rise to 20-21^{o}C by 2045 and ~23-24^{o}C by 2085, and in the south basin to ~23^{o}C by 2045 and to ~26^{o}C by 2085. Under the less GHG intensive B2 emission scenario, midsummer surface temperature rise to ~21-22^{o}C in the north basin and ~24^{o}C in the south basin by the end of the 21st century.

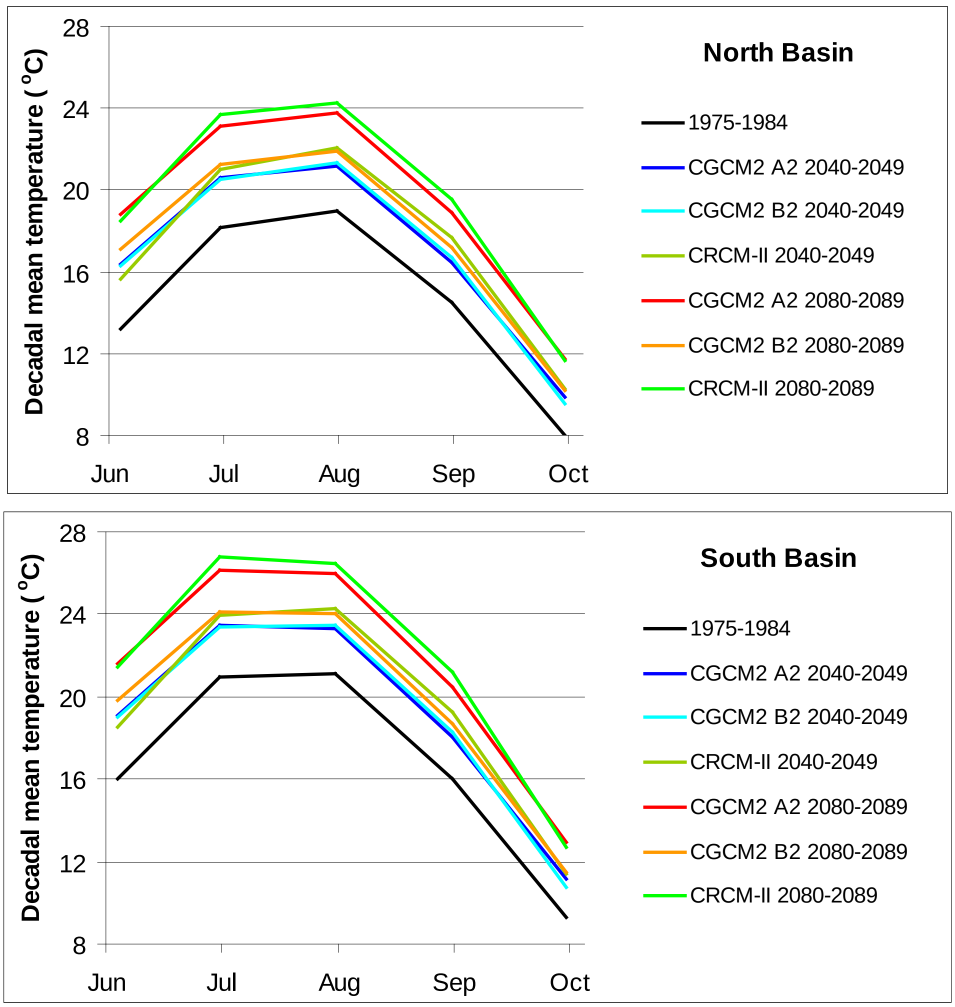

Figure 24: Historic and predicted decadal means of monthly mean water temperatures in the North and south basins of Lake Winnipeg. 1975-84: by regression on the historic air temperature record at Berens. 2040-2049 and 2080-89: by regression on adjusted

CGCM2 air temperatures, with two forcing emissions scenarios, A2 and B2. (McCullough 2005)

The timing of ice break-up and freeze-up on Lake Winnipeg is correlated with April and November air temperatures. McCullough (2005) determined the timing of melt and break-up of the ice cover on Lake Winnipeg using satellite images. "*From 1987-2004, the north basin was 50% clear of ice as early as 1 May in 2000 and as late as 5 June, or on average by 19 May. Ice cover on the south basin broke up on average two weeks earlier – it was half ice-free as early as 16 April to as late as 27 May and on average by 5 May.*" Freeze-up dates were established using 1956-1990 ice-cover observations at Gimli; the satellite imagery was unreliable because cloud and fog are common over the lake in fall. "*First ice was recorded as early as 28 October on the south basin, and full ice cover was completed as late as 17 December. The median date of the freeze-up period ranged from 10 November-1 December.*" There were no significant 20th century trends in the break-up or freeze-up time series.

