Future Possible Dry and Wet Extremes in Saskatchewan, Canada

Prepared for the Water Security Agency, Saskatchewan

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# Table of Contents

**SUMMARY** 4  
**INTRODUCTION, OBJECTIVE AND METHODS** 6  
  - Objectives and Study Area 6  
  - Method, Time Periods, and Research Framework 7  
**CLIMATE EXTREMES OF THE INSTRUMENTAL RECORD** 7  
  - Drought History Overview 8  
  - Extreme Precipitation Events Overview 9  
**FUTURE POSSIBLE DROUGHTS** 12  
  - Summary of Probable and Worst-case Drought Scenarios 19  
**FUTURE POSSIBLE PRECIPITATION EXTREMES** 21  
  - Introduction and Objective 21  
  - Reasons for Changes in the Hydrological Cycle 21  
  - Changes in Frequency, Intensity and Type of Precipitation Extremes 22  
  - Projections of Extreme Precipitation for the Canadian Prairies 23  
  - Estimates of Maximum Precipitation 24  
  - Summary of Possible and Worst-Case Future Scenarios of Extreme Precipitation 26  
    - Probable Future Extreme Precipitation Scenarios 26  
    - Worst-Case Extreme Future Precipitation Scenarios 26  
**CONFIDENCE IN FUTURE PROJECTIONS** 27  
**DISCUSSION AND CONCLUSIONS** 28  
**ACKNOWLEDGEMENTS** 30  
**REFERENCES** 31
Droughts and extreme precipitation are extreme climate events and among the most costly and disruptive environmental hazards. Therefore, it is crucial to both plan and to deal with them in cost-effective and efficient manners. Adaptations are especially needed in Saskatchewan, a location prone to extreme climate events. Another factor that emphasizes this adaptation need is the warming climate. Assessments of drought and even precipitation extremes are more common on a global basis than those for Canada. This work examines the world and Canadian literature, but emphasizes the study area of eastern agricultural Saskatchewan. The literature concludes that drought and extreme precipitation are expected to become more common in the future. Several topics require further research, of course, including the drought/wet indices, but all of those indices, climate models and emission scenarios agree on this finding.

Future climate change due to rising greenhouse gas concentrations is projected to increase the frequency, intensity and extent of moderate to extreme droughts in the Saskatchewan. At the other extreme, climate change is projected to increase the frequency of severe storms and unusually wet periods. Future probable droughts would likely be similar or longer compared with the severe and intensive drought of 1999-2005, but with the potential for even more damage. The possible worst-case scenario dry and wet events such as mega-droughts and super-storms are expected to be worse than the pre-instrumental droughts and maximized rainstorms. Future droughts may have a different set of causes, migrate from different places, be punctuated by super storms and may be quite unlike any in the period of record.

The risk of drought and extreme precipitation events is changing. Research shows that future dry and wet periods will be different than those of the historical record. This report examined research regarding the range of possible future droughts and excess precipitation, including the worst-case scenarios. The study area is southeastern agricultural Saskatchewan, an area that is already prone to climate extremes. Main findings include:

Some Characteristics of Possible Future Droughts

- Have increased intensity of dryness, driven by increased evaporation potential. Drying likely overwhelms projected increases in average precipitation amounts.
- Droughts at least 6-10 months long increase in frequency by about an additional 4 events by the 2050s. The number of longer droughts doubles towards 2099.
- The number of droughts of at least five years doubles towards 2099.
- Decade-long droughts triple in frequency towards 2099.
- Storms with extreme precipitation are interspersed with droughts.
- Surprises result as the new combinations of climate variables occur.
- Worst-case scenarios of mega-droughts with even more intensity, frequency, duration and area are possible, but with low probability.

Some Characteristics of Possible Future Extreme Precipitation Events

- The number of 1 in 20y maximum precipitation events doubles by 2099. Worst cases indicate doubling of the number of 1 in 100y storms.
• Extreme rainfall amounts increase by 5 to 20% by the 2050s and by more than 20% for the worst-cases.
• Many more wet periods similar to the worst wet periods of the historical record occur by the 2050s.
• Sequences of large storms are more likely.
• Switching between dry and wet events increases.

A main conclusion is that wet times become wetter and dry times become drier (Summary Figure). Several driving factors are behind this finding, as illustrated in the figure.

Improved understanding of the characteristics, driving mechanisms, and impacts of these extremes, especially on a regional basis, will lead to projections with greater certainty. Despite uncertainties about the risk of severe events, the identification and understanding of past events and projections of the future provide opportunities to plan and take action to adapt to these events in ways that will reduce the danger and costs to society.

Summary Figure: Wet times become wetter and dry times become drier.
INTRODUCTION, OBJECTIVE AND METHODS

“More importantly, projections based on the PDSI ([Palmer Drought Severity Index] i.e., incorporating future temperature changes) indicate that Canadian Prairie twenty-first century droughts will be longer and more frequent than those associated with the current twentieth century warming...”) (Bonsal et al. 2012).

Droughts and excessive precipitation are extreme climate events and among the most costly and disruptive environmental hazards. Both of these extreme events have plagued Saskatchewan and several other parts of Canada especially during the past fifteen years or so, bringing considerable damage. Water supplies are especially threatened by droughts and can also be impacted by extreme precipitation. Droughts are especially costly as documented by Wheaton et al. (2008) for the example of the intense and extensive 2001 to 2002 drought. Because of its mid-continental location, Saskatchewan has experienced extremes of several climatic variables and may likely experience even more pronounced extremes in the future.

We use the Intergovernmental Panel on Climate Change (IPCC 2012) definition of ‘climate extreme’ which is “the occurrence of a weather or climate variable above (or below) a threshold value near the upper (or lower) ends of the range of observed values of the variable. For simplicity, both extreme weather events and extreme climate events are referred to collectively as ‘climate extremes’.”

Objectives and Study Area

An improved knowledge of the expected characteristics of extreme events is required to enhance adaptation to such events with the goal to invest in actions to reduce negative impacts and to increase benefits. If strategic planning is conducted with only a limited understanding of such extremes, it is incomplete. Prairie people have much experience with climate extremes, but the adverse impacts of past extremes are strong reminders that adaptation can be improved. Research shows that droughts and extreme precipitation events may increase in frequency, intensity, extent, and duration in the future. Even based on information about historical climate, Saskatchewan that already has record or near record extremes as compared with the rest of Canada.

The main objective of this work is to characterize projections of future severe climate events and to identify worst-case scenarios of drought and excessive moisture events using existing literature. The focus is on the range of projections for possible and worst-case climate scenarios for the study area and surrounding region, as required. Other selected extremes that accompany drought and pluvials and affect adaptation are described, as possible.
The study area is the Upper and Lower Qu’Appelle River Basins in eastern agricultural Saskatchewan. Surrounding areas are also examined, as needed, to give a suitable picture of expected climate and weather extremes. The surrounding regions have similar climates that offer more information about extreme values than just the Qu’Appelle River Basins.

**Method, Time Periods, and Research Framework**

The method used is a critical literature review, emphasizing recent publications and using the context of older literature. Almost 100 journal articles, reports, and other documents were reviewed. About 60 were selected for further use here. Information for global scenarios is more common than that for Canada and Saskatchewan, but where possible, information is gleaned for eastern agricultural Saskatchewan and surrounding regions with suitable estimates.

Emphasis is placed on the 30-year periods centered on the time frames of the 2020s (2011-2041), the 2050s (2041-2070), and the 2080s (2071-2100) depending on the study used. Time series work to 2100 was also available. The most recent period was emphasized, when possible, but the literature included a wide range of periods. Seasonal and decadal projections will become more useful with continued research.

This work covers specific scenarios for three cases: 1) current, i.e., instrumental record, 2) possible future, and 3) worst-case future scenarios (Harrison p. comm. Jan 2013). The latter is a special subset of the possible future scenarios. Those are often constructed by means of ensemble averages to provide a clearer signal. This approach of the three cases is useful in anticipating the range of different possible futures. The current case sets the context for comparison of the possible and worst-case future scenarios. The possible scenarios are useful benchmarks, ones that seem most likely to occur, but they are still uncertain. The worst-case scenario has the greatest uncertainty, yet it should be considered as it has some possibility of occurrence and major possible impacts.

