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Science, Impacts and Adaptation

# Assessment of Climate Change and Impacts on Soil Moisture and Drought on the Prairies.

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## Table of Contents


Table of Contents ..... ii
List of Figures ..... iii
Acknowledgement ..... iv
Executive Summary ..... v

2. Research Objectives ..... 2

3. Methods ..... 3

3.1 Climate Change Scenarios ..... 3
3.1.1 Historic (baseline) Climate Database ..... 3
3.1.2 GCM Grid Statistics ..... 4
3.1.3 Downscaling GCM Statistics ..... 4
3.1.4 Generating Climate Change Scenarios ..... 5

3.2 Characterizing the Impact of Climate on Agriculture ..... 6
3.2.1 Agroclimate Indices ..... 6
3.2.2 Aridity Index ..... 7
3.2.3 Climate Classification ..... 8

4. Results and Discussion ..... 8

4.1 Climate Scenarios ..... 8
4.1.1 Minimum Air Temperature ..... 8
4.1.2 Maximum Air Temperature ..... 9
4.1.3 Precipitation ..... 11

4.2 Agroclimate Indices ..... 12
4.2.1 Seeding and Harvest Dates ..... 12
4.2.2 Growing Degree-Days ..... 14
4.2.3 Evaporation ..... 15
4.2.4 Soil Moisture ..... 15
4.2.5 Aridity ..... 17
4.2.6 Climate Classification ..... 18

5. Conclusion ..... 19

6. References ..... 22

## List of Figures

Figure 1: Average historic minimum temperature (°C) for the periods a) December to February and b) July to August. ... 24

Figure 2: Difference between GCMII and historic values for minimum temperature (°C) for the period a) December to February and b) July to August. ... 25

Figure 3: Difference between CGCMI-A and historic values for minimum temperature (°C) for the periods a) December to February and b) July to August. ... 26

Figure 4: Average historic maximum temperature (°C) for the period a) December to February and b) July to August. ... 27

Figure 5: Difference between GCMII and historic values for maximum temperature (°C) for the period a) December to February and b) July to August. ... 28

Figure 6: Difference between CGCMI-A and historic values for maximum temperature (°C) for the period a) December to February and b) July to August. ... 29

Figure 7: Average historic precipitation (mm) for the period a) December to February and b) July to August. ... 30

Figure 8: Difference between GCMII and historic values for precipitation (mm) for the period a) December to February and b) July to August. ... 31

Figure 9: Difference between CGCMI-A and historic values for precipitation (mm) for the period a) December and February and b) July to August. ... 32

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## Executive Summary

Climate data from the Canadian Centre for Climate Modelling and Analysis (CCCma) were used to generate best and worst-case climate change scenarios. Five climate scenarios were generated and downscaled to a 50 by 50 km grid to reflect the regional nature of agriculture in the Canadian Prairies. In total four climate change scenarios were generated and one historic climate scenario. For each of the four climate change scenarios, the change in daily temperature and precipitation were generated from model outputs for a current (1x) and doubling (2x) atmospheric carbon dioxide forcing factor. These changes were imposed on a historic climate scenario to generate a time series for climate change. Two of the climate change scenarios were produced containing GCM-generated temperatures and precipitation (model versions GCMII and CGCMI-A), and two scenarios were GCM-generated temperatures combined with historic precipitation amounts and temporal distribution. The fifth climate scenario comprised of the historic 30-year time series was also downscaled to the same grid locations as the climate change scenarios. Incoming solar radiation data from the historic climate scenario was used for the climate change scenarios.

The climate scenarios were used to describe the shift in temperature and precipitation timing and spatial patterns across regions of the Canadian Prairies. These data were also used to document the shift in agroclimatic indices and drive soil moisture and aridity models. Results show that across all three provinces maximum air temperature is predicted to increase of 4.0 to 5.7°C (GCMII) and 2.5 to 3.3°C (CGCMI-A). Minimum air temperature is expected to increase between 5.0 to 5.6°C (GCMII) and 3.0 to 3.3°C (CGCMI-A). Precipitation is predicted to have a mean increase of 29 to 36% (GCMII) and 3 to 7% (CGCMI-A). Overall, the CGCMI-A results appear more consistent with historic large-scaled spatial patterns (latitude/elevation/air mass effects). The soil moisture model predicted advancement of seeding dates for spring wheat of between 18 to 26 days depending on the climate change scenario used. This was shown to be an appropriate adaptive strategy, especially for CGCMI-A scenario in SE Saskatchewan and S Manitoba, which avoids arid conditions during the late summer. The soil water deficit is predicted to be lower under GCMII than historic values by 46 mm (between seeding and soft dough growth stage of spring wheat). For CGCMI-A, the soil water deficit is predicted to lower by 7 mm across the provinces compared to historic values.

In summary, all climate change scenarios predict as much, or more, soil water in the top 120 cm soil across the Canadian Prairies, compared to the current soil moisture amounts. Aridity and climate classification indices back up this finding that even under the worse case scenario, the growing season will not become any more restrictive for crop production under climate change. When combined with the predicted $CO_2$ fertilization effect, the possibility exists that production will increase. However, our study does not account for the potential increase in pests, weeds or plant diseases. There were regions of greater concern such as SE Saskatchewan and S Manitoba where reductions in summer rainfall (for CGCMI-A) were predicted. In this case there was a greater advantage in adapting earlier seeding dates, compared to the more western regions of the Canadian Prairies.

## 1. Introduction

The climate has a role in determining the potential of agriculture production in a region, while weather controls the degree of success in a given year. Over the years agriculture production systems have evolved to minimize the constraints imposed by weather and climate. Examples of this in Canada include the limitation of summer heat units at higher latitudes that delineates corn production or the use of summer fallow in the semi-arid Prairie in response to marginal rainfall. With the possibility of global warming of 1.4 to 5.8°C by 2100 (IPCC 2001), insights on the avenues of regional climate change and the impact on regional sustainability of agriculture are essential. In Canada, understanding climate change for the prairie region is critical since this area accounts for 82% of the cultivated land in Canada and is an important supplier of food for the global community (Parry 1990). Canada is identified to become even more prominent as supplier of food with projected climate change (IIASA 2001). The need for increased production comes not only from the estimated 50% increase in world population by 2050, but also from the projected decreased capacity of agriculture in developing countries under climate change (IIASA 2001).

Prairie agriculture is a highly managed system that is subject to failure under extremes in weather and climate. As such, there is a continuing need to evaluate the potential of farming practices that minimize deleterious elements of weather and take advantage of situations that promote production and food quality. With the potential of climate change on the prairies in the next fifty years, it is expected that the agriculture sector will need to adapt accordingly. Lead-time is essential especially if climate change is predicted to have a dramatic impact on our current agricultural systems. Understanding the vulnerability and developing adaptation strategies can only be accomplished with some prior understanding of the range in expected climate change, e.g., best to worst-case scenarios. Adaptation through altering management practices can be explored under climate change scenarios with the use of agronomic models.

With a warmer climate, there is potential to develop more diverse crops on the prairies where temperature and soil moisture now limits crop potential. However, there is uncertainty in the estimate of soil moisture for crop production with a warmer climate. Although global circulation models (GCM) can provide information on soil moisture (Laprise *et al.* 1998), they lack the agronomic and soil considerations, and spatial resolution, to estimate available soil water for crops in a growing season. To overcome this, agriculture models can be linked to regional climate change data derived from GCM elements like air temperature and precipitation.

Soil temperature and moisture reserves are two critical components of Canadian Prairie agriculture. For example, earlier seeding dates, which can reduce the impact of late summer aridity on yield, are determined by soil temperature and moisture in the spring. Characterizing the impact of climate on agricultural drought intensity is of interest because it is fundamental to quantifying the risk to prairie agriculture production. In addition, near-surface soil moisture and temperature also account for most of the variability found in soil respiration (Akinremi *et al.* 1999). It follows that a warmer prairie may lead to increased soil organic decomposition, and a decrease in soil quality (Kirschbaum 1995).

Some work on climate change and its impact on soil and crop systems have been completed for Alberta, as a result of a multi year study funded by the Nat Christie

Foundation of Calgary (McGinn *et al.* 1999). This work included the development of climate databases (historic and climate change scenarios grids), soil moisture mapping, seeding dates and drought analysis.

A key tool to understanding climate change and its impact is the use of agriculture models. The modified Versatile Soil Moisture Budget, mVSMB (Akinremi *et al.* 1996; Akinremi and McGinn 1996) is an example of a soil moisture model that has been used for the Canadian Prairies. The mVSMB model simulates soil moisture in various soil layers, and requires simple meteorological and soil input data. Associated with the VSMBm model is a crop growth module to determine evapotranspiration over the growing season. The spatial and temporal resolution of weather data necessary to model agronomic parameters of a region is the focus of recent research (Easterling *et al.* 1990). In some regions, weather observations are too sparse to enable detailed modelling of agronomic parameters at a useful scale. In this case, data are interpolated between observation sites (Nalder and Wein 1998; Robeson 1994). Where a more regional assessment is required, a spatial resolution of <10 to 50 km is useful. These regional scales are perhaps the best compromise for climate change work because it encompasses key agronomic variables (i.e., soil types and topography) and can be related to the large-scale GCM output locations. Work on developing a fine resolution climate database has been carried out for Alberta (McGinn *et al.* 1999) but similar data for the remaining Prairie Provinces are lacking. There is a need for both common baseline historic and climate change data, in the order of 50 by 50 km intervals, to allow the comparison of output of agriculture models.