McCullough (2005) estimated the future timing of break-up and freeze-up using temperature output from CGCM2 and the A2 and B2 GHG-forcing scenarios (Table 3). By 2045, under both scenarios, the north basin is projected to break-up about a week and a half earlier than in the 20th century, and the south basin about a week earlier. The two scenarios diverge later in the 21st century. Under B2 forcing, the north basin breaks-up two weeks earlier by 2085, and the south basin a week and a half earlier. With the A2 forcing, ice cover on the north and south basins breaks up three weeks and two weeks earlier, respectively. Neither forcing scenario includes significant changes the timing of freeze-up.

Table 3: Mean and standard deviation of break-up [B(N)50 and B(S)50] and freeze-up [F(S)median] estimated by regression on the date when the 40-day moving average air temperature warmed to +5 (dropped below -5oC for freeze-up) using the record at Berens River for 1976-89 and output CGCM2 (scenarios A2 and B2) for the periods 2040-42 and 2076-88. n=13 for each sample. (McCullough 2005)

	Berens R. (1976-89)	CGCM2 A2 (2040-52)	CGCM2 B2 (2040-52)	CGCM2 A2 (2076-88)	CGCM2 B2 (2076-88)
north basin Melt and Break-up, [$B(N)_{50}$]					
mean	21 May	10 May	13 May	02 May	08 May
s.d.	9	6	7	4	5
south basin Melt and Break-up, [$B(S)_{50}$]					
mean	07 May	29 Apr	01 May	23 Apr	28 Apr
s.d.	6	5	5	3	4
South Basin Freeze-up [$F(S)_{median}$]					
mean	18 Nov	19 Nov	18 Nov	20 Nov	19 Nov
s.d.	7	3	2	2	2

For the State of Lake Winnipeg study (Environment Canada and Manitoba Watershed Stewardship 2011), McCullough and Levesque (2011) produced updated projections of break-up and freeze updates using output from version 3 of the Canadian Global Climate Model (CGCM3). He used air temperatures from two sources: historical data from1970 to 1992 and output from CGCM3 for the periods 2040 to 2059 and 2080 to 2099. Results for dates of mid-break-up, which is when the basin is half clear of ice in the spring, are plotted in Figure 25. By mid-21st century, mid-break-up could occur on average four to six days earlier in the south basin and about a week earlier in the north basin. There would be little further change over the next half-century under the weakest GHG forcing, B1. With the strongest forcing, A2, the timing of break-up could continue to advance, so that by the end of the 21st century, it would be one and a half weeks earlier in the south basin, and nearly two weeks earlier in the north basin. These projected changes in break-up and freeze-up can be compared to an average ice-free season (from last observed ice in spring to first observed ice in autumn) of 180 days in the south basin of Lake Winnipeg from 1946 to 1991. The ice-free period is about two weeks less in the north basin.

Figure 26 shows the McCullough and Levesque (2011) historic and projected dates of mid-freeze-up on the south basin, when the basin is half covered by ice. Freeze-up, on average, occurs about a week later by mid-21st century; the projections then diverge depending on the GHG forcing scenario. With the least GHG forcing (scenario B1), little further change occurs over the next half-century, while under the strongest emission scenario (A2), the timing of freeze-up is further delayed by another two weeks later, such that the ice-free season will be nearly a month longer by the end of the 21st century; about 194 days in the north basin and 204 days in the south basin. These projections differ from the previous study by McCullough (2005), based on the earlier version 2 of the Canadian Global Climate Model (CGCM2), that simulated only small increases in autumn air temperature, and therefore negligible change in the mean timing of freeze-up.