Several different drought or moisture indices are used. The two most common are the Palmer Drought Severity Index (PDSI) and the Standardized Precipitation Index (SPI). The PDSI was developed by Palmer (1965) and uses a water balance approach, measuring the cumulative departure of moisture supply in a hydrological accounting method. The SPI interprets measured precipitation as a standardized departure with respect to a probability distribution function (McKee et al. 1993). Negative values of both indices indicate dry to exceptional drought conditions and positive values represent wet to exceptional wet conditions. Both indices have several advantages and disadvantages, depending upon their applications. Values around zero are normal conditions. Other drought indices are introduced as needed.

The report first introduces the observed extreme dry and wet events of the instrumental record to give some context for the future events. Then the nature of future possible droughts is discussed, followed by future possible precipitation extremes. The confidence in future projections of such extreme events is then described, followed by discussions and conclusions.

**CLIMATE EXTREMES OF THE INSTRUMENTAL RECORD**

The past should be considered only a partial guide to the future, because of the climate changes that are occurring. A brief description of past extremes of drought and precipitation is needed.
because that is the basis of people’s experience and this is useful to build upon and to compare with future extremes.

**Drought History Overview**

How frequent are droughts, especially the longer events? Since 1900, the Canadian Prairies has experienced many droughts, with multi-year droughts occurring during the 1910s, 1930s, late 1950s to early 1960s, 1980s, 1999 to early 2000s and even 2008 to early 2010 (Wheaton 2000, Bonsal and Regier 2007, Wittrock et al. (2010). The study area in eastern agricultural Saskatchewan appears to have avoided much of the effects of this last drought and was much wetter than areas farther west.

When and where have the worst droughts occurred? The reply depends on which measure of drought is used. Wheaton and Nicolichuk (2010) found that the most intense drought, as measured by the monthly Palmer Drought Severity Index (PDSI), occurred in July 2002 north of Lake Winnipeg as part of a drought corridor westward to Edmonton. The period of record examined was 1901 to 2005 and the extreme value was -10.3. The study area suffered a secondary region of intense drought just north of Regina and south to the international border at this time (July 2002). Monthly PDSI values were about -4 to -5, indicating the class of extreme drought. This finding demonstrates that among the worst PDSI droughts in the entire region of the Canadian Prairies can occur in the study area. The impacts of droughts are affected not only by intensity, but also by the drought’s persistence, timing and extent.

Bonsal and Regier (2007) found the worst and most persistent droughts across the Canadian Prairies to be those of the 1920s and 1930s. They used PDSI and the Standardized Precipitation Index (SPI) as drought indicators for the 1915 to 2002 period. Quiring and Papakyrakou (2005) used Palmer’s Z index to characterize shorter term June to July moisture anomalies across the agricultural Prairies for 1920 to 2002. They found the most intense summer droughts to be in 1961, 1988, 1936, 1929 and 1937, in order of severity.

Which major droughts covered the most area of the Canadian Prairies? Bonsal et al. (2011a) found that the largest area of severe to worse droughts (PDSI of -3 and less) during the 1940 to 2005 period occurred in 1961, 1988, and 2001. The years 2001-2004 resulted in the largest area multi-year drought. Almost half of the agricultural prairies was in severe drought or worse during 2001. For the older droughts of the 1900 to 1950 period, the 1930s were the largest multi-year droughts, and 1961 and 1919 were the single-year severe droughts that covered the largest area.

Many characteristics of major droughts were determined by Bonsal et al. (2011) for the first time. They examined the life stages of major droughts in the prairies, including onset, growth, peak, retreat, and termination. Findings important for monitoring and adaptation include:

- Several major droughts have migrated into the Canadian Prairies from the United States Great Plains States, including the 1999-2005 drought. This means that it is important to monitor the northern US droughts for expansion or migration into Canada.
- Drought may emerge and even peak during the winter months, then persist into the growing season. Therefore, even if winter drought seems less important than in the warmer months, it may be a harbinger of longer, more problematic drought into the rest of the year(s).
- Major droughts do not have the same main causes and these causes may be changing (Bonsal and Wheaton 2005). Therefore drought projections should consider many causes.
What are the trends in droughts? Although significant increases in annual and seasonal temperatures have occurred across Canada, and especially in Saskatchewan, a corresponding increase in drought frequency is not apparent (Bonsal et al. 2011). The temporal pattern of droughts appears to follow decadal variations similar to precipitation. This also reflects the influence of the many causes of drought, such as sea surface temperatures, soil moisture, vegetation, and snow and ice cover (Maybank et al. 1995). Precipitation in Saskatchewan has among the highest variability, second only to the Arctic (Wheaton 2000), and this contributes substantially to drought variations.

Snow cover has an important role in the nature of drought. Snow can also store enormous quantities of water that is released in the spring (Brown and Mote 2009). The snow pack and air temperature are very related. Monthly mean snow cover extent has a strong negative correlation with air temperature (Dery and Brown 2007).

The trends in snow cover in the Northern Hemisphere have been tracked and trends analyzed (e.g., Brown 2000, Dery and Brown 2007, Brown and Mote 2009 and Brown and Robinson 2011). Brown and Robinson (2011) documented that the Northern Hemisphere spring snow cover extent has undergone significant decreases over the past 90 years and the rate of decrease in snow cover extent has accelerated over the past 40 years. These trends were driven mainly by warmer temperatures in the mid-latitudes (Brown and Robinson 2011). Brown (2000) found that the North American snow cover has increased in the fall half of the year, but decreased in the spring. Significant decreases occurred in the 1980s and early 1990s in April snow water equivalent averaging 4.4% per decade.

In summary, droughts can be frequent, very intense, and affect large areas in the Canadian Prairies, including the study area of eastern Saskatchewan. Precipitation is highly variable and this results in a strong monthly, seasonal, annual and decadal variation of drought.

**Extreme Precipitation Events Overview**

Drought conditions can shift very quickly in both time and space to wet conditions and vice versa, although spatial patterns of drought seem to be more uniform and cover wider areas than wet conditions (e.g., Wheaton and Nicolichuk 2010). This section provides a brief overview of past extreme precipitation events to provide context to the information about future possible extreme precipitation events. The extremes are considered on various time scales from daily, to monthly and yearly. The space scale focuses on the Qu’Appelle River Basin and eastern agricultural Saskatchewan, but extends beyond into neighboring areas as well. This is necessary as storms of surrounding areas may be of the type that affects the study area in the future, especially with pole-ward movement of the atmospheric circulation systems.

When and where have the most extreme wet conditions occurred? Peterson et al. (2008) used several indices to track the changes in precipitation from 1950. They found that annual precipitation from days with precipitation equal to or greater than the 95th and 99th percentiles as well as the maximum one and five-day precipitation amounts have been increasing in North America. They note that these observed changes in extremes are consistent with those expected with a warming planet.

PDSI and other drought indices are indicators of water balance and therefore can be used to explore wet as well as dry events. For more local findings, Wheaton and Nicolichuk (2010) found that the wettest period, as indicated by extreme high monthly PDSI values in the Canadian Prairies during 1901 to 2005, was 10.2 occurred in November 1973. The location of this extreme
is northeast of Meadow Lake. Five of the other extreme wet conditions occurred during the next year, i.e., 1974, also occurred in that similar area. The secondary exceptionally wet area in 1973 occurred in eastern Manitoba and could have also affected the study area with just a shift in the storm tracks somewhat westward.

Using the same database, Wittrock (2012) found the highest (indicating wettest) PDSI for the agricultural year for all four Saskatchewan watersheds examined was in the Upper Qu’Appelle River Watershed and was 9.9 PDSI in 1954. The agricultural year PDSI for 1974 for that watershed was ranked eighth. Even wetter years have occurred since these studies as their records ended at 2005.