## 2. Research Objectives

The adaptation strategies that best maintain or enhance agriculture production under climatic change will differ between regions across Canada and must be investigated with a regional perspective. It is clear that to understand adaptation of agriculture, the potential impact of climate change must first be addressed and the vulnerable agricultural activities identified. The main focus of our study was to determine the impact of possible avenues of climate change on soil moisture, temperature and overall aridity. Other features of the agroclimate were also evaluated under climate change, such as seeding dates, growing season duration and degrees days, which are relevant to the diversity of crops.

The first year of the study was devoted to database development (grid of historic and climate change scenarios) and initial soil moisture and drought model runs. Historic databases were necessary to establish baseline information for climate change and in the case of soil moisture, to validate prior to the application of the climate change scenarios. The historic data from individual weather stations were gridded at regular intervals. These grid coordinates corresponded to the coarser resolution of the Canadian Climate Centre Global Circulation Model (CCC-GCM). Output temperature and precipitation data from the CCC-GCM (Saunders and Byrne 1994) were interpolated to the fine grid points where historic weather data existed. Climate change scenarios were developed at each grid point using the approach of Mearns *et al.* (1992) that included a change in variability of each element.

During the second year of the study, existing models were used in conjunction with the climate data to evaluate impacts and some adaptation options for crop diversity. In addition to soil moisture and agricultural drought, other agroclimate indices that characterize the thermal and moisture environment for crop growth were examined. In particular, the time of seeding and thermal intensity of the growing season (length and accumulated degree days) were determined to allow speculation on the change in crop production diversity within each region.

## 3. Methods

### 3.1 Climate Change Scenarios

Maximum and minimum air temperature, and precipitation data were obtained on a daily time-step from two Global Circulation Models (GCM), the Canadian Climate Centre's GCMII and CGCMI-A. The GCMII version was an older model that was uncoupled, meaning there was no influence of oceans processes. The newer CGCMI-A version was coupled to ocean processes and included the effect of aerosols in the atmosphere, decrease in irradiance at the surface. Each GCM was compiled using a current (1x) and double (2x) carbon dioxide concentration. The difference between the 1x and 2x version of each GCM was attributed to the enhanced greenhouse effect.

A limitation of a GCM is that each datum is an average over a large area and therefore a GCM cannot discern small-scaled differences, i.e., GCMII and CGCMI-A each consisted of 23 grid locations distributed across the Canadian Prairies.

Climate change scenarios were generated by 1) creating a regional grid of current climate data using historic weather station data, 2) generating statistical values from the GCM 1x and 2x simulations, 3) downscaling these statistics to the same spatial scale as the current climate data, and 4) imposing the GCM statistics on the historic (baseline) regional climate database. The result of this process was three climate scenarios, 1 current climate and 2 for climate change (GCMII and CGCMI-A). The final process was to combine the current and GCM climate scenarios to generate two additional climate change scenarios. All climate scenarios were scaled to a regional level consisting of 368 points across the agriculture region of the Canadian Prairies at approximately 50 by 50 km grid intervals.

#### 3.1.1 Historic (baseline) Climate Database

The development of the historic climate database originally constructed by McGinn *et al.* (1999) was updated to include more recent weather data (1989-95) and to cover all three Prairie Provinces. Weather data archived by Environment Canada from weather stations across the three Prairie Provinces, British Columbia and the Northwest Territories were screened for the quality and record length of data. Missing maximum and minimum air temperature, rainfall, snowfall and total precipitation data were estimated at locations where less then 20% of the data were missing and where more than 20 years of daily data existed. In total, data from 142 weather stations were used. Historic daily weather data for the northwest United States were also incorporated into the weather archive. A comparison was made for stations along the international border and a correction was made to the US snowfall data. Estimating missing datum was done by using data from the nearest neighbouring stations where otherwise concurrent data existed. For air temperature, the mean monthly station-to-neighbour difference for adjacent months ($\Delta T_m$) and the missing value was estimated ($T_e$). The actual temperature (T) and $T_e$ were then used to determine the root-mean-square error (RMSE) for the month and neighbouring station of interest. The actual missing temperature was then estimated as a weighted average of four nearest stations estimate of temperature, each weighted by the respective RMSE. The estimate for missing total precipitation was similar to temperature, except that station-to-neighbour ratios were used instead of differences. Missing solar radiation data were estimated according to a procedure outlined by Barr *et al.* (1996).

With missing data estimated, the completed time series of weather station data (30 years) were used to develop a baseline dataset of 9x5 grid points per GCM grid point (3.71° latitude by 3.75° longitude). The final grid interval was approximately 50 km intervals. The interpolated data of air temperature, solar irradiance, rainfall, snowfall and total precipitation were generated using the nearest-neighbour approach where each neighbour-estimate was weighted by the inverse-distance-squared method. Up to five neighbouring weather stations for each GCM grid location was used. The fine-scaled dataset consisted of 30 years of daily data ending in 1995.

### 3.1.2 GCM Grid Statistics

For each grid point y of the GCMII and CGCM-A models, the difference in the temperature means ($\Delta T$) and ratio of precipitation means ($\Delta P$) were calculated from their respective 1x and 2x GCM data.

$$\Delta T = \bar{T}_{2x} - \bar{T}_{1x} \qquad (1)$$

$$\Delta P = \bar{P}_{2x} / \bar{P}_{1x} \qquad (2)$$

The ratio of the variance ($\delta$) for temperature and precipitation at each grid point was calculated for each month as:

$$\delta = \text{variance}_{(2x)} / \text{variance}_{(1x)} \qquad (3)$$

### 3.1.3 Downscaling GCM Statistics

The calculated $\delta$ and $\Delta$ values derived from GCM data (Eq. 1-3) and the daily maximum and minimum air temperature, and the total precipitation amounts were downscaled to match the fine grid historic (baseline) data locations. This was accomplished by weighting each neighbouring value by the separation distance (inverse distance squared method). For example, to calculate the temperature (T) at a new grid point x, the nearest seven GCM grid point temperatures ($T_a$ to $T_g$) where divided by their respective distance squared ($D_a^2$ to $D_g^2$) (Eq. 4).

$$Tx = \frac{Ta}{Da^2} + \frac{Tb}{Db^2} + \frac{Tc}{Dc^2} + \frac{Td}{Dd^2} + \frac{Te}{De^2} + \frac{Tf}{Df^2} + \frac{Tg}{Dg^2} \qquad (4)$$

### 3.1.4 Generating Climate Change Scenarios

Five climate scenarios were generated at the same 50 by 50 km spatial scale, consisting of a historic (baseline) scenario, two climate change scenarios (based on output from GCMII and CGCMI-A) and two climate change which were a combination of the GCM and historic scenarios.

The climate change scenarios were created by imposing change using the GCM statistics ($\delta$, $\Delta$ , $T_x$ and $P_x$) on the 30-year historic (baseline) data using a modified procedure of Mearns *et al.* (1992). For example, the new daily air temperature (maximum or minimum; $T_{new}$ ), was calculated as:

$$T_{new} = [\, \bar{T} + \sqrt{\delta}\, ( T - \bar{T} ) \,] + \Delta T \qquad (5)$$

where $\bar{T}$ is the mean daily temperature obtained from a 30-year normal record, T is the historic temperature for the day in question and $\Delta T$ is the difference between the 2x and 1x $CO_2$ temperature. Only the variance ratio ($\delta$) was based on a monthly time step, with the value for a month applied to all days in that month.

The precipitation data used in generating the new precipitation data were first transformed using a natural logarithm due to the skewed nature of precipitation data. The log-transformed monthly precipitation $\chi^*$ was calculated similar to Eq. 5 as:

$$\chi^* = [\, \bar{\chi} + \sqrt{\delta}\; (\chi - \bar{\chi}) \qquad (6)$$

where $\bar{\chi}$ is the log-transformed mean monthly precipitation and $\chi$ is the log-transformed historical monthly precipitation. The mean effect of climate change on precipitation (P*) was obtained using:

$$P^* = \exp(\chi^*)\, (P_{2x} / P_{1x}) \qquad (7)$$

Finally, the new daily precipitation ($P_{new}$) was calculated as the product of the daily historic precipitation ($P_d$) and the ratio of P* to the monthly historic precipitation ($P_m$):

$$P_{new} = P_d\, (P^*/P_m) \qquad (8)$$

Equations 6 to 8 change the amount of monthly precipitation but not the frequency of precipitation.

The sensitivity of the variance ratios was tested on temperature using variances ratios of 0.5, 1.0, 2.0 and the variance ratio from the GCM (Eq. 1). Very little difference was observed in the resulting test grid temperature values indicating that the step change due to $CO_2$ doubling predominated. As a result, the variance ratio from the GCM (close to unity) was used in generating all climate change scenarios.