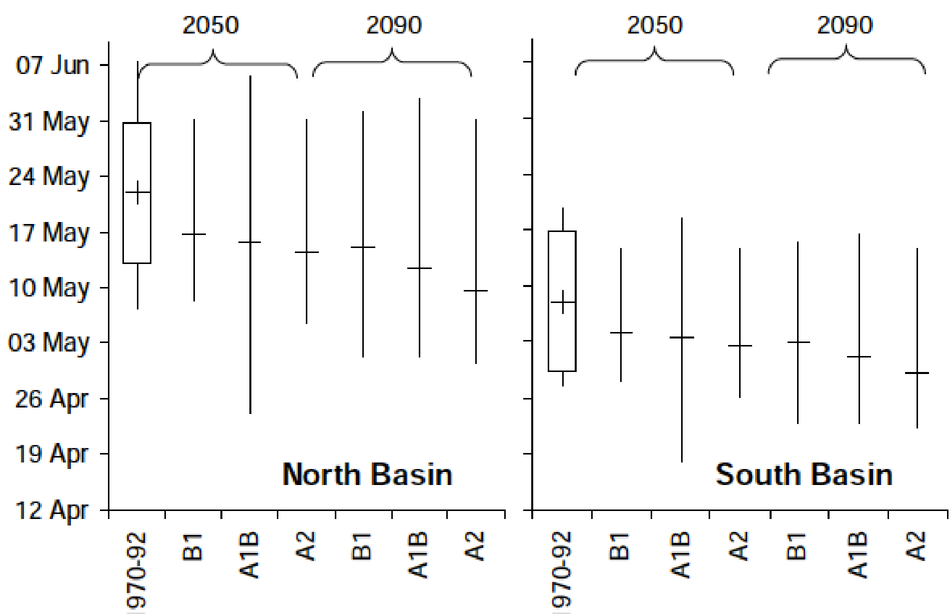

Figure 25: Historic and predicted dates of mid-break-up (date when the basin becomes half clear of ice) on the north and south basins of Lake Winnipeg.
Crosses indicate means. For 1970 to 1992 data, boxes indicate 1 standard deviation and whiskers indicate range of values (n = 20). For predicted 21st century values, only the means and ranges are shown. 2050 refers to the 20-year period 2040 to 2059; 2090 refers to 2080 to 2099. (McCullough and Levesque 2011)

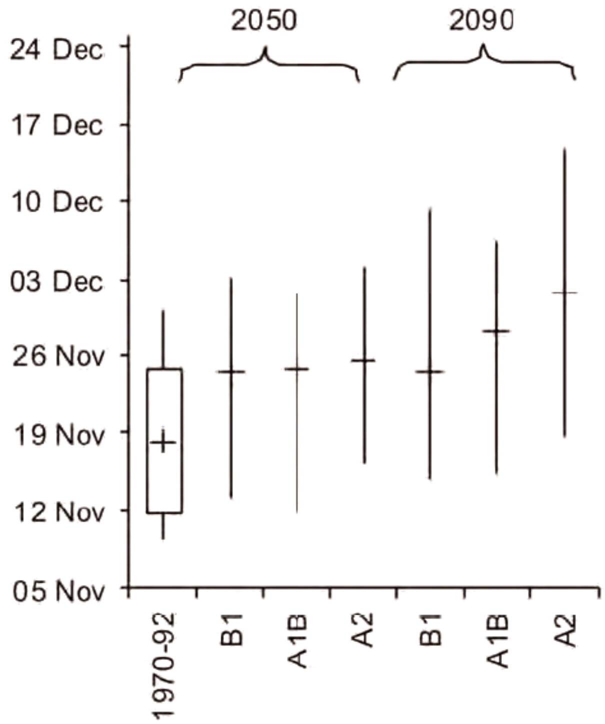

Figure 26: Historic and projected dates of mid-freeze-up (date when the basin becomes half covered by ice, estimated using the 40-day moving average air temperature as described in the text) on the south basin of Lake Winnipeg. The north basin typically freezes over within a few days of the south basin. (McCullough and Levesque 2011)