The years 2010, 2011, and 2012 provide excellent examples of very wet periods and are recent, so may be more representative of near future events. Environment Canada’s Climate Bulletin provides rankings of temperature and precipitation seasonal totals for the climate regions of Canada (EC 2013). Spring 2010 was the wettest in the period 1948 to 2012, at 64% greater than the areal average for the prairie climate region. Spring 2012 was the third wettest spring season at 52% higher than average. Summer 2010 was also very wet with precipitation amounts fourth highest on record at 40% of normal. Other summers in the early 2000s were also among the top ten with 2005 and 2002 the top second, fifth and sixth highest. 2012 had the sixth highest summer areal average precipitation amounts.

Severe flooding on the prairies was the top weather story for 2011 in the top ten weather stories in Canada compiled by Phillips (2011). Management of the flooding problems lasted from October 2010 when a torrential rainstorm hit the southern Prairies with a 50 to 100 mm event, and wet conditions lasted through to late July 2011. More land was under water than ever recorded. The highest water levels and flows in modern history were recorded across Saskatchewan and parts of Manitoba (Phillips 2011).

Individual climate stations showed amazingly high annual precipitation amounts for these recent years. For example, the relatively dry location, Saskatoon, had a record amount of total annual precipitation in 2010 at 707.4mm, or 103% higher than the normal of 348.2mm (Beaulieu and Wittrock 2011). The years 2005 and 2006 had the fourth and third highest total annual precipitation amounts for the period of record since 1964. This wet period of 2010 to 2012 is a good example of the switch from dry to wet as severe to extreme drought was entrenched in many parts of the Canadian Prairie Provinces from 2008 to early 2010 (Wittrock et al. 2010).

Another large switch from dry to wet was the series of storms in the southern prairies that began in June 2002 during the major drought of 1999 to 2000. Szeto et al. (2011) documented the catastrophic rainstorm on 8-11 June 2002 that brought as much as 175mm (30% of the annual for 2002) to the Lethbridge area and affected an area at least from Pincher Creek in western Alberta to Winnipeg, Manitoba. The authors wrote “it was the driest of times; it was the wettest of times.” This outcome may also be representative of future possible events.

The duration of the rainstorm at 64h was a record for Lethbridge during the summer of 2002 (June to August) (Szeto et al 2011). A surprise finding of that work is that the atmospheric conditions of the extreme drought before the storm may have enhanced the probability of the storm. Flooding damage resulted in a large area from Alberta across into Manitoba. The return period of a rainstorm of this extent was estimated to range from 258 to 1,486 years (Groenveld et al. 2004 cited in Szeto et al. 2011).
These shifts from wet to dry and vice versa have also occurred in other countries. For example, Europe had widespread floods in summer 2002. Then 2003 brought record-breaking heat waves and drought (Trenberth 2011).

The earlier extreme rainstorm of 3 July 2000 in the Vanguard area of Saskatchewan also occurred during that major drought of 1999-2005. This storm is the largest area eight-hour event to occur in the Canadian Prairies. It brought up to 375mm of rainfall an intense and persistent thunderstorm. This amount even exceeded the average annual precipitation total of 360 mm for Vanguard (Hunter et al. 2002).

Previous to the Vanguard storm, the most extreme rainfall amount for the 24 h period in Saskatchewan was 179 mm at Willmar, Saskatchewan in July 1984 (Phillips 1993). Willmar is in the far southeast corner of Saskatchewan east of Weyburn. Although it is in the Souris River Basin, storms do not respect basin boundaries and could have easily affected other nearby basins such as the Qu’Appelle.

The most amazing record is Canada’s record wettest hour when 250 mm rainfall occurred at Buffalo Gap, Saskatchewan. This location is in south central Saskatchewan near the US border. The rainstorm amount is almost comparable to the world’s wettest hour at the Kilaeua sugar plantation, Kauai, Hawaii at 305 mm (Phillips 1993).

As with droughts, antecedent conditions for excessive precipitation events are also relevant in determining the level of negative impacts that will occur with such events. A good example is the high precipitation levels experienced in southeastern Saskatchewan in spring 2011. The precipitation levels in 2010 were above average resulting in high soil moisture. The amount of precipitation southeastern Saskatchewan received in the April to June 2011 period was 150 to over 200% of its normal precipitation levels. There were also multiple events of 20 mm or greater prior to a 1:100 year precipitation event on 17 June 2011 (Hopkinson 2011). These three factors likely resulted in unprecedented flood level in the Souris River watershed causing state of emergency declarations in Weyburn and Estevan with communities such as Roche Percee evacuating almost every home (US Army Corps of Engineers 2012).

In summary, the Canadian prairies and Saskatchewan have experienced extremely wet conditions on various time and spatial scales, as summarized in Table 1. This table is illustrative of the extremes in agricultural Saskatchewan and surrounding provinces. The list may not be comprehensive for many reasons including lack of observational data and the fact that severe storms may have passed through the network undetected because of the resolution of the network. The Buffalo Gap storm has the most rainfall in this set of severe storms.

Torrential rainstorms have occurred even during major droughts. Severe droughts have shifted within days to very wet conditions. These situations appear indicative of what may be expected and should be prepared for in the future.
Table 1 Major and record observed extreme rainstorms in and surrounding southern Saskatchewan. (These storms are meant to be illustrative of extremes and not comprehensive).

<table>
<thead>
<tr>
<th>Storm Name &amp; Area</th>
<th>Amount of Rain (mm)</th>
<th>Duration</th>
<th>Date</th>
<th>Reference</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vanguard SK</td>
<td>375</td>
<td>8h</td>
<td>July 2000</td>
<td>Hunter et al 2002</td>
<td>Record 8h storm for large area</td>
</tr>
<tr>
<td>Willmar SK</td>
<td>179</td>
<td>24h</td>
<td>July 1984</td>
<td>Phillips 1993</td>
<td>Record for SK (official) to about 1990</td>
</tr>
<tr>
<td>Lethbridge AB</td>
<td>175</td>
<td>About 4 days</td>
<td>June 2002</td>
<td>Szeto et al 2011</td>
<td>Large area storm from west AB to Winnipeg MB</td>
</tr>
<tr>
<td>Buffalo Gap SK</td>
<td>250</td>
<td>1h</td>
<td>May 1961</td>
<td>Phillips 1993</td>
<td>Record 1h rainfall in Canada, non-official record</td>
</tr>
<tr>
<td>Eckville South AB</td>
<td>213</td>
<td>24h</td>
<td>June 1970</td>
<td>Phillips 1993</td>
<td>Record for AB to about 1990</td>
</tr>
<tr>
<td>Riding Mt Park MB</td>
<td>217</td>
<td>24h</td>
<td>Sep 1975</td>
<td>Phillips 1993</td>
<td>Record for MB to about 1990</td>
</tr>
</tbody>
</table>

**FUTURE POSSIBLE DROUGHTS**

What is future drought expected to be like? Questions to address include: What are the likely characteristics of future drought? Will drought be more intense, cover larger areas, occur more often, or will it affect different areas than before? Will it have the same or a different set of causes? Will times of occurrence change? Will droughts originate from different places than in the past? Which characteristics do we have more confidence in projecting? What surprises will future drought bring?

Most authors find their estimates for future drought in the world and in the Canadian prairies point towards more frequent, more severe and larger area droughts. The literature for the world is discussed first briefly, and then Canadian Prairie conditions are examined. Although emphasis is placed on the near future to about mid-century, the relevant literature contains information for the period to 2100. The main periods examined are the 2020s (2011-2040), 2050s (2041-2070) and the 2080s (2071-2100).

Sheffield and Wood (2008) used soil moisture data to estimate future changes in drought for the low to high greenhouse gas emission scenarios. Even though the frequency of droughts longer than 12 months is over-estimated, the models do reasonably well in tracking historical data. All the models show future decreases in soil moisture on a global basis for all the emission scenarios. A doubling of the area of severe soil moisture deficits and the frequency of droughts of four to six month durations is estimated for 2070 to 2099. Even the low emission scenario (B1) shows small but substantial increases in drought for most regions.

Dai (2010) completed an extensive review of literature concerning drought with continued global warming and concludes: “Given the dire predictions for drought, adaptation measures for future
climate changes should consider the possibility of increased aridity and widespread drought in coming decades.”