The daily irradiance that existed historically was not altered in the new climate change scenarios. It was deemed that changes to air temperature would have a far greater impact on crop growth and water use than would a relatively small change to irradiance.

Four climate change scenarios were decided upon based on the preliminary tests conducted (Table 1). The four scenarios provided a range in temperature and precipitation to allow the sensitivity of the subsequent modelling of agroclimate and crop yield to be evaluated. The variance ratio used in all scenarios was set equal to that of the GCM (about one). The first scenario (GCMII) consisted of daily (fine grid) GCMII output of temperature and precipitation. The second scenario (CGCMI-A) comprised of data from CGCMI-A. The third scenario (GCMI_HP) was a combination of the GCMII but instead of the GCMII precipitation, the historic precipitation (HP) amount and frequency were used. The final scenario (CGCMI-A_HP) was the CGCMI-A temperature and historic precipitation.

Table 1. Combinations of historic and GCM data used to generate four climate change scenarios and a historic climate database.

| | GCMII | CGCMI-A | GCMII_HP | CGCMI-A_HP | Historic |
|---|---|---|---|---|---|
| Historic Temperature | | | | | x |
| Historic Precipitation | | | x | x | x |
| GCMII Temperature | x | | x | | |
| GCMII Precipitation | x | | | | |
| CGCMI-A Temperature | | x | | x | |
| CGCMI-A Precipitation | | x | | | |
| Historic Solar Radiation | x | x | x | x | x |

The range in climate change scenarios is expected to invoke impacts that will give some indication of the sensitivity (vulnerability) of prairie agriculture to climate change. A worst-case scenario will set the extreme boundary under which adaptation strategies can be examined

### 3.2 Characterizing the Impact of Climate on Agriculture

The growing environment of agriculture systems is characterized by the thermal and hydrological regimes of a region. Agroclimatic indices such as growing-degree days and accumulative soil water deficit are a useful indicator of these environmental constraints on potential agriculture production. In addition to simple indices, the use of agronomic models allows prediction of the impact of climate change on specific components such as available soil water for crop growth throughout the season.

#### 3.2.1 Agroclimate Indices

The five climate scenarios were used in conjunction with a modified Versatile Soil Moisture Budget, mVSMB, (Akinremi *et al.* 1996) in order to document seeding date, harvest date, degree day, accumulated precipitation, accumulated actual evapotranspiration, accumulated potential evapotranspiration and daily average moisture content. All accumulated parameters were accumulated between the dates calculated for seeding and harvest. All parameters are averages for the province, both spatially and over 30 years.

The mVSMB is a water-budgeting model requires both daily weather and soil data in defining soil moisture at specific sites. It simulates variations in soil moisture content using generally accepted concepts of water movement in the soil and water loss through evaporation from soil evaporation or transpiration from crops (Baier *et al*. 1979). The water requirement of the crops in relation to the atmospheric conditions is simulated through crop coefficients for different phenological stages of crop growth through a growing season.

The seeding date is set when specific conditions are attained concerning soil moisture, precipitation, and air temperature. Simulated crop growth through the phenological stages depends upon accumulated temperature. As a result, the seeding and harvest dates are influenced by soil moisture content and weather data.

The available water capacity of soils required in as input to mVSMB was obtained for all fine grid points across the Canadian Prairies. Previously these data were on file for Alberta (McGinn *et al*. 1999) while those for Saskatchewan and Manitoba required downloading from the Canadian Soil Inventory system, CanSIS, (Shields *et al*. 1991). This was accomplished using a Geographical Information System to extract the digitized soil water data by overlaying soil polygon data with grid point locations.

The mVSMB model was used for all five scenarios and for generating spatial averages, by province and for north and south Alberta, Saskatchewan and Manitoba. The north-south boundary was set at 53.38°N latitude. This was based on the changing vegetation at vegetation at this latitude, north of this boundary (around Edmonton in Alberta) the prairie changes to a more forested landscape. Alberta was divided into 61 northern grid points and 99 southern, Saskatchewan divided into 22 northern points and 127 southern, and Manitoba divided into 7 northern and 52 southern. The relatively small number of northern grid points does not reflect a particularly biased geographical extent of the north-south dividing line, but rather the sparse amount of complete meteorological data available for the grid points in northern regions.

Simulating the growing season under GCM climate date, but retaining historic seeding and harvest dates, will affect the number of degree-days in the season, precipitation, and evapotranspiration, plus the daily soil moisture content for that season. By comparing these parameters resulting from historic seeding/harvest dates with parameters resulting from a GCM-induced early season, it is possible to document the effect of adaptation to earlier seeding on the growing environment.

### 3.2.2 Aridity Index

Two methods were used to measure aridity, i.e., the water deficit needed to maintain non-water limited crop growth over a growing season. The Aridity 1 index is based on the accumulated daily difference between available soil water content and available water holding capacity. For any day when the available soil water declines below 50% of the available water holding capacity, the difference is accumulated. At the end of the growing season the Aridity 1 index indicates the water storage associated with crop water stress throughout the season. The Aridity 2 index is based on the accumulated daily difference between actual evapotranspiration and potential evapotranspiration. Each aridity index was calculated for each climate scenario at all grid points, and provincial averages were then tabulated as for the agroclimatic indices.

#### 3.2.3 Climate Classification

The classification of climate used in our study follows that given by Thornthwaite (1931) and used by Williams *et al.* (1988) in evaluating the effect of climate change in Saskatchewan. The index is a measure of climate influenced vegetation classes and is calculated as:

$$I = \sum_{i=1}^{n} 115 \frac{[P_i / 25.4]^{1.11}}{[1.8T_i + 22]} \qquad (9)$$

where P is the mean monthly precipitation for month i and T is the mean air temperature. The Thornthwaite values of 32-63 indicate a sub-humid climate (grassland), and values of 16-31 indicate a semi-arid climate (steppe).

## 4. Results and Discussion

### 4.1 Climate Scenarios

The following sections describe the air temperature and precipitation patterns under the five climate scenarios (historic and climate change). Of the five climate scenarios, only the historic and two GCM scenarios are discussed, as the remaining two are combinations of the historic and GCM scenarios. In addition to average changes across the three Prairie Provinces, the data were also contoured to allow a description of the pattern of change in winter (December to February) and summer (June to August). The winter period is important in agriculture as it dictates the survival of perennial crops and insect pests. Summer temperature and precipitation amounts are critical in characterizing the growing environment of crops on the prairies.

#### 4.1.1 Minimum Air Temperature

Annually the historic minimum air temperature ($T_{mn}$) averages between –4.0 (Alberta) to –4.2°C (Saskatchewan and Manitoba) (Table 2). However, the Canadian Prairies experience considerable seasonal variability in air temperature. For $T_{mn}$, the historic (baseline) climate indicates that the average summer temperature is about 28° C higher than that in winter. Historically during winter across the prairies, a well-defined gradient exists in $T_{mn}$, extending from a high of around –14.5°C in southern Alberta and decreasing to the east and north to -20.5°C and more (Fig. 1a). This pattern is speculated to reflect both a latitudinal effect and the effect of a colder continental air mass in winter. The prairie-wide summer minimum temperature pattern is less distinct, however, an elevation effect of cooler air to the west is evident. In summer, the highest minimum air temperatures exist in the central south prairie (Fig 1b). The higher winter minimum temperature in southern Alberta coincides to a region known for the frequency of warm Chinook winds, which has a moderating effect on the average winter temperature.

The GCMII scenario, for the winter period, produced a $T_{mn}$ pattern with a similar SW (-4°C) to NE (-12°C) gradient across the prairies that existed historically. The greatest warming in $T_{mn}$ in winter (Fig. 2a) was found in southern Saskatchewan (increases of about 9°C). The warming decreases concentrically with distance from this core region, reaching increases of between 7 and 7.5° C in the northern prairie region. During the summer months (Fig. 2b), the changes imposed by GCMII are much less than in winter, where $T_{mn}$ was shown to increase by around 4.6°C in SE Saskatchewan and SW Manitoba, decreasing to 4.0°C to the west.

In the GCMII scenario, there was an eastward shift of the region of greatest warming between winter and summer (from SW to SE Saskatchewan).

For the CGCMI-A scenario, $T_{mn}$ increased more in the winter ($\Delta T_{mn}$ = 4.0°C) than in summer ($\Delta T_{mn}$ = 2.4°C) relative to the historic baseline value. In winter (Fig. 3a), the greatest increase in $T_{mn}$ over historic values was in southern Manitoba and southeastern Saskatchewan, which warmed by approximately 5.25°C. The smallest increases in $T_{mn}$ were found in Alberta, which warmed by between 3.8 and 4.5°C. In summer (Fig. 3b), there was also an east – west gradient in the magnitude of warming where the eastern Prairie shows increases of 2.6°C while the west is predicted to warm by 2.2°C.