The two studies by McCullough (2005; and Levesque 2011) used only spring and autumn air temperature as predictors of break-up and freeze-up, and did not consider other factors. Ice thickness at the onset of spring melt is an important factor, dependent not on spring temperatures but on winter temperatures and snow cover, which may be affected by climate change. Consistent model projections of higher winter temperatures imply a thinner ice cover and thus possibly even earlier break-up than modeled using only spring air temperatures. Global climate model simulations of winter precipitation are not sufficiently reliable to project the influence on snow accumulation on ice thickness. Modeling of timing of freeze-up, on the other hand, is not sensitive to factors besides radiative and evaporative cooling as a function of the heat flux into a cooling atmosphere.

CLIMATE CHANGE AND WATER MANAGEMENT

Climate change will exacerbate threats to clean water and aquatic ecosystems, our most essential water resources. The natural health and wealth of the Prairie Provinces is intimately linked to the quality and quantity of the water resources. Environment Canada (2001; 2004) documented the threats to water quantity and quality across the country, including many problems facing the Prairie Provinces. Diversions from one watershed to another, dams to store water (mainly for irrigation), as well as chemical, biological and thermal pollution have already seriously altered water quality and aquatic ecosystem health in most prairie regions.

With the potential for higher rates of soil erosion from intense rainfall, especially when vegetation cover is reduced by drought or fire, climate change may produce sedimentation problems and add nutrients to local water systems, leading to eutrophication of local water bodies. Runoff may also carry waste products and could lead to increased pathogen loading in streams in summer. Pathogen loads are already an issue in many prairie watercourses (Johnson *et al*. 2003; Little 2003; Hrudey and Hrudey 2004). Urban runoff and sewage effluent contribute additional chemicals, nutrients and microbial populations.

Green masses of cyanobacteria, often called algal blooms, routinely cover much of Lake Winnipeg in summer (Casey 2006). These blooms may cover so much of the lake that they are best documented from space. Dilution capacity will decline under climate change as streamflows decrease and lake residence times increase accordingly. Therefore, global warming is further reason to change the long- standing view that “dilution is the solution to pollution.” This attitude and cumulative pollution loads could, when amplified by climate change, push aquatic ecosystems beyond a threshold of ecological collapse (Couillard *et al*. 2008). A warmer climate regime will likely increase the risk of impact to both ecosystems and human health, if watercourses have lower volumes of water, and likely warmer water that will enhance algal growth and alter ecosystems evolved for cooler temperatures.

Declining water supplies and increasing water demands will lead to calls for increased storage, which may support the construction of more dams and reservoirs. However, reservoirs are not greenhouse gas neutral, and such structures disrupt and segment ecosystems. Impacts of dams and diversions on water include (St. Louis *et al*. 2000; Environment Canada 2001):

- thermal stratification within the reservoir and modification of downstream water temperatures;
- eutrophication;
- promotion of anoxic conditions in hypolimnetic water and related changes in metal concentrations in outflow;
- increased methylation of mercury;
- sediment retention;
- associated changes in total dissolved solids, turbidity and nutrients in the reservoir and discharged water; and
- increased erosion/deposition of downstream sediments and associated contaminants.

Flow diversions can also produce major changes in water quality. The most dramatic shifts result from mixing of waters from disparate hydro-ecological systems (*e.g.* across major hydrologic divides or from freshwater to estuarine environments), resulting in changes in chemistry, temperature and sediment. In addition, the transfer of fish, parasites and pathogens can accompany such mixing.

The combined effects of changes to water quantity and quality will require changes to land and water management practices. Currently accepted best management practices may no longer fully address the expected changes from a future climate. New water management strategies may be required (*e.g.* earlier releases to irrigators; balancing water competition between agricultural, energy and urban uses). The timing of spring seeding and fall harvesting may shift earlier in each season, and changes to pest management and soil moisture management may be required. With potentially increased frequency of extreme events and wider hydrologic variability (drought, flood), new adaptation strategies will likely be necessary to help dryland agriculture and irrigated agriculture cope with a more volatile climate. Research and planning are necessary to determine future adaptive practices to help local decision-makers address new challenges and opportunities posed by a different climate and water regime.