Turning to more local conditions, Barrow (2010) analyzed an ensemble of regional climate models (RCMs) for potential evapotranspiration (PET) and moisture deficit, or precipitation minus evapotranspiration (P-PET) results for the Prairies. PET was calculated using two methods, Thornthwaite and Penman-Monteith. PET is projected to increase over time in all the simulations as to be expected with increasing temperatures. Such results are confirmed by the increases in PET in the Prairie Ecozone of the Prairie Provinces shown by Thorpe (2011) (Figure 1). PET climbs very quickly, especially for the warmer scenarios.

![Potential Evapotranspiration (mm)](image)

**Figure 1 Average potential evapotranspiration for the Prairie Ecozone of Alberta, Saskatchewan, and Manitoba, for the 1961-1990 baseline climate and for two scenarios for the 2020s, 2050s and 2080s (Thorpe 2011:5).**

Barrow’s (2010) results from the two PET methods were compared and the simplified Penman method was found to have increases about 100mm higher than the Thornthwaite method. This difference is likely because of the use of maximum temperature in the Penman method. Other researchers find that the use of simple or complex methods provide similar results for PET (e.g. Mavromatis (2007) cited in Vicente-Serrano et al. 2010).

The RCMs were shown to simulate the observed precipitation values better than the GCMs that have a much larger grid size (Barrow 2010). Most of the models showed increases in both intensity and area of moisture deficit in the future (2041-2070 period) over the Saskatchewan and Alberta area examined. P minus PET for our study area of eastern agricultural Saskatchewan is shown to decrease by about 200 to 300 mm or more, farther south, indicating drying (Figure 2). The P-PET of the current climate (1971-2000 baseline) is about -100 to 0 mm in our study area. PET was also found to increase farther into the future with all the climate models. Note these are mean annual values and seasonal and annual values would have much more variation, including more extreme drying that would be smoothed by averaging.
Figure 2 Spatial pattern of the future (2041-2070) total annual moisture deficit (P minus PET) (mm) for the water year (October to September). PET is calculated using the simplified Penman method. (Barrow 2010:21) and for results of three Canadian Regional Climate model experiments.

A key question is whether increases in evapotranspiration caused by warmer temperatures would be offset by increased precipitation? If evapotranspiration increases by 200mm (average annual moisture deficit), then the region will become drier unless precipitation increases by at least 200mm. With no change in precipitation, the moisture deficit increases by 200mm by the 2050s. These are average annual values, however, and the high variability of precipitation would lead to the potential for more severe periods of drought. Both annual and summer precipitation values generally increase in the future to about 100 to 200mm for the 2041-2070 period, but these increases are more than offset by increases in evapotranspiration (Barrow 2010, 2011). Summer dryness is projected to increase (as measured by P-PET) and drier events become more likely. Seasonal changes (e.g., summer) are projected to show decreased precipitation by as much as 20 to 30% for the 2050s. Future average drying is slightly less pronounced in southeast Saskatchewan.

The current average annual precipitation deficit for the southwest part of the watershed, the driest part, is about 180mm (1961-1990) (Lundqvist 1999). A further increase in average annual precipitation deficit of 200mm (indicated in some scenarios in Figure 2) would approximately double the baseline deficit and result in a much drier climate. The effectiveness of precipitation
also depends on precipitation type, whether it occurs in an intense event or several light rainfalls. Snowmelt events can be an effective recharge mechanism. The intense events result in more runoff and the lighter events contribute more to soil moisture recharge.

Barrow (2009) calculated another indicator of the water balance, the annual moisture index (AMI), for selected stations including Weyburn and Yorkton. This index is the ratio of annual growing degree-days (base 5 degrees C) and annual precipitation. A higher value indicates an increase in heat and/or a decrease in precipitation, therefore increased dryness. The index increases for both sites for the period to 2100. Both sites show drying of about 1 degree-day/mm by the 2050s compared with the 1961-1990 baseline of 3.4 for Yorkton and about 4.3 for the drier location of Weyburn. This work also indicates precipitation changes of about 10% decrease to 10% increase in the southeast grassland area. To give perspective, this means that Weyburn’s future AMI climate would become similar to the current driest area in Saskatchewan in the extreme southwest. Williams and Wheaton (1998) found that increased annual precipitation of about 7-10% would be needed to compensate for an increase in mean annual temperature of 3 degrees C in the Regina area.

Price et al. (2011) developed high-resolution climate scenarios for Canada from General Circulation Model (GCM) simulations. They described future possible climates by ecozones. Eastern agricultural Saskatchewan, our study area, is in the semi-arid to sub-humid portions of the prairies ecozone. They noted that in the current climate of the semiarid subzone annual precipitation is less than potential evapotranspiration, so it is already a dry climate. They project temperature, precipitation and solar radiation trends that “imply that multiyear droughts will become more common and more intense”, especially with the high emission scenario (A2) and by 2100.

Many climatic factors produce drought conditions and one of the most important is lack of precipitation. But others, including temperature, radiation, and wind also play roles through evaporation resulting in loss of available water. Price et al. (2011) projected solar radiation levels to increase slightly in summer and would contribute to increasing evaporation. Vapor pressure levels are projected to increase and would offset some of the effects of warming on evaporative demand, but overall evaporation rates are still expected to increase. Inter-annual variation in precipitation is expected to increase and this would tend to exacerbate both droughts and floods.

Evaporative demand is usually met by precipitation in the current climate of the sub-humid subzone (Price et al. 2011). The northern and eastern parts of the watershed are in this climate zone. Trends in this subzone for A2 scenario by 2100 also indicate more frequent water stress, with more southerly areas suffering from permanent dieback of trees. Wind is another climate variable that affects evaporation, and therefore precipitation effectiveness. The authors found little change in wind speed, on average, with slight reductions in summer and increases in spring in both subzones, so wind speed is not expected to contribute to increased evaporation on average. However, substantial evaporation can occur on windy days that may not be reflected in the average wind speed.

PaiMuzumder et al. (2012) estimated the future durations of drought severity for three, six and ten month lengths. They found the six and ten-month duration droughts become more frequent over southern Saskatchewan and Manitoba for the 2041 to 2070 period compared with the 1971 to 2000 baseline. The number of ten-month droughts was calculated to increase by as many as four additional events in the 2050s. They used the Canadian Regional Climate Model (CRCM) and the A2 high emission scenario with monthly precipitation deficits for drought severity indices
to obtain these projections. Limitations reside in the CRCM’s simulation of precipitation and the use of precipitation alone to describe droughts.

The most vulnerable watersheds have projected increases in both severity and frequency of the 10-month drought events for the five pairs of climate simulations for the 2050s (PaiMuzumber et al. 2012). The ensemble mean locates these most vulnerable watersheds in the southern prairies and the authors note it as a hot spot with high likelihood of severe and more frequent droughts in the future. Results for the Qu’Appelle River Basin (QRB) can be determined from their map of projected changes of 10-month drought events by watershed (Figure 3). The QRB is marked in dark blue in Figure 3 map (i,a). The range for severity change for the QRB appears to be about -15% to 10%, for frequency change is -2 to +4 events, with a maximum duration up to 10 months. These findings are reinforced by the work showing the number of dry spells is expected to increase in the southern prairies (Sushama et al. 2010). For example, the number of dry days (precipitation less than 2 mm) increases up to about 5 days for the 2050s in southern Saskatchewan (including the QRB).

Bonsal et al. (2012) appear to have the first assessment of the three time periods of prairie drought from the pre-instrumental, through the instrumental to the future. They also give one of the most comprehensive pictures of future drought for the Canadian Prairies. They used five scenarios, downscaled values from CGCM2, CGCM3, and HadCM3, for future periods of the 2020s, 2050s, and the 2080s, as well as the baseline of 1961-1990.

The PDSI time series from the present to 2099 shows drying to 2020, then a slight improvement with much variability to 2040, then a possible shift to a permanently more arid climate occurs as the PDSI become consistently negative (Bonsal et al. 2012) (Figure 4). These PDSI values are area-averaged summer values for an ensemble mean values from five climate models runs. Unfortunately, their study area only extends eastward to slightly east of Moose Jaw, but their findings are still very indicative of eastern Saskatchewan’s possible future climates.