Table 2. Averaged annual minimum air temperature for the climate scenarios across the three Prairie Provinces of Canada.

| Scenario | Minimum Air Temperature °C | | |
|---|---|---|---|
| | Alberta | Saskatchewan | Manitoba |
| Historic | -4.0 | -4.2 | -4.2 |
| GCMII | 1.0 (5.0) | 1.4 (5.6) | 1.2 (5.4) |
| CGCMI-A | -1.0 (3.0) | -1.0 (3.2) | -0.9 (3.3) |

( ) indicates the difference (°C) between the historic and changed climate

4.1.2 Maximum Air Temperature

Historically, the maximum air temperature ($T_{mx}$) for the agricultural regions in Alberta, Saskatchewan and Manitoba throughout the year is 8.4, 8.3 and 7.6°C, respectively (Table 3). The seasonal effect results in $T_{mx}$ values that are 22°C higher in summer than in winter over most of the prairies.

In winter, $T_{mx}$ decreases from about –2.5°C in SW Alberta to more than –10.5°C as depicted by the isotherm (Fig. 4a) extending from northern Alberta through central

Saskatchewan and into southern Manitoba. This $T_{mx}$ gradient, as in the case for $T_{mn}$ in winter, reflects the influence of the cold continental air mass contrasting with more mild Pacific air.

In summer, the southern Canadian prairies experience $T_{mx}$ values in the order of 25.5°C, which decreases concentrically to the east, north (latitude effect) and west (elevation effect) (Fig. 4b). Low values of 19.5°C are found in the northern agricultural region of Alberta.

In comparison to the historic values, the annual GCMII $T_{mx}$ predictions increased across Alberta, Saskatchewan and Manitoba by 4.0, 5.2 and 5.7°C, respectively (Table 3). In the summer $T_{mx}$ predictions produced a more irregular pattern with isolated cooler spots along the Alberta–Saskatchewan border. Winter predictions of $T_{mx}$ are more evenly distributed, displaying the same southwest-northeast gradient pattern as found in the historic data.

The GCMII predictions show the greatest increase in southern Manitoba (5.5°C increase in summer, 6°C increase in winter) (Fig. 5). In both the summer and winter, GCMII predicts that $T_{mx}$ will decrease in the west to between 3.5 and 4.0°C, respectively.

CGCMI-A predictions indicated less of an increase in $T_{mx}$ compared to GCMII values. Over the entire average year, $T_{mx}$ is expected to increase by 2.5, 2.9 and 3.3°C across Alberta, Saskatchewan and Manitoba, respectively (Table 4). Not only is the magnitude of change smaller, but the differences between the averages across the three provinces are also less (smaller range in values) compared to the GCMII scenario (0.8 verses 1.7°C); the smaller change is more uniform for CGCMI-A.

Table 3. Averaged annual maximum air temperature for the climate scenarios across the three Prairie Provinces of Canada.

| Scenario | Maximum Air Temperature °C | | |
|---|---|---|---|
| | Alberta | Saskatchewan | Manitoba |
| Historic | 8.4 | 8.3 | 7.6 |
| GCMII | 12.4 (4.0) | 13.5 (5.2) | 13.3 (5.7) |
| CGCMI-A | 10.9 (2.5) | 11.2 (2.9) | 10.9 (3.3) |

( ) indicates the difference (°C) between the historic and changed climate

The greatest increase in $T_{mx}$ is found in winter and summer in southern Manitoba (3.6 and 3.5°C, respectively). In both seasons a concentric pattern of highest temperature increase is centred on southern Manitoba (Fig. 6). The region showing the smallest increase in $T_{mx}$ in winter is southwestern Alberta (2°C) and in summer central Alberta and Saskatchewan (1.8°C).

Overall, both climate change scenarios show $T_{mx}$ will increase the most in southern Saskatchewan and Manitoba. The increase is greater for GCMII compared to CGCMI-A in both winter and summer.

#### 4.1.3 Precipitation

Historically, the agricultural regions in Manitoba receive slightly more precipitation on average (486 mm) compared to that in Alberta (482 mm) (Table 4). The agricultural regions within Saskatchewan receive the least amount (395 mm). The pattern of winter precipitation (Fig. 7a) indicates regions in a southern corridor of Alberta and southern Saskatchewan receiving 40 mm or less. The southern border of Alberta and Saskatchewan (around Cypress Hills) receives more precipitation, speculated to be an elevation effect. The greatest winter precipitation received, greater than 60 mm, is found north of central Alberta and along the foothills, as well as in Manitoba. In summer, between 120 to 145 mm is received in the SE Alberta - SW Saskatchewan area (Fig. 7b). There is a concentric pattern where summer precipitation increases to the west (foothills), north and east. The maximum average precipitation is found in central-northern Alberta (200 to 300 mm) and in eastern Manitoba (225 mm).

There is generally a smaller range in winter precipitation across the prairies, ranging from a high of around 70 mm to a low of 40 mm, relative to the summer situation (ranging from 145 to +300 mm). Although precipitation averages characterize the climate, considerable spatial variability is expected as a portion of this amount is related to convective (locally generated) activity (especially for rainfall) as well as related to changes in synoptic patterns. Hence the uncertainty in precipitation averages in any given year is currently, and no doubt will continue into the future, to be a limitation for agriculture on the semi-arid prairies.

The GCMII scenario predictions indicate precipitation increases of 29-30% in Alberta and Saskatchewan, and as much as 36% in Manitoba (Table 4). Precipitation is predicted to increase above historic amounts during summer (average increase of 40 mm) and winter (average increase of 20 mm) throughout the prairies. The winter precipitation pattern (Fig. 8a) shows a concentric pattern centred on SE Saskatchewan and SW Manitoba, from an area of no change, increasing to a change of 30 mm in central Alberta. In summer, GCMII showed increased precipitation across the prairies (Fig.8b) with the greatest increase in central Alberta of +60 mm (24% above historic). The smallest increase was found across Saskatchewan to Manitoba of +30mm (15% above historic). The pattern during the summer is quite different for the GCMII prediction in SE Saskatchewan and southern Manitoba, i.e., 30 mm increase in summer compared to no change in winter. In central Alberta, GCMII precipitation is predicted to increase by 30 mm in winter to 60 mm in summer.

CGCMI-A predictions for summer precipitation show the greatest change against historic data, on average summer data shows a -10 mm change and the winter period a 2 mm change. There is a general decrease in CGCM1 accumulated precipitation for June-August inclusive. Predicted changes during winter are minimal with Alberta receiving a small precipitation increase nearer the mountains (Fig. 9a). In summer, the CGCMI-A predicts that central Alberta will become slightly wetter (5 mm) while the south will become drier (-10 mm, a decrease of 7%) (Fig. 9b). Southern Saskatchewan is progressively drier west (-5 mm) to east (-30 mm, or a decrease of 17%). Manitoba is progressively drier north (0 mm) to south (-30 mm, or a decrease of 15%).

Both the GCMII and CGCMI-A indicate that overall central Alberta will benefit the most during the summer and winter from increased precipitation, whereas the eastern prairie will see little change (winter), smaller increases (30 mm under GCMII) or a decrease (30 mm under CGCMI_A).

Over all seasons, the predicted increase in precipitation in both the GCMII (large) and CGCMI-A (small) data coincides with a speculated intensification of the hydrological cycle resulting form global warming in general (more evaporation and atmospheric water). Akinremi *et al.* (2001) reported that across the Canadian Prairies, significant increases in rainfall of 16% have occurred between 1956-95, attributed to early spring and summer period. They indicated that the smallest increase in rainfall was found in southern Manitoba. This finding coincides with our CGCMI-A data in the eastern prairie showing a 30 mm decrease in SE Saskatchewan and southern Manitoba in summer. Although it may be premature to suggest the processes are the same between the historic trends and those responsible for CGCMI-A results (i.e., climate change), further investigated is warranted.

Table 4. Averaged annual precipitation for the climate scenarios across the three Prairie Provinces of Canada.

| Scenario | Precipitation mm | | |
|---|---|---|---|
| | Alberta | Saskatchewan | Manitoba |
| Historic | 482 | 395 | 486 |
| GCMII | 622 (29%) | 514 (30%) | 663 (36%) |
| CGCMI-A | 518 (7%) | 405 (3%) | 503 (3%) |

( ) indicates the difference (%) between the historic and changed climate

## 4.2 Agroclimate Indices

Several agroclimate indices were evaluated under the historic and climate change scenarios across the three Prairie Provinces. Results from the comparison on these indices were used to indicate the change in the growing environment and allowed an examination of the impact of, and adaptation strategies to, these environmental changes.

### 4.2.1 Seeding and Harvest Dates

Historically, the earliest seeding date of the Prairie Provinces is May 19 (day of the year DOY 139[1]) in Saskatchewan and the latest is found in Alberta on May 24th (DOY 144).

[1] Non – Leap Year Assumed for DOY

These are averages for the province, so specific locations in S. Alberta and S. Saskatchewan may have an earlier date than the provincial average. Similarly, Saskatchewan has the earliest and Alberta the latest harvest dates, August 27th and September 8th, respectively. Seeding and harvest dates for Manitoba are intermediate to those for the other provinces (Table 5). On average it takes 93-100 days to grow a spring wheat crop across the prairies.