The studies of hydrologic variability and trends reviewed in this report have important implications for water resource management in the Prairie Provinces. The recognition of significant natural modes of hydrological variability leads to a more rigorous interpretation of recent trends and fluctuations in raw water supply (Sauchyn, Pietroniro and Demuth, 2008). Much of the variability in streamflow, including emerging trends, can be linked to the influence of large-scale ocean-atmosphere circulation patterns. At the same time, there are significant trends in some gauge records that span shifts in the phases of these teleconnections. These consistent trends most likely represent a fundamental change in hydrologic regime in response to regional climate and land use change.

The various scales of variability in the regional runoff and hydroclimate require different management practices and adaptation strategies to ensure the efficient and sustainable supply and use of water resources. The historical adaptations to the Prairie's dry and variable climate, including current water resource management practices, deal relatively well with the large intra-annual variability and the short cycles driven in part by the ENSO. Longer-term cycles, and associated severe and sustained drought, exceed the length of most instrumental records and water supply planning horizons. Because scientific understanding of this lower frequency variability, and the drivers (*i.e.,* the PDO, the Atlantic Multidecadal Oscillation (AMO)), is relatively recent, and the adverse consequences are relatively infrequent, there are fewer options for dealing with sustained severe drought or excessive moisture. Recognition and understanding of this mode of variability is the first step towards anticipating and mitigating the impacts. The long-term trends in water levels that are consistent with a warmer climate and loss of permanent land cover require yet another mode of adaptation involving fundamental institutional and systemic changes in water allocation and use. Detecting these long-term trends and separating them from transient trends, that are artifacts of low frequency periodic variability, informs decision making to achieve adaptation to climate change.

CONCLUSIONS

In this report, we reviewed a wide range of scientific studies that have reported recent and expected changes to the climate and water cycle of the Canadian Prairies under global warming. These studies present various tendencies in observed and projected precipitation and water levels. Generally, differences among studies do not represent disagreement among the scientists, but rather the variability and complexity of the water cycle, such that the monitoring and modeling of precipitation and water levels can reveal different trends for different time periods and watersheds. Dry climates, like in the Canadian Prairies, have the most variable precipitation and runoff from year to year. Streamflow also varies at other time scales, from a few years multiple decades. In Western Canada, this low-frequency variability in the hydroclimate has been linked to oscillations in sea surface temperature in the Pacific Ocean. As a result of these wet and dry cycles, what seems like conflicting trends in water levels can in fact be the response of watersheds to climate forcing at different rates. Therefore, the analysis and interpretation of streamflow trends depend very much on the length of gauge records and the period of time modelled or observed (Sauchyn and St. Jacques 2009).

Despite this complex behaviour of hydrological systems, there are some common tendencies in the response of prairie water resources to climate change. Among the more consistent scenarios is the shift in precipitation and runoff from late spring and early summer to winter and early spring. Less surface and soil moisture can be expected in the mid-to-later stages of the longer and warmer summers. Rainfall will be more concentrated in time, with larger amounts in fewer storms. As a result, we can expect some unusually wet conditions, but also long dry spells between the less frequent rainstorms. The net result of these hydrological changes is potentially greater risk of more extreme events and more variability in the distribution of precipitation, affecting ecosystems and human needs. These more extreme conditions, and a wider range of water levels and moisture conditions, likely will determine much of the impact of climate change in the Prairie Provinces. Adaptation to avoid the most adverse impacts on prairie ecosystems, communities and economies must include integrated and adaptive water resource planning and policy to manage a range of variability and extremes that exceeds our past experience. As advised by Sauchyn, Pietroniro and Demuth (2008):“water resource managers and agencies accept and accommodate a lesser degree of determinacy, certainty and stationarity”.

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APPENDIX A: TRENDS IN ANNUAL (OR WARM SEASON) FLOW FOR 86 NATURALLY FLOWING AND FIVE REGULATED STREAMFLOW RECORDS FROM THE PRAIRIE PROVINCES (FROM ST. JACQUES *ET AL*. IN PRESS).