In contrast, the future SPI time series calculated by Bonsal et al. (2012) show no strong change as compared with the instrumental period to about 2040. This pattern is consistent with the summer precipitation projections of little change and because temperature effects are not considered in the method (Figure 4).

The areas affected by droughts of different severities were also calculated by Bonsal et al (2012). They show a substantial increase in the area and frequency of severe drought and worse (PDSI = -3 or less) in the Canadian Prairie area studied. Again, SPI does not show a strong upward future trend, however, a big difference is that most summers in the future have severe drought in some part of the area. The authors suggest that severe droughts will be a more permanent feature in certain areas of the prairies in terms of occurrence, duration, and/or severity.

Spatial changes for both PDSI and SPI for the 2080s show much worse droughts with the A2 scenario, as expected, and all PDSI results show drier conditions over the entire Prairie study area (Bonsal et al. 2012). An important finding for the Qu’Appelle Basin is that the most pronounced increases in drought were found in the eastern and southern areas with lower PDSI of -2 to -4, (compared with 1961-1990 values), indicating much drier conditions. SPI also shows drying in the east, but with less consistency than the PDSI.
Figure 3 Projected changes to the a) severity (%), b) frequency and c) maximum duration (months) for 10 month drought (DRO10) events at the watershed scale, and d) classification of watersheds based on projected changes to severity and frequency (S and F) of DRO10 events for the 47 watersheds in the Canadian Prairies for five pairs (i-v) of Canadian Regional Climate Model simulations. (PaiMuzumber et al. 2012:Figure 12)
Figure 4 Summer PDSI (a) and SPI (b) area-averaged values for the instrumental period (1901 to 2005) and the future (2011 to 2099). The black line in the future is the ensemble-mean values from the five climate model runs and the red lines are the nine-year running means. The minimum and maximum climate projections for each summer are in grey. (Bonsal et al. 2012: Figure 9)

Multi-year droughts were also considered by Bonsal et al. (2012). They were found to be more frequent during the projected future period for PDSI compared with the instrumental record. The length of PDSI drought is the average number of consecutive summers with a negative value. The summer PDSI droughts five years and longer have a frequency of 1.9/100 years in the instrumental record and this is expected to more than double to 4.2/100 years during 2010 to 2100. The frequency of 10 y or greater summer droughts increases to 3.1/100 years during 2010 to 2100. The possible future frequency of these droughts is even worse than the pre-instrumental rate of 3.0/100 years (3% frequency). A worse case scenario is ten years or more of consecutive summers with negative PDSI values. These cases would have increased frequency, even greater
than during the pre-instrumental 1365-1900 period when several severe and prolonged droughts were identified.

Reconstruction of the PDSI using dendro-climatological methods reminds us that even more severe and prolonged droughts than during previous 100 years occurred in the Canadian prairies during the 1700s and 1800s (Sauchyn and Bonsal 2012). Therefore, we should not find it too unusual for more arid conditions to reappear at some time and global warming is increasing this risk.

The potential for regular and persistent severe future droughts in parts of the Canadian Prairies is clear, with some assumptions, of course. Warnings of worse future droughts are also found in older publications, including Williams et al (1988), Barrow and Yu (2005), Sauchyn et al. (2005), Gameda et al. (2005) and Bonsal and Regier (2006). These findings are similar to results regarding future possible droughts on a global basis. Therefore, current and even pre-instrumental droughts may appear mild compared with future droughts.

**Summary of Probable and Worst-case Drought Scenarios**

**Possible future droughts** in eastern agricultural Saskatchewan, although not the worst case, have the power to slowly erode adaptive capacity of human and natural capitals with each occurrence. These droughts would occur much more frequently than the worst-case events, and perhaps occur in smaller areas, rather than across the prairies, or even Canada. A summary of drought indices, projections for the future, spatial patterns (as available), and references is compiled in Table 2 using the results found in the previous section. Some main characteristics of possible future droughts include:

- Increased intensity of dryness occurs, driven by increased evaporation potential with higher temperatures and longer warm seasons. This intensity is projected to overwhelm the projected increases in precipitation
- Droughts of six to 10 months become worse, with the longer droughts increasing frequency by about 4 events by the 2050s
- Frequency of long duration droughts of five years and longer more than doubles in the future to 2100, and
- Frequency of decade long droughts and longer increases from the instrumental period of one event to more than three events in the future to 2100.

**Worst-case scenarios for future droughts** in eastern agricultural Saskatchewan may:

- Be much longer and more commonly multi-year droughts, with as much longevity as the decades-long droughts of hundreds of years ago. Note that these are the lower probability, but very high impact and costly extremes
- Multi-year droughts (e.g., 5 to 10 years, or so) would occur more than twice as often for the period to 2100
- Come with more evaporative power and be more intense as they will have much higher temperatures and much longer warm seasons
- Cover much more area than even the across-Canada drought of 2001-2002
- Be interspersed with more powerful rain and snow storms that increase the risk of floods
- Occur more frequently, more than twice to several times as common
- Be intensified by decreasing snow-melt recharge to precious water reserves, and
- Come with surprises as new combination of climate characteristics emerge.
Table 2 Summary of projections of probable future drought patterns, with emphasis on eastern agricultural Saskatchewan

<table>
<thead>
<tr>
<th>Drought Indices</th>
<th>Projections</th>
<th>Time Period</th>
<th>Spatial Pattern</th>
<th>Climate Models</th>
<th>Comments</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>P-PET</td>
<td>Decrease of about 200mm and more farther south</td>
<td>2050s mean annual water year</td>
<td>Greater increase farther south</td>
<td>CRCM with CGM3 HRM3</td>
<td>PE increases in intensity and area with time for all simulations; risk of moisture deficit becomes more severe</td>
<td>Barrow 2010</td>
</tr>
<tr>
<td>AMI</td>
<td>Increase of about 1 degree-day/mm from current 3.5</td>
<td>2050s</td>
<td>Greater increase or dryness farther east</td>
<td>56 climate scenarios with range selected by AMI</td>
<td>Increased dryness occurs for all sites and time periods in the grassland region</td>
<td>Barrow 2009</td>
</tr>
<tr>
<td>Precipitation deficits (monthly)</td>
<td>6 and 10 month droughts become worse</td>
<td>2050s</td>
<td>For south SK and MB</td>
<td>CRCM with A2</td>
<td>The longer, 10 month drought adds about 4 events in the future</td>
<td>PaiMazumder et al 2012</td>
</tr>
<tr>
<td>PDSI negative for consecutive summers</td>
<td>Frequency of 3.1/100y for 10y+ droughts, more than 3x current rate</td>
<td>2080s</td>
<td>Statistically downscaled, 5 climate model runs</td>
<td>Frequency also increases for 5y+ droughts compared with instrumental and pre-instrumental</td>
<td>Bonsal et al 2012</td>
<td></td>
</tr>
<tr>
<td>Summer PDSI (areal average)</td>
<td>Permanent drought occurs after about 2040</td>
<td>2011 to 2100 time series</td>
<td>Conditions are worse in the eastern prairies</td>
<td>Statistically downscaled with 5 climate model runs</td>
<td>Most statistics show worse droughts, including area, frequency and intensity</td>
<td>Bonsal et al 2012</td>
</tr>
<tr>
<td>Multi-year droughts PDSI</td>
<td>Frequency more than doubles to 4.2/100y of 5y or longer droughts</td>
<td>2011 to 2100 time series</td>
<td>Frequency of 10y+ droughts or longer triples</td>
<td>Five scenarios ensemble-mean</td>
<td></td>
<td>Bonsal et al 2012</td>
</tr>
</tbody>
</table>

Notes: Where, PET is potential evapotranspiration; PETth is PET using the Thornthwaite methods; PETpm is PET calculating using the Penman-Monteith method; P-PET is also the CMI or climate moisture index; P is precipitation; GDD/P is the annual moisture index (AMI), i.e., the annual growing degree days (base 5 degrees C) divided by the total annual precipitation; AMI is the annual moisture index, GDD/P; Multi-year drought mean duration is the average number of consecutive summers with a negative value of PDSI; HRM3 is the UK Hadley Regional Climate Model driven by HadCM3; CRCM is the Canadian Regional Climate Model driven by CGCM 3 T47.
Worst-case droughts have the potential to be more severe than experienced historically. Increased risk of severe droughts interspersed with severe rainstorms is projected to be a feature of the new climate.