Table 5. Average provincial seeding and harvest dates for five climate scenarios.

| | Seeding Date (day of the year) | | | | |
|---|---|---|---|---|---|
| | GCMII | CGCMI-A | GCMII_HP | CGCMI-A_HP | Historic |
| Alberta | 123 (22) | 122 (22) | 118 (26) | 124 (20) | 144 |
| Saskatchewan | 114 (25) | 120 (19) | 110 (29) | 121 (18) | 139 |
| Manitoba | 122 (19) | 124 (17) | 117 (24) | 125 (16) | 141 |

| | Harvest Date (day of the year) | | | | |
|---|---|---|---|---|---|
| | GCMII | CGCMI-A | GCMII_HP | CGCMI-A_HP | Historic |
| Alberta | 220 (31) | 227 (24) | 217 (34) | 229 (22) | 251 |
| Saskatchewan | 205 (34) | 215 (24) | 203 (36) | 216 (23) | 239 |
| Manitoba | 207 (33) | 215 (25) | 203 (37) | 216 (24) | 240 |

( ) indicates the difference (days) between the historic and changed climate

Under GCMII scenarios Saskatchewan and Alberta continue to have the earliest and latest seeding dates of the provinces, respectively. Under CGCM1 scenarios Saskatchewan and Manitoba have the earliest and latest seeding dates, respectively.

Alberta's seeding date is moved earlier by 20 days (CGCMI-A_HP) to 26 days (GCMII_HP). The same GCM scenarios are responsible for moving Saskatchewan's seeding date 18 days to 29 days earlier, respectively, and Manitoba's seeding date 16 days to 24 days earlier. Earlier seeding dates reflect the predicted higher maximum and minimum GCM temperatures, having the greatest effect in Saskatchewan coinciding with higher annual temperatures (Tables 2 and 3).

Harvest dates in Alberta are advanced by 22 days (CGCMI-A_HP) to 34 days (GCMII_HP). The same scenarios are responsible for moving Saskatchewan's harvest date 23 to 36 days earlier, and Manitoba's harvest date 24 to 37 days earlier. An earlier harvest reflects a greater number of thermal units accrued over the growing season using a climate change scenario than using historic weather, in addition to an earlier start to the season.

In all provinces under the historic climate, the seeding date and harvest date for the southern region (below 53.38°N) were shifted earlier than the province average (up to 2 and 3 days, respectively), and in the north delayed compared to the province average (up to 8 and 12 days, respectively). Under GCM scenarios the above pattern remains the same. Between the north and the south, seeding and harvest dates vary most under scenario GCMII_HP, up to 5 and 3 days earlier respectively, for the south than the provincial average, and up to 21 and 15 days later respectively, for the north than the provincial average. The northern regions of Saskatchewan and Manitoba vary the most from provincial averages, indicating that thermal units drop rapidly in these areas from the average, and indicating the influence of the southern results on the average.

### 4.2.2 Growing Degree-Days

Historically, Manitoba and Saskatchewan have the highest degree-day accumulations for the growing season, 1183 and 1154 degree-days, respectively, followed by Alberta with 984 degree-days (Table 6). This lower value reflects the elevation effect on air temperatures found in Alberta where the plains slope gradually eastward dropping some 900 m between Alberta foothills to eastern Manitoba (Padbury *et al.* 2000). The historical seeding and harvest dates and degree-days may also be partly influenced by the higher summer minimum temperatures found further east (a rise of one degree per growing day in Manitoba over SE Alberta). When split into values for the southern region, below 53.38°N, there is a general increase of degree-days over all provinces of 1.5%.

Table 6. Average degree-days by province under five climate scenarios.

| | Degree-Days | | | | |
|---|---|---|---|---|---|
| | GCMII | CGCMI-A | GCMII_HP | CGCMI-A_HP | Historic |
| Alberta | 1201 (22%) | 1132 (15%) | 1194 (21%) | 1139 (16%) | 984 |
| Saskatchewan | 1273 (10%) | 1203 (4%) | 1264 (10%) | 1210 (5%) | 1154 |
| Manitoba | 1301 (10%) | 1221 (3%) | 1277 (8%) | 1230 (4%) | 1183 |

( ) indicates the difference (%) between the historic and changed climate

The result of each GCM scenario is to increase the degree-days of the season in each province (an increase of 94 to 217 under GCMII, and 38-155 under CGCMI-A). GCMII scenarios (with simulated or historic precipitation) raise the temperatures further than the CGCMI-A incorporated scenarios and so simulate the highest degree-days for a growing season.

Under each GCM scenario Manitoba's season has the highest number of degree-days of the provinces, yet the smallest increase from historic values. Manitoba has a 3 to 10% increase, Saskatchewan is similar (4 to 10%), and Alberta has a 15 to 22% increase in degree-days. Alberta has the greatest relative increase in degree-days, attributed to the increase in days-to-maturity under GCM scenarios. If Alberta's historic days-to-maturity had been the same as Saskatchewan (100 days), the relative degree-day increase from historic to GCM scenario would have been more in-line with changes for the other provinces (7-14%). When split into southern averages below 53.38°N, under GCM scenarios there was a higher seasonal accumulation of degree-days than the average value (an increase of 0.9% to 1.3%).

A shift of the growing season from historic dates to earlier seeding and harvest dates, under GCM scenarios, decreases the accumulated degree-days throughout the season. In Alberta, GCMII scenarios decreased by 200 degree-days, and in Saskatchewan and Manitoba by 400 degree-days. In Alberta, CGCMI-A scenarios decreased by 100 degree-days, in Saskatchewan by 200 degree-days and in Manitoba by 300 degree-days. This reflects the shift of part of the growing season to an earlier cooler spring temperatures, and an earlier harvest means a shorter duration of the season in the warmer late summer.

### 4.2.3 Evaporation

Actual evapotranspiration was calculated in mVSMB from potential evaporation (using Priestly Taylor method) and correcting the value based on the available soil moisture. Between seeding and harvest for a spring wheat crop (dryland), the historic water use by the crop varies between 220 to 270 mm where water use in Saskatchewan was the lowest (Table 7). With GCMII the evapotranspiration is predicted to increase between 7 to 18% where the greatest increase is found in Alberta and least in Manitoba; the increase in Saskatchewan is intermediate. This increase in evapotranspiration coincides with the increase in air temperature and precipitation. With the newer CGCMI-A model, only Alberta is predicted to see an increase (6%) while the remaining Prairie Provinces show a decrease of –5%. This reduction in both Saskatchewan and Manitoba may be related to combination of the relatively smaller increase in precipitation and the slightly higher warming. Similarly, combining the historic precipitation (less precipitation) with the GCM warming scenarios (GCMII_HP and CGCMI_HP) reduced evapotranspiration further, except for CGMI-A_HP in Saskatchewan and Manitoba, which changed slightly.

Table 7. Accumulated evaporation from a small grain cereal crop (spring wheat) throughout the growing season by province (mm).

| | Growing Season Evaporation (mm) | | | | |
|---|---|---|---|---|---|
| | GCMII | CGCMI-A | GCMII_HP | CGCMI-A_HP | Historic |
| Alberta | 312 (18%) | 280 (6%) | 260 (-2%) | 270 (2%) | 265 |
| Saskatchewan | 249 (13%) | 208 (-5%) | 198 (-1%) | 210 (-5%) | 220 |
| Manitoba | 289 (7%) | 257 (-5%) | 242 (-10%) | 254 (-6%) | 270 |

( ) indicates the difference (%) between the historic and changed climate

### 4.2.4 Soil Moisture

Generally, the most critical parameter for crop growth on the semi-arid Canadian prairies is soil moisture. The historic mean daily soil moisture content is 82 mm per 120 cm soil

(Alberta), 47 mm (Saskatchewan) and 76 mm (Manitoba) (Table 8). The low value for Saskatchewan is reflected in the fact that Saskatchewan has the lowest rainfall during the growing season (191 mm compared to 244 mm for Alberta and 220 mm for Manitoba). In addition, the historic ratio of actual evapotranspiration to potential evapotranspiration ($ET_a/ET_p$) is 0.69 (Alberta and Manitoba) and 0.54 (Saskatchewan), e.g., the amount of $ET_a$ relative to $ET_p$ is less in Saskatchewan than in Alberta or Manitoba. The lower value in Saskatchewan reflects the grater aridity of this region. Daily average soil moisture is higher in north Alberta than in the south (90 and 77 mm per 120 cm soil depth, respectively), does not vary between north and south Manitoba and is only slightly higher in South Saskatchewan than the north. The relatively large difference in soil moisture between north and south Alberta is consistent with the relatively large difference in precipitation for this province.