Table A.1: The 86 naturally flowing and five regulated streamflow records from the Prairie Provinces.
A check mark indicates whether the gauge operates during ice-free conditions only (generally March to October) and is in the Reference Hydrometric Basin Network (RHBN) (Harvey *et al.*, 1999). The total change in flow over the period of record, and mean change per years, represents statistically significant trends if they are shown in red (decreasing) or blue (increasing).

Station name	**RHB**	**Ice-Free Only**	**WSC station code**	**Period of record**	***Total change(%)***	***Mean Δ/yr(%)***
Sage Creek	√	√	11AA026	1935-2010	**-72.4**	**-0.95**
Waterton River	√		05AD003	1912-2010	-8.8	-0.09
Rolph Creek		√	05AE005	1936-2010	-16.5	-0.22
Manyberries Creek		√	05AF010	1913-1930, 1957-2010	**-72.7**	**-0.74**
Pincher Creek		√	05AA004	1919-1930, 1966-2010	-23.3	-0.25
Prairie Blood Coulee		√	05AD035	1970-2010	28.4	0.69
Trout Creek		√	05AB005	1919, 1922-1923, 1978-2010	105.8	1.15
Blood Indian Creek		√	05CK001	1964-1974, 1976-2010	**-13.1**	**-0.28**
Jumpingpound Creek		√	05BH009	1966-2005	5.1	0.13
Bow River at Banff	√		05BB001	1911-2010	**-14.1**	**-0.14**
Rosebud River		√	05CE006	1959-2010	-6.3	-0.12
Mistaya River	√		05DA007	1967-2010	-4.4	-0.10
Threehills Creek		√	05CE018	1971-2010	12.4	0.31
Prairie Creek			05DB002	1962-2010	6.0	0.12
Bigknife Creek		√	05FC002	1968-2010	-40.7	-0.95
Buffalo Creek		√	05FE002	1972-2010	-10.8	-0.28
Athabasca River at Hinton			07AD002	1962-2010	**-10.4**	**-0.21**
McLeod River			07AF002	1955-2010	-13.6	-0.24

Pembina River			07BB002	1915-1922, 1955-2010	0.4	0.004
Waskatenau Creek		√	05EC002	1967-2010	**-104.2**	**-2.37**
Beaver River at Cold Lake Reserve			06AD006	1956-2010	**-91.0**	**-1.65**
Athabasca River at Athabasca		√	07BE001	1913-1930, 1938-2010	-10.0	-0.10
Little Smoky River			07GH002	1960-2010	**-47.1**	**-0.92**
Saddle River		√	07FD006	1967-2010	-52.3	-1.19
Smoky River			07GJ001	1916-1920, 1956-2010	**-37.8**	**-0.40**
Pine River	√		07FB001	1965-2010	-14.1	-0.31
Heart River		√	07HA003	1963-2010	**-81.6**	**-1.70**
Clearwater River	√		07CD001	1958-2010	-20.8	-0.40
Athabasca River			07DA001	1958-2010	**-30.9**	**-0.59**
Notikewin River			07HC001	1962-2010	**-43.4**	**-0.88**
Birch River	√	√	07KE001	1968-2010	-15.2	-0.35
Richardson River	√	√	07DD002	1971-2010	7.3	0.18
Boyer River		√	07JF002	1963-2010	-5.2	-0.11
Ponton River		√	07JF003	1963-2010	1.8	0.04
Sousa Creek		√	07OA001	1971-2010	-7.5	-0.19
Chinchaga River			07OC001	1970-2010	-16.0	-0.39
Hay River	√		07OB001	1964-2010	37.6	0.80
Rock Creek		√	11AE009	1916-1926, 1957-2010	**-79.6**	**-0.84**
Poplar River		√	11AE008	1931-2010	-24.8	-0.31
Long Creek			05NA003	1912-2010	-1.5	-0.02
Lyons Creek	√	√	11AB075	1927-2010	**-46.5**	**-0.55**
Lightning Creek	√	√	05NF006	1974-2010	-2.0	-0.05
Antler River near Wauchope	√	√	05NF010	1965-2010	-31.0	-0.67
Notukeu Creek	√	√	05JB004	1975-2010	28.4	0.79
Swift Current Creek		√	05HD036	1955-2010	-21.2	-0.38
Bridge Creek		√	05HA015	1916-1922, 1963-2010	-45.2	-0.48
Cottonwood Creek		√	05JF011	1974-2010	-13.0	-0.35