**FUTURE POSSIBLE PRECIPITATION EXTREMES**

“Basic theory, climate model simulations and empirical evidence all confirm that warmer climates, owing to increased water vapor, lead to more intense precipitation events, even when the total annual precipitation is reduced slightly, and with prospects for even stronger events when the overall precipitation amounts increase.” (Trenberth 2011:132)

**Introduction and Objective**

Extreme rainfall and resultant flooding can result in considerable damages for agriculture, businesses, communities, and infrastructure. Effects of floods include damages to infrastructure, tourism, recreation, quality of life, health, and uncertainty of public policies (Kulkarni 2002). Wittrock et al. (2008) documented many costly flood impacts in prairie communities including flooding of homes and businesses, compromised drinking water supplies, damaged roads and overwhelmed emergency services. “The sustainability of economic development and living conditions depends on our ability to manage the risks associated with extreme events.” (Tank et al. 2009). Improved knowledge of the possibility of changed patterns of extreme precipitation events with shifting climates is needed for more successful adaptation.

The objective of this section is to explore estimates of future possible extreme precipitation events of various time and space scales of relevance to eastern agricultural Saskatchewan. Much less information is available for projections of future precipitation extremes than for drought, especially for the region. This may be because drought has caused more problems than flooding, until recent years. This section begins with literature for the global to North American areas, and then focuses on eastern agricultural Saskatchewan. That larger area is used as well as the Qu’Appelle River Basins because extremes from surrounding areas are indicative of future extremes that could occur within the basin.

**Reasons for Changes in the Hydrological Cycle**

Trenberth (2011) reminds us of the reasons for expecting hydrological cycle changes under the influence of global warming. Increased heating drives increases in evaporation rates that result in increased drying and risk of droughts, as discussed in the section on future droughts. However, the increased heating results in increased moisture for storms as well. The water holding capacity of the atmosphere increases by about 7% for each 1°C of warming. The author lists much evidence of clear indications of observed increases in water vapor over both land and oceans. This increased moisture supplied to storms can increase intense precipitation events. So a shift in the type of precipitation events is expected from less frequent rains to more intense rainfalls.

Trenberth’s (2011) summary is that dry areas become drier and wet areas become wetter, especially in mid to high latitudes. Increased atmospheric water vapor is not only related to changes in precipitation events, but is a strong greenhouse gas and therefore is part of the modeling of global warming as a positive feedback effect. As stated in the introductory quote, overwhelming evidence from many sources from theory to models and empirical evidence point to more extreme precipitation events. “A warmer climate, therefore, increases risks of both
drought, where it is not raining, and floods, where it is, but at different times and/or places.” (Trenberth 2011:131). This means that water management would have to face challenges of how to collect and store more water during the high precipitation events for the times of high temperature and low precipitation during droughts.

**Changes in Frequency, Intensity and Type of Precipitation Extremes**

The IPCC (2012) report on managing risks of extreme climate events provides information about both extreme high and low precipitation events. The frequency of heavy precipitation or the proportion of total rainfall from heavy falls will likely increase in the 21st century over many areas of the globe. The meaning of “likely” in this context is a 66-100% probability. This is particularly the case in the high latitudes and tropical regions, and in winter in the northern mid-lattitudes. In some regions, increases in heavy precipitation are projected to occur despite projected decreases in total precipitation (medium confidence). Based on a range of emissions scenarios (B1, A1B, A2), a 1-in-20 year annual maximum daily precipitation amount is likely (probability of 66-100%) to become a 1-in-5 to 1-in-15 year event by the end of the 21st century in many regions. In most regions the higher emissions scenarios (A1B and A2) lead to an even stronger projected increase in risk of occurrence (IPCC 2012:11).

The IPCC (2012) show the areas of expected changes of the return period of intense daily rainfall events globally. For central North America, including agricultural Saskatchewan, they project a decrease in return period of a maximum 20-year daily precipitation event by 5 to 10 years. This means that an extreme daily rainfall could occur as much as twice as often. This result is for the middle 50% of models for the medium (A1B) to extreme (A2) emission scenarios.

Dominguez et al. (2012) completed a review of many journal articles with findings that future winter precipitation events are expected to be more intense and frequent, larger than the change in the mean, and with a signal of change larger than that of natural climate variability. They estimated changes in the intensity of future extremes with Regional Climate Models (RCMs) (A2) and found the ensemble average to show generalized statistically significant increases across western United States. The mean of all the eight simulations averaged across the area has a 12.6% increase in 20-year precipitation and 14.4% increase in 50 year return period daily winter precipitation for 2038-2070, as compared with the 1968-1999 period. Although these results are not specifically for southern Saskatchewan, it is important to consider results close to the study area. The northeast part of their study area just passes across southeast Saskatchewan. Their results are also useful as they are for the winter season and findings are less common for that season.

Wang and Zhang (2008) determined statistically downscaled changes in the risks of 20-year return period daily precipitation in winter (December to March) as compared with observed values. Large area changes in humidity and circulation were found along with increases in extreme precipitation risks for most parts of North America for 2050-2099. The increase of extremes at high and middle latitudes was found to be stronger than the increase of mean precipitation. They used just one GCM, the Canadian GCM3.1 with the IPCC high emission scenario (A2).

Dai (2010) reports that the type of rainfall is expected to change with continued warming to more intense rainfall events and fewer light rainfalls. This pattern would tend to exacerbate drought as the intense rainfalls do not recharge soil moisture as well, but they do provide more runoff than lighter rainfalls. Fewer light rainfalls would tend to provide less soil moisture recharge. Drier
Soils are a positive feedback to drought, as heating is used to warm soils to higher temperatures instead of evaporating soil water.

**Projections of Extreme Precipitation for the Canadian Prairies**

Mladjic et al. (2011) use ensemble of five 30-year integrations of the Canadian Regional Climate Model over Canada for the current baseline of 1961-1970 and future 2040-2071 periods. They estimated projected changes to several return periods of April to September maximum precipitation amounts. They found statistically significant increases in the size of precipitation extremes for seven of ten climate regions. The validation of the model’s return levels of single and multiday precipitation extremes indicates that the CRCM underestimates extreme events of the instrumental record for most of Canada.

Maps of Canada from Mladjic et al. (2011) show results for the future period (2041-2071) in eastern agricultural Saskatchewan appears to be in the range of a 5 to 20% increase in extreme one day precipitation amounts for the 20 year return period (Figure 5). The three and five day precipitation extremes increase by about similar amounts, but the higher values are smaller in area (Mladjic et al. 2011).

![Figure 5 Percentage change between future and reference period (left) 20-, 50- (middle) and 100-year (right) return levels of a) 1 day b) 3 day c) 6 day precipitation extremes. These were obtained using the grid box analysis approach at the CRCM grid cell level (Mladjic et al 2011:2582).](image)
Although Bonsal et al. (2012) focused on droughts, the drought indices they used (PDSI and SPI) are also useful indicators of wet periods. For the Palmer Drought Severity Index (PDSI), future projections over the 2011 to 2100 period show some very high values indicating wet periods for the maximum and minimum values of individual Atmosphere-Ocean Global Climate Model (GCM) runs (Figure 4). Some of the future values before 2030 appear to be as high as those of the wet period of the 1970s. The number of future wet periods diminish rapidly after about 2040, although a couple of sequences appear as intense as the wet times in the 1990s. When the effect of temperature is not considered as with the Standardized Precipitation Index (SPI), many more wet periods appear in the future. The values from the individual runs regularly equal or exceed the peaks of the instrumental period (1900-2010) over one SPI unit, especially after 2060. However, the mean of the climate model runs shows few events close to one SPI unit, indicating a signature towards drier times.