Table 8. Average daily soil moisture through the growing season by province (mm per 120 cm soil depth) and the average daily soil moisture increase (water savings) attributed to the adoption of earlier seeding dates.

| | Soil Moisture (mm/120 cm soil depth) | | | | |
|---|---|---|---|---|---|
| | GCMII | CGCMI-A | GCMII_HP | CGCMI-A_HP | Historic |
| Alberta | 100 (22%) | 81 (0%) | 74 (-10%) | 73 (-10%) | 82 |
| Saskatchewan | 66 (40%) | 51 (8%) | 47 (0%) | 47 (0%) | 47 |
| Manitoba | 102 (34%) | 82 (8%) | 75 (0%) | 75 (0%) | 76 |

| | Average Daily Soil Moisture Increase (mm/120 cm soil depth) | | | |
|---|---|---|---|---|
| | GCMII | CGCMI-A | GCMII_HP | CGCMI-A_HP |
| Alberta | 8 | 2 | 5 | 1 |
| Saskatchewan | 11 | 9 | 8 | 6 |
| Manitoba | 16 | 15 | 15 | 12 |

( ) indicates the difference (%) between the historic and changed climate

Under GCM scenarios a combination change in temperature and precipitation resulted in changes to soil moisture. In each scenario Saskatchewan had the lowest soil moisture (47 to 66 mm per 120 cm soil depth), while Alberta and Manitoba have very similar amounts (73 to 102 mm per 120 cm soil depth); these are province averages. The CGCMI-A scenario using simulated rainfall (CGCMI-A) does not decrease soil moisture in any province despite higher predicted temperatures (Saskatchewan and Manitoba experience a slight increase of 7%). The CGCMI-A scenario using historic precipitation (CGCM-A_HP) had little effect on Manitoba and Saskatchewan, but reduces Alberta's soil moisture from 82 to 73 mm per 120 cm soil depth (a reduction of 11%). This is surprising since temperatures simulated by this scenario are predicted to change very little in Alberta, although the potential ET is predicted to rise 383 to 406 mm while the actual ET is only predicted to rise from 265 to 269 mm over a season.

The GCMII (simulated precipitation) scenario when used to drive the soil moisture model, showed a substantial increase in the average daily soil moisture (22% in Alberta, 40% in Saskatchewan, 34 % in Manitoba). These increases coincide with the predicted increase of seasonal precipitation. GCMII_HP (using historic precipitation) resulted in a predicted slight decrease in the soil moisture of Saskatchewan and Manitoba, but a large decrease in Alberta (10%), similar to that of CGCMI-A_HP. It is possible that the predicted increase in temperatures (coinciding to increased evaporation) together with the historically arid southern Alberta could be the influencing factor here. Under the worst-case scenario (GCM with historic precipitation) soil moisture is not predicted to change in Saskatchewan and Manitoba, and only decrease in Alberta (-10%). However, these worse case scenarios are not very likely given that precipitation in general is expected to increase according to both GCM scenarios we investigated.

The patterns between north and south are consistent under GCM scenarios but there are some unexpected results. Under all GCM scenarios southern Saskatchewan and southern Manitoba grid points have higher average daily soil moisture than their northern counterparts, but only S. Manitoba also has a higher precipitation than its north. Hence, actual evapotranspiration is also consistently higher in southern Manitoba than the north.

Particularly noticeable under GCMII scenario predicting an increase in precipitation, there is a large difference of 34 mm between north Manitoba's precipitation over a growing season and its wetter south, and a greater difference in soil moisture between north and south than for most Manitoba scenarios (a difference of 12 mm per 120cm soil depth).

Overall, Alberta is the province displaying the greatest difference between north and south soil moisture content, the south being more arid, as is typically shown by a mean difference of 15 mm per 120 cm soil depth for all GCM scenarios.

It is speculated that the effect of early and shorter growing season compensates for the reduction in precipitation to give increased soil moisture in all provinces under all scenarios. As seen in Table 8 under GCMII average daily soil moisture through the growing season increases by 8, 11 and 16 mm per 120 cm soil depth (Alberta, Saskatchewan and Manitoba, respectively). Under CGCM1 soil moisture increases by 2, 9 and 15 mm per 120 cm soil depth (Alberta, Saskatchewan and Manitoba, respectively).

### 4.2.5 Aridity

Aridity index 1 (Aridity1 based on soil moisture) gives a slightly higher value than aridity index 2 (Aridity2 based on evapotranspiration) (Table 9). Using historic weather for Alberta, Aridity1 gives a value of 148 mm compared with 117 mm for Aridity2, similarly Saskatchewan has values of 203 and 157 mm, and Manitoba has values of 143 and 109 mm for Aridity1 and Aridity2, respectively. This difference is expected as the one index reflects the need for supplementary water in the soil to ensure non-water stress conditions, while the second index reflects the deficit in potential water loss from the crop where high water use is associated with non-water stress conditions. In both indices, large deficits reflect water stress and therefore reduced growth and grain yield.

There is no single scenario responsible for producing consistent higher values of aridity than the historic weather. This is consistent with the results found for soil moisture. The lowest aridity values (less dry) occur under the GCMII scenario, which is to be expected with the increased rainfall this scenario produces. Values for Alberta, Saskatchewan and Manitoba are 105, 149 and 102 mm (Aridity1), respectively, and 84, 114 and 79 mm (Aridity2). Aridity values for the growing season under other scenarios are close to the historic values.

Under all scenarios Saskatchewan has higher aridity figures than other provinces, i.e., crops growing in Saskatchewan experience a greater water deficit.

Table 9. Accumulative growing season aridity values by province (mm water deficit) for different climate scenarios. Note that positive values in brackets (difference in mm between historic and climate change scenario) indicate more arid conditions.

| | Aridity1 (mm) | | | | |
|---|---|---|---|---|---|
| | GCMII | CGCMI-A | GCMII_HP | CGCMI-A_HP | Historic |
| Alberta | 105 (-43) | 145 (-3) | 149 (1) | 154 (6) | 148 |
| Saskatchewan | 149 (-54) | 194 (-7) | 194 (-6) | 194 (-7) | 203 |
| Manitoba | 102 (-41) | 133 (-10) | 138 (-5) | 134 (-9) | 143 |

| | Aridity2 (mm) | | | | |
|---|---|---|---|---|---|
| | GCMII | CGCMI-A | GCMII_HP | CGCMI-A_HP | Historic |
| Alberta | 84 (-33) | 115 (-2) | 118 (1) | 123 (6) | 117 |
| Saskatchewan | 114 (-43) | 153 (-4) | 155 (-2) | 157 (0) | 157 |
| Manitoba | 79 (-30) | 103 (6) | 107 (-2) | 109 (0) | 109 |

### 4.2.6 Climate Classification

Historically the climate classifications for Alberta, Saskatchewan and Manitoba, when calculated as the Thornthwaite Index, return indices of 44, 37 and 46, respectively (Table 10). These indices all fall into the classification of a sub-humid climate, with Saskatchewan being the most arid.

Under all climate change scenarios Saskatchewan has consistently the lowest values. All climate scenarios had the effect of lowering the Thornthwaite Index except GCMII with simulated precipitation that raises the index to 50 (Alberta), 39 (Saskatchewan) and 50 (Manitoba).

The scenario reducing the index most severely is GCMII using historic precipitation, which gives indices of 37 (Alberta), 30 (Saskatchewan) and 36 (Manitoba). Climate classification, useful as an indicator of environmental constraints on potential agricultural production, indicates that the result of certain situations border on the threshold of its definition of a sub-humid to semi-arid class. For example, Saskatchewan under climate scenario GCMII using historic precipitation would be considered a semi-arid landscape, since historically Saskatchewan has low precipitation values compared to other provinces, and temperatures are predicted to rise over historic values without an increase in precipitation.

However, under most scenarios the index stays within the sub-humid class, i.e., 32 to 63, its category under historic weather. This indicates that in general the predicted increase in precipitation, together with earlier seeding and harvest dates, will moderate the effect of a predicted increase in temperature on vegetation vis-à-vis evapotranspiration.

Table 10. Thorthwaite index values by province (mm) for different climate scenarios.

| | Thornthwaite Index (mm) | | | | |
|---|---|---|---|---|---|
| | GCMII | CGCMI-A | GCMII_HP | CGCMI-A_HP | Historic |
| Alberta | 50 | 43 | 37 | 39 | 44 |
| Saskatchewan | 39 | 34 | 30 | 33 | 37 |
| Manitoba | 50 | 42 | 36 | 40 | 46 |

## 5. Conclusion

Both GCM scenarios investigated in our study report an increase in annual minimum (3 to 5.6°C) and maximum (2.5 to 5.7°C) air temperature across the three Prairie Provinces. The greatest annual warming was found for the GCMII model (4 to 5.7°C) relative to that for CGCMI-A model output (2.5 to 3.3°C). This latter model was deemed to give more consistent spatial patterns relative to the historic temperature pattern and for this reason, may better reflect the spatial pattern of future climate. This was also the newest model that included a greater understanding of climate change forcing factors re: ocean coupling and aerosols effects. The increase in annual precipitation across the three Prairie Provinces was much greater for GCMII (29 to 36% increase) compared to the CGCMI-A model (3 to 7% increase). There was considerable spatial variability in the predicted change in precipitation patterns between GCM predictions. For example, GCMII indicated large increases in summer rain in central Alberta (60 mm) and in southern Manitoba (30 mm). However, CGCMI-A predicts central Alberta will receive just slightly more than the historic amount in summer, but that SE Saskatchewan and southern Manitoba is expected to receive less rain (-30 mm) compared to historic amounts. The overall annual increase in precipitation is consistent with the global ‘intensification’ theory that reports with global surface warming, greater surface evaporation and therefore greater precipitation is expected. The reduced increase to the eastern Prairie also coincides with the historic trend in rainfall reported in a previous study, suggesting the climate change rainfall pattern may already be evident.