Stony Creek		√	05MD010	1971-2010	43.3	1.08
Opuntia Lake West Inflow		√	05GC007	1960-2010	-35.6	-0.70
Maloneck Creek	√	√	05LE011	1974-2010	36.6	0.99
Quill Creek		√	05MA020	1973-2010	54.2	1.43
Lilian River		√	05MC003	1970-2010	-12.6	-0.31
Red Deer River near Erwood		√	05LC001	1954-2010	-20.0	-0.35
Overflowing River near Hudson Bay	√	√	05LD003	1975-2010	59.7	1.66
Sturgeon River		√	05GF002	1967-2010	13.8	0.3
Shell Brook		√	05GF001	1966-2010	18.1	0.4
Carrot River		√	05KC001	1955-2010	-38.8	-0.7
Beaver River near Dorintosh		√	06AD001	1963-2010	**-77.1**	**-1.6**
Churchill River	√		06CD002	1964-2010	-12.5	-0.27
Haultain River	√		06BD001	1969, 1972-2010	12.9	0.31
Gelkie River	√		06DA004	1967-2010	-7.9	-0.18
Waterfound River			07LB002	1975-1976, 1978-2010	-4.7	-0.13
MacFarlane River			07MB001	1968-2010	1.1	0.03
Fond du Lac River	√		07LE001, 07LE002	1947-2010	8.4	0.13
Mowbray Creek		√	05OB021	1962-2010	**117.5**	**2.40**
Antler River near Melita	√	√	05NF002	1943-2010	-37.5	-0.55
Graham Creek		√	05NF008	1943-1996, 2010	-34.7	-0.51
Shannon Creek	√	√	05OF014	1960-2010	47.9	0.94
S. Tobacco Creek	√	√	05OF017	1964-2010	9.5	0.20
Whitemouth River			05PH003	1957-2010	52.4	0.97
Brokenhead River	√	√	05SA002	1956-2010	42.2	0.77
Little Saskatchewan River		√	05MF001	1915-1929, 1959-2010	32.0	0.33
Pelican Creek S. Tributary	√	√	05LL027	1974-2010	48.3	1.31

Shell River			05MD005	1957-2010	**61.9**	**1.15**
Icelandic River		√	05SC002	1959-1996, 2010	-35.5	-0.68
Ochre River	√	√	05LJ005	1956-2010	14.3	0.26
Fisher River			05SD003	1962-1996	-20.5	-0.59
Waterhen River	√		05LH005	1953-2010	5.5	0.09
Pigeon River			05RD008	1958-2010	**39.1**	**0.74**
Overflowing River	√	√	05LD001	1956-2010	7.5	0.14
Island Lake River			04AC007	1933-1964, 1966-1975, 1977-1979, 1981, 1983-1984, 1986-1993	-8.2	-0.13
Gods River			04AC005	1934, 1937-1944, 1948-1993	**-31.6**	**-0.53**
Grass River	√		05TD001	1960-1984, 1986-1988, 1991-2010	-32.9	-0.65
Kettle River			05UF004	1966, 1969-1996, 1998, 2000-2010	-4.4	-0.10
Little Beaver River	√		06FB002	1974-2010	6.9	0.19
Seal River	√		06GD001	1955-1996, 2000-2003, 2005, 2007, 2009	**25.8**	**0.47**
REGULATED FLOW						
S. Saskatchewan River at Medicine Hat			05AJ001	1912-2010	**-41.2**	**-0.41**
Red Deer River at Red Deer			05CC002	1912-2010	-16.0	0.16
N. Saskatchewan River at Edmonton			05DF001	1912-2010	-13.5	-0.14
N. Saskatchewan River at Prince Albert			05GG001	1912-2010	**-19.5**	**-0.20**
Saskatchewan River at The Pas			05KJ001	1913-2010	**-31.2**	**-0.32**