The preceding suggests that even though the overall climate will be drier, substantial year-to-year variability would occur. This variability would be coupled with the distinct possibility of extreme shifts from dry to wet periods (and vice versa), similar to those recently observed over the Canadian Prairies.

**Estimates of Maximum Precipitation**

“We conclude that the most scientifically sound projection is that PMP values will increase in the future and raise the risk of damaging floods. These conclusions apply not only to the U.S. but also globally to almost all other areas.” Kunkel et al. (2013).

Another approach to estimating future extreme rainfall events is to examine results from probable maximum precipitation studies. Wheaton and Whiting (1986) estimated precipitation extremes for southeastern Saskatchewan by both the statistical and rational methods. The highest point estimates for the probable maximum precipitation was about 556 mm for the 24h storm duration. The highest basin averages were lower at 395 mm for 24h hour storm durations up to almost 449 mm for the 72h storm duration. Probable maximum precipitation is defined as “the theoretically greatest depth of precipitation for a given duration that is physically possible over a particular drainage basin at a particular time of year.” (Huschke 1980).

The implications for the future of this probable maximum precipitation work by Wheaton and Whiting (1986) for the study area need consideration in light of factors such as the increased atmospheric water vapor and changed atmospheric circulation patterns. The authors noted that the highest recorded 24h rainfall to the period ending 1980 was 167.6mm at Indian Head. They also describe the Buffalo Gap storm of 1961 with 266.7mm of rainfall in less than two hours.

A summary of maximized storm rainfall for relevant locations shows that the highest estimate for 24 h is 660mm for a relatively small area (Table 3). The estimates by Ho and Riedel (1980) are for the United States, but the maps clearly depict the southeast corner of Saskatchewan and can be used to indicate relevant values.

The critical need for research regarding the implications of climate change for PMP estimates has been noted for some time (e.g. Wheaton and Whiting 1986), but work seems to be just beginning on this topic. England et al. (2011) reviewed PMP procedures recently and also asked this question. They suggest that PMP may be increased by a few percentage points to about 5% or so because of important factors such as the increase in maximum dew-point temperature and length of the convective season when severe storms could occur.
Table 3 Maximized (Probable Maximum Precipitation, PMP) storm rainfall for southeastern Saskatchewan. PMP values are shown for a range of durations from 6h to 72h and for a range of areas, from point to basin averages. These findings are meant to be illustrative of possible future maximized events and not comprehensive.

<table>
<thead>
<tr>
<th>PMP Amount (mm)</th>
<th>Duration (h)</th>
<th>Area</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>556</td>
<td>24</td>
<td>Point estimate</td>
<td>Wheaton Whiting 1986</td>
</tr>
<tr>
<td>395</td>
<td>24</td>
<td>Basin estimate</td>
<td>Wheaton Whiting 1986</td>
</tr>
<tr>
<td>449</td>
<td>72</td>
<td>Basin estimate</td>
<td>Wheaton Whiting 1986</td>
</tr>
<tr>
<td>508.0</td>
<td>6</td>
<td>Ten square mile</td>
<td>Ho Riedel 1980</td>
</tr>
<tr>
<td>660.4</td>
<td>24</td>
<td>Ten square mile</td>
<td>Ho Riedel 1980</td>
</tr>
<tr>
<td>736.6</td>
<td>72</td>
<td>Ten square mile</td>
<td>Ho Riedel 1980</td>
</tr>
<tr>
<td>488</td>
<td>Unknown</td>
<td>Basin average including snowmelt</td>
<td>AAFC 2012~</td>
</tr>
</tbody>
</table>

Kunkel and Easterling (2011) agree and warn that findings require careful consideration because of the implications for design and safety of infrastructure, including dams. Easterling and Yin (2012) has continued this work and finds that the PMP estimates for 1981 to 2010 period have increased as much as 20% compared with those based on the 1951 to 1980 baseline for global land areas. Even an increase of 5% means that PMPs are now in the range of 415mm to 693mm for the 24h values using the PMPs of Table 2.

Even more recent work by Kunkel et al. (2013) continued the analysis of the effects of climate change on PMP estimates. They use both methods of climate model simulations and conceptual models of relevant meteorological systems. They find considerable projected increases in maximum values of water vapor concentrations for the continental U.S. by 2071-2100 in the range of 20 to 30%. Water vapor changes are considered to be the dominant control on the amount of extreme precipitation in these cases. Changes in other controls, such as winds, are projected to be too small to offset the water vapor increases. These findings are relevant for most places globally.

In Canada, Climate Research Division, Environment Canada scientist M. Shephard is investigating the impacts of climate change on PMP (Shephard, p. comm. 2013). He is using a similar approach to Kunkel et al. (2013), but is also using RCM simulations over North America as well as the GCM output. This work is in a preliminary phase and early results are expected within months.

It is anticipated that snow cover will decrease in response to a warming climate (Brown and Mote 2009). The largest and quickest decreases will be in the coastal regions of North America with dry continental locations, such as Saskatchewan, likely to experience slower snow cover decreases (Brown and Mote 2009). These changes have already been documented with trend analysis of the March-April snow cover extent (SCE) for the 1922-2010 period providing evidence of these changes in the Northern Hemisphere (Brown and Robinson 2011).

The authors were unable to locate any site-specific information for the study area regarding changing snow cover now and in the future. It is recommended that an assessment be undertaken to determine if sufficient data is available to undertake a trend analysis of this parameter and if so perform a trends analysis as snow has a major influence on the Canadian Prairie ecosystem.
Summary of Possible and Worst-Case Future Scenarios of Extreme Precipitation

This section sought to find estimates of future possible extreme precipitation events of various time and space scales relevant to eastern agricultural Saskatchewan. Much less information is available regarding future possible precipitation extremes than future droughts. In summary, the events can be organized by two sets, those of 1) possible future scenarios and 2) worst-case scenarios.

Probable Future Extreme Precipitation Scenarios

The possible future scenarios are expected to be enhanced versions of those of the past, especially in intensity and perhaps frequency. Not much is mentioned about area. In terms of numbers, this means that:

• the 1:20y maximum precipitation event becomes twice as frequent by 2100 (IPCC 2012:11)
• the extreme maximum events increase by 5 to 20% by the 2050s (Mladjic et al. 2011)
• many wet periods similar to those of the 1950s and 1970s occur by the 2030s (inferred from Bonsal et al. 2012 time series)
• the probable maximum precipitation storms increase in amount by at least 5% (England et al. 2011), and
• Come with surprises as new combinations of climate characteristics emerge.

Even in the probable case, the more intense storm patterns of the northern US plains are moving northward and are another mechanism to enhance the probable pattern of storms and thus extreme precipitation events. The location of some of the most powerful thunderstorms in North America is in the central plains with a corner in southeast Saskatchewan currently and this area will spread or is likely already spreading into Saskatchewan and Manitoba.

Worst-Case Extreme Future Precipitation Scenarios

The worst-case scenarios are super versions of the current probable maximum precipitation scenarios. Information about worst-case scenarios is much more sparse and less well documented than for more likely scenarios. Preliminary estimates include:

• probable maximum precipitation storm amounts increase by about 20% and more
• not only the 1:20y storms increase in frequency, but the 1:100y year storms also double. This means that the sequence of large storms closely following one another could become more common. This situation would be more problematic as less drying would occur between storms.
• increases in intensity are expected so that run-off and flooding increase twice as much as for the baseline climate
• switching between dry and wet events increases, and
• as for future droughts, future extreme precipitation events may exceed the extremes of the instrumental record.
CONFIDENCE IN FUTURE PROJECTIONS

“Confidence has increased that some extremes will become more frequent, more widespread and/or more intense during the 21st century” (IPCC 2007).

Many factors affect the level of confidence in the projections of extreme low and high precipitation events in the future. These include the type of extreme, the region and season, the amount and quality of observational data, the level of understanding of the underlying processes, and the reliability of their simulation in models (IPCC 2012). Temperature variables are estimated with much greater confidence than precipitation variables and drought indices are sensitive to temperature. Therefore, drought events are projected with more confidence than precipitation events.