The increase in air temperatures under the different climate change scenarios is reflected in the agroclimatic indices. With spring warming occurring earlier under climate change, there is an opportunity for the advancement of seeding dates. The provincially averaged advancement varied between 16 and 29 days depending on the chosen scenario. The CGCMI-A scenario predicted advancement of seeding by between 17 to 22 days. In more southern regions of each province, the seeding dates were advanced and additional 2 to 3 days compared to the provincial averages.

Growing degree-days are a measure of the accumulative thermal regime that dictates, in part, the rate of maturation of a crop. In mid latitude temperate regions warming is expected to enhance growing degree-days and result in opportunities for greater diversity of crops. This was the case in our study where degree-days under GCMII are predicted to increase by between 10 to 22% (provincial averages) while for CGCMI-A these values increase by between 3 to 15%. The two climate change scenarios using historic precipitation (GCMII_HP and CGCMI-A_HP) produced similar values of increased degree-days as their associated GCM (GCMII and CGCM-A). The slight difference was attributed to the change in growing period that altered the thermal regimes. The greatest increase was found for Alberta for all scenarios suggesting that this region would benefit the greatest from warming during the growing season (seeding to harvest).

Soil moisture is a key indicator of the status of surface hydrology, agriculture drought and crop growth potential on the semi-arid prairies. It is reflects the antecedent precipitation and integrates the overall net exchange of water at the soil and crop surface as driven by seasonal weather. As such, soil moisture proved to be a key element in defining the vulnerability of prairie agriculture to climate change. Soil moisture is predicted to increase between 22 to 34% using GCMII scenario, no doubt related to the predicted increase in precipitation. However, under a CGCMI-A climate change scenario, soil moisture status is predicted to change very little (0 to 8% increase). The climate change scenarios with warming but no change in precipitation (GCMII_HP and CGCMI-A_HP) resulted in –10% decrease in soil moisture in Alberta and no change in Saskatchewan and Manitoba. The increase in soil moisture under GCMII an CGCM-A scenarios was attributed in part to the advancement in the growing season dates and decreased maturity period. In this manner, the adoption of earlier seeding dates with conventional short season crops is a simple adaptive strategy that results in water savings. The shift in seeding dates is expected to produce the greatest water savings in southern Manitoba where summer rainfall is predicted to decline (CGCMI-A) or increase the least (GCMII).

Two methods were used to describe the aridity changes attributed to climate change. The results from both methods predict that that aridity during the growing season will decrease dramatically under a GCMII scenario (wetter conditions), to only slight changes with the remaining scenarios (CGCMI-A, GCMII_HP and CGCM-A_HP). These findings support the conclusion found for soil moisture levels. In similar fashion, the Thornthwaite climate classification changes greatest for GCMII (more humid) but generally all scenario values fall within the current climate classification of semi-humid climate (grassland).

Overall, there is an expectation that some of current climate-related constraints on the Canadian prairies will be the same or somewhat less according to the climate change scenarios investigated in our study. With the possibility of a more conducive growing environment for crops, production potential and crop diversity is may increase. Even under the worst case scenario (no change in annual precipitation amount or pattern), the shift in seeding dates are expected to compensate for increased evaporation during the summer with surface warming, essentially producing a growing period more equivalent to today's growing period thermal regime.

There is also the expectation that carbon dioxide fertilization (increased $CO_2$ concentration of the atmosphere leading to an increase in water use efficiency of temperate crops) may promote the crop production ability in the Canadian prairies. On the negative side, surface warming will also mean the possibility of better over-winter survival (expansion in intensity or area) of many pests, weeds and diseases on the prairies. Examples include crop pests such as grasshoppers, wheat stem sawflies and lygus bugs; cattle pests such as stable flies; invasion of herbaceous perennials such as Rush Skeleton weed; and plant diseases such late blight on potatoes and Fusarium head blight on wheat. However, given better management to control these secondary effects of climate change on agricultural production, the climate of the prairies is predicted to lead to Canadian prairie agriculture playing an increasingly important role in national and world food supply.

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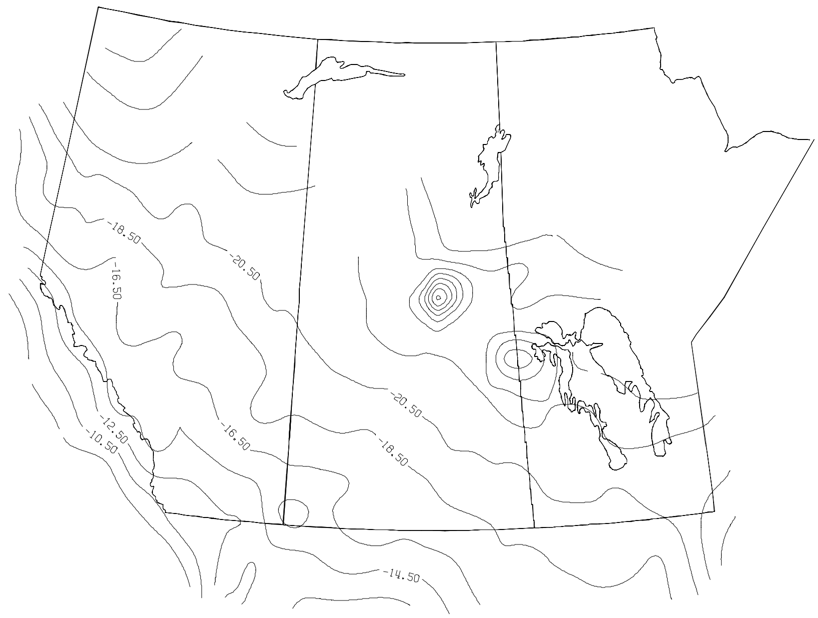
Figure 1: Average historic minimum temperature (°C) for the periods a) December to February and b) July to August.

a)




b)

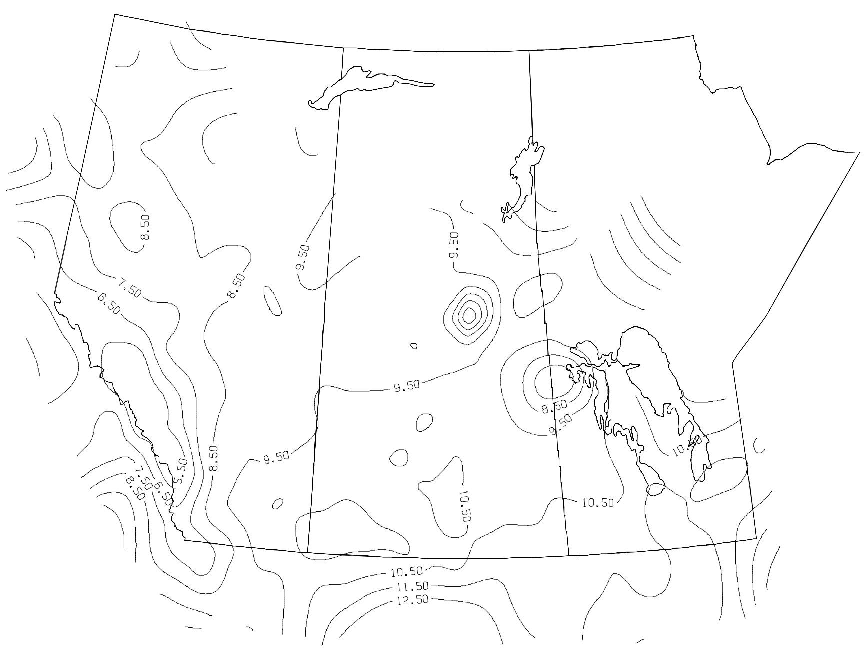
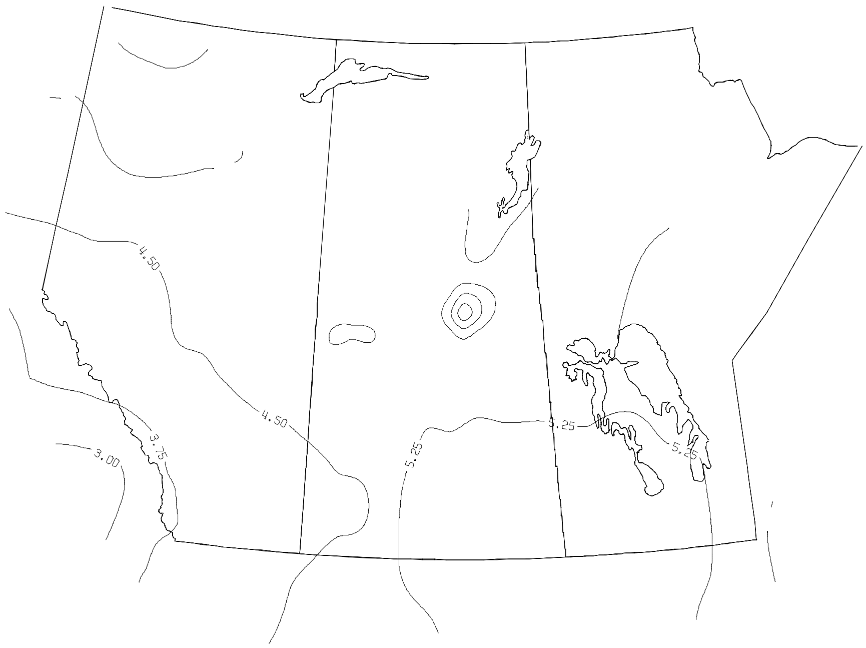


Figure 2: Difference between GCMII and historic values for minimum temperature (°C) for the period a) December to February and b) July to August.