The IPCC (2012) report on managing risks of extreme climate events provides information about both extreme high and low precipitation events. For drought they write “There is medium confidence that droughts will intensify in the 21st century in some seasons and areas, due to reduced precipitation and/or increased evapotranspiration. This applies to regions including southern Europe and the Mediterranean region, central Europe, central North America, Central America and Mexico, northeast Brazil, and southern Africa. Elsewhere there is overall low confidence because of inconsistent projections of drought changes (dependent both on model and dryness index). Definitional issues, lack of observational data, and the inability of models to include all the factors that influence droughts preclude stronger confidence than medium in drought projections.” (IPCC 2012:11). Confidence in the validity of a finding is “based on the type, amount, quality, and consistency of evidence (e.g. mechanistic understanding, theory, data, models, expert judgment) and the degree of agreement.” The level of confidence is “expressed qualitatively…using five qualifiers: very low, low, medium, high and very high.” (IPCC 2012: Box SPM.2).

The IPCC (2012) map of projected changes in consecutive dry days and soil moisture anomaly shows insufficient model agreement for estimates for both periods of 2046-2065 and 2081-2100. These results use 15 to 17 GCMs with the high emission scenario.

Sheffield et al. (2012) evaluate the terrestrial climate simulations of the fifth Climate Model Inter-comparison Project (CMIP5). They find that most models represent the seasonal cycle of precipitation and evapotranspiration, but underestimate precipitation in western regions of North America and overestimate precipitation, especially in the cooler months. The multi-model ensemble represents the main features of precipitation over North America reasonably well. The models also depict the spatial and seasonal changes in sea surface temperature reasonable well, but have regional warm or cool biases. The extent and decline of the extent of the sea ice are generally under-estimated.

Sheffield et al (2012) evaluate the use of the PDSI in evaluating the future changes of drought with global warming. Because the PDSI uses a simplified model of potential evaporation, it may over estimate the increase in future drought. They argue that other variables such as humidity and wind speed changes and other factors of evaporation should also be considered with additional research. Hoerling et al. (2012) indicate that the PDSI may be less useful for future assessments of drought.

Ruiz-Barradas and Nigam (2010) assess spring and summer precipitation patterns over North America and connections with sea surface temperature effects on the general circulation. They
find that the portrayals of sea surface temperature forcing effects and land surface with atmosphere interactions could be improved in the climate models. Maloney et al. (2013) agree with these areas of knowledge gaps and list several others. They do find that the frequency of the El Nino-Southern oscillation of the CMIP5 models is similar to the historical frequency.

Min et al (2011) show that human-induced increases in greenhouse gases have contributed to the observed intensification of heavy precipitation events over two-thirds of the Northern Hemisphere land areas with available data. They find that the increase in heavy precipitation projected for the future may be underestimated because climate models appear to be underestimating the observed increase in intense precipitation with warming.

The location and migration of storm tracks determines the area and timing of areas affected by storms. Chang et al. (2013) assess the climatological storm tracks simulated by 17 models of the phase three Coupled Model Inter-comparison Project (CMIP3). The amplitude of the storm track is either too strong or weak in both north and south hemispheres, but does improve with as grid size decreases. The CMIP5 preliminary results are similar. Dominguez et al. (2012) also report that the regional climate models (RCMs) are better than GCMs at representing both mean and extreme precipitation events at the regional scale. Bengtsson et al. (2008) write that extreme precipitation is likely to be more pronounced in results using climate models with higher spatial resolution, such as the RCMs.

Even though they used the Canadian RCM, and RCMs are reported to simulate precipitation with higher accuracy than GCMs, Mladjic et al. (2011) also acknowledge many uncertainties. They result from factors including the lack of high quality observational records and the limitations of the CRCM, including model parameterization and aspects of scenario development. Uncertainty can result in both under-estimates and the over-estimates, depending on many factors such as those listed above. Therefore, the use of the lower estimates alone is not advised. Ensemble averages of several simulations are used to find the strongest climate signals. Averages, however, may mask the range of findings, especially those with large variabilities.

Bonsal et al. (2012) show that the methods they used to assess past, present, and future droughts are reasonable. “Nonetheless, in all cases, the tree-ring and downscaled series capture the persistent drought episodes of the 1980s and early 2000s and the major pluvial periods during the early 1990s. This suggests that the proxy and downscaled methods used to quantify droughts and particularly, extended dry periods are adequate for assessing and comparing drought variability in this region (a large portion of the Canadian Prairies) over the three identified periods.” The three periods are the past, present and future (Bonsal et al. 2012).

In conclusion, the estimation of both future droughts and extreme high precipitation suffers from several limitations. However, even though estimation of any future occurrence is difficult, the projections using several different climate indices, climate models, and emission scenarios provide strong convergence of evidence of increased intensity and frequency of future droughts and intense precipitation.

**DISCUSSION AND CONCLUSIONS**

The characteristics of historical droughts and extreme precipitation events were briefly examined for the Canadian Prairies with emphasis on the study area of eastern agricultural Saskatchewan.
Many short term and multi-year extensive droughts have occurred in the study area. The region is noted for very variable climate and very intense rainfall and flooding events.

Measuring, monitoring, modeling and projecting wet and dry extremes are becoming even more critical as the climate shifts. Sufficient information is needed to guide planning for and implementation of effective actions to adapt to climate extremes, especially for the regional scale. More information exists for the scenarios based on ensemble averages rather than the worst-cases for both dry and wet extremes. Work is only in the early stages for both potential maximum drought and potential maximum precipitation events and the research needs to be accelerated.

Risks of more severe, frequent and extensive dry and wet extremes are projected for the future. This has been confirmed by a range of different types of research and from the local to global scales. This report examined research regarding the range of possible future droughts and excess precipitation, including the worst-case scenarios. The study area is southeastern agricultural Saskatchewan, an area that is already prone to climate extremes. Main findings include:

Some Characteristics of Possible Future Droughts

- Have increased intensity of dryness, driven by increased evaporation potential. Drying likely overwhelms projected increases in average precipitation amounts.
- Droughts at least 6-10 months long increase in frequency by about an additional 4 events by the 2050s. The number of longer droughts doubles towards 2099.
- The number of droughts of at least five years doubles towards 2099.
- Decade-long droughts triple in frequency towards 2099.
- Storms with extreme precipitation are interspersed with droughts.
- Surprises result as the new combinations of climate variables occur.
- Worst-case scenarios of mega-droughts with even more intensity, frequency, duration and area are possible, but with low probability.

Some Characteristics of Possible Future Extreme Precipitation Events

- The number of 1 in 20y maximum precipitation events doubles by 2099. Worst cases indicate doubling of the number of 1 in 100y storms.
- Extreme rainfall amounts increase by 5 to 20% by the 2050s and by more than 20% for the worst-cases.
- Many more wet periods similar to the worst wet periods of the historical record occur by the 2050s.
- Sequences of large storms are more likely.
- Switching between dry and wet events increases.

A main conclusion is that wet times become wetter and dry times become drier (Figure 6). Several driving factors are behind this finding, as illustrated in the figure. Research shows that future dry and wet periods will be different than those of the historical record. This is a significant risk because society relies to some extent upon experience in adapting to climate extremes. Improved understanding of the characteristics, driving mechanisms, and impacts of these extremes, especially on a regional basis, will lead to projections with greater certainty. Despite uncertainties about the risk of severe events, the identification and understanding of past events and projections of the future provide opportunities to plan and take action to adapt to these events in ways that will reduce the danger and costs to society.
Figure 6. Wet times become wetter and dry times become drier.

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REFERENCES


Easterling, D and X Yin. 2012. Observed increases in probable maximum precipitation over global land areas. American Geophysical Union Fall Meeting, San Francisco, 3-7 December. NOAA/National Climatic Data Center, Asheville, NC.


Thorpe, J. Vulnerability of prairie grasslands to climate change. Prepared for the Prairies Regional Adaptation Collaborative. Saskatchewan Research Council, Saskatoon, Saskatchewan. 71pp.