Figure 3: Difference between CGCMI-A and historic values for minimum temperature (°C) for the periods a) December to February and b) July to August.

a)

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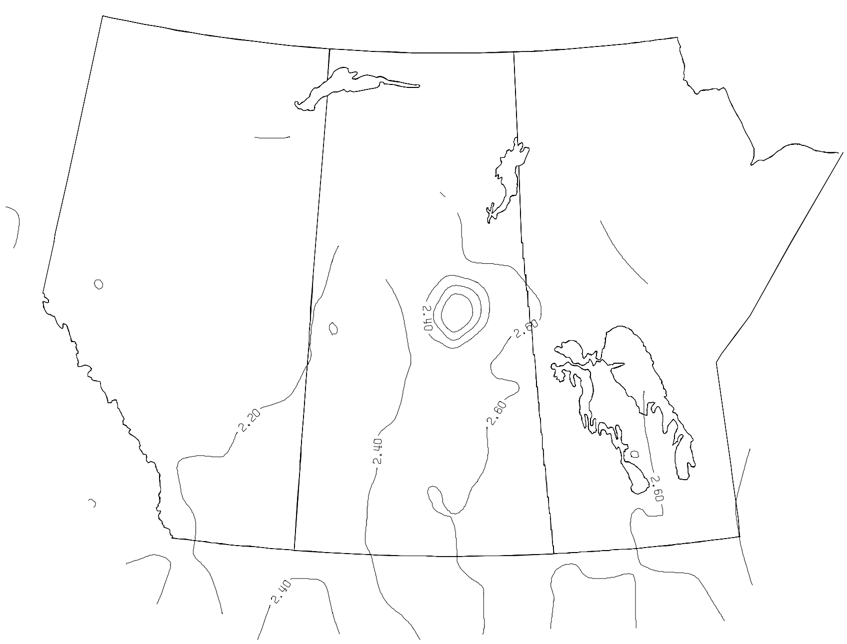


Figure 4:  Average historic maximum temperature (°C) for the period a) December to February and b) July to August.

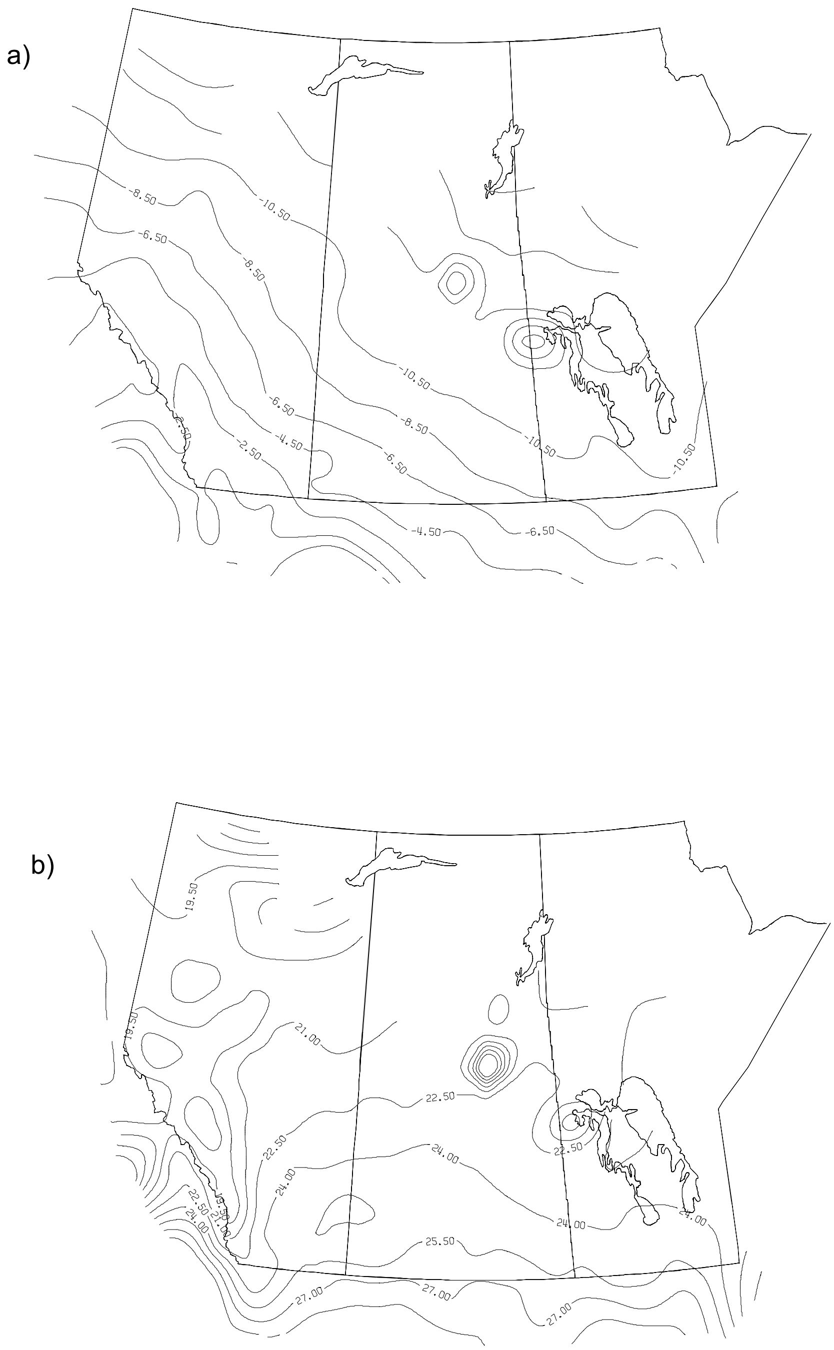
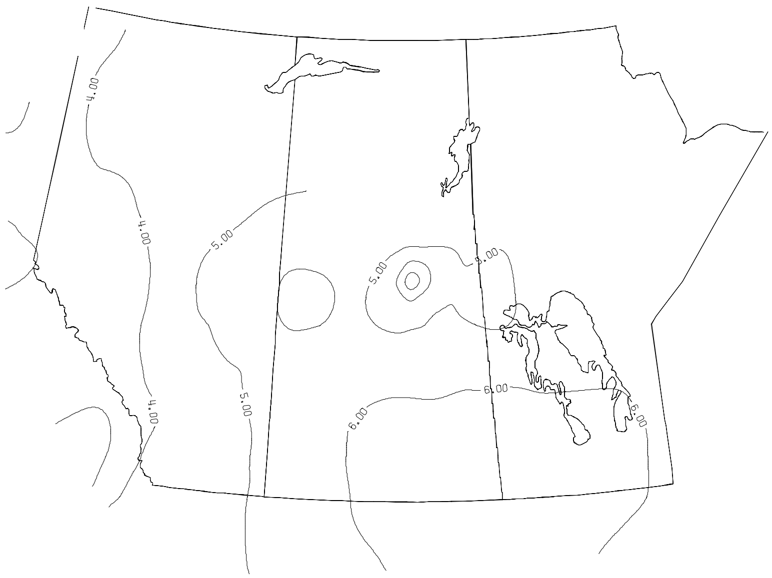


Figure 5: Difference between GCMII and historic values for maximum temperature (°C) for the period a) December to February and b) July to August.

a)




b)

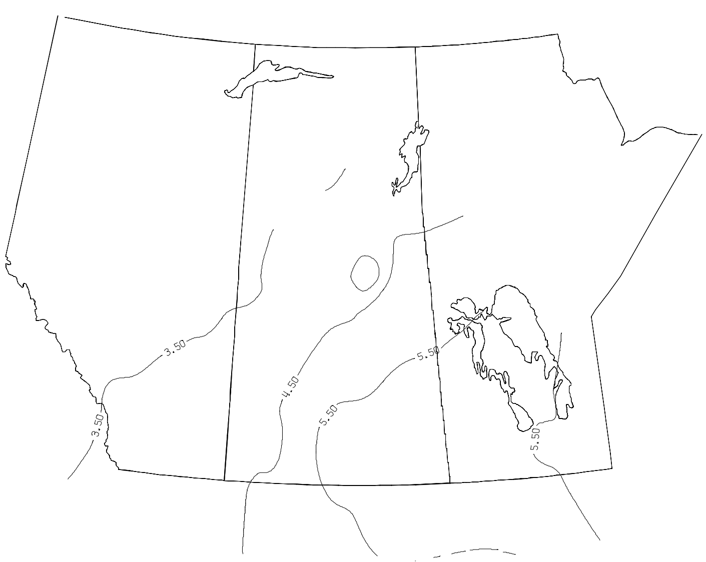


Figure 6: Difference between CGCMI-A and historic values for maximum temperature (°C) for the period a) December to February and b) July to August.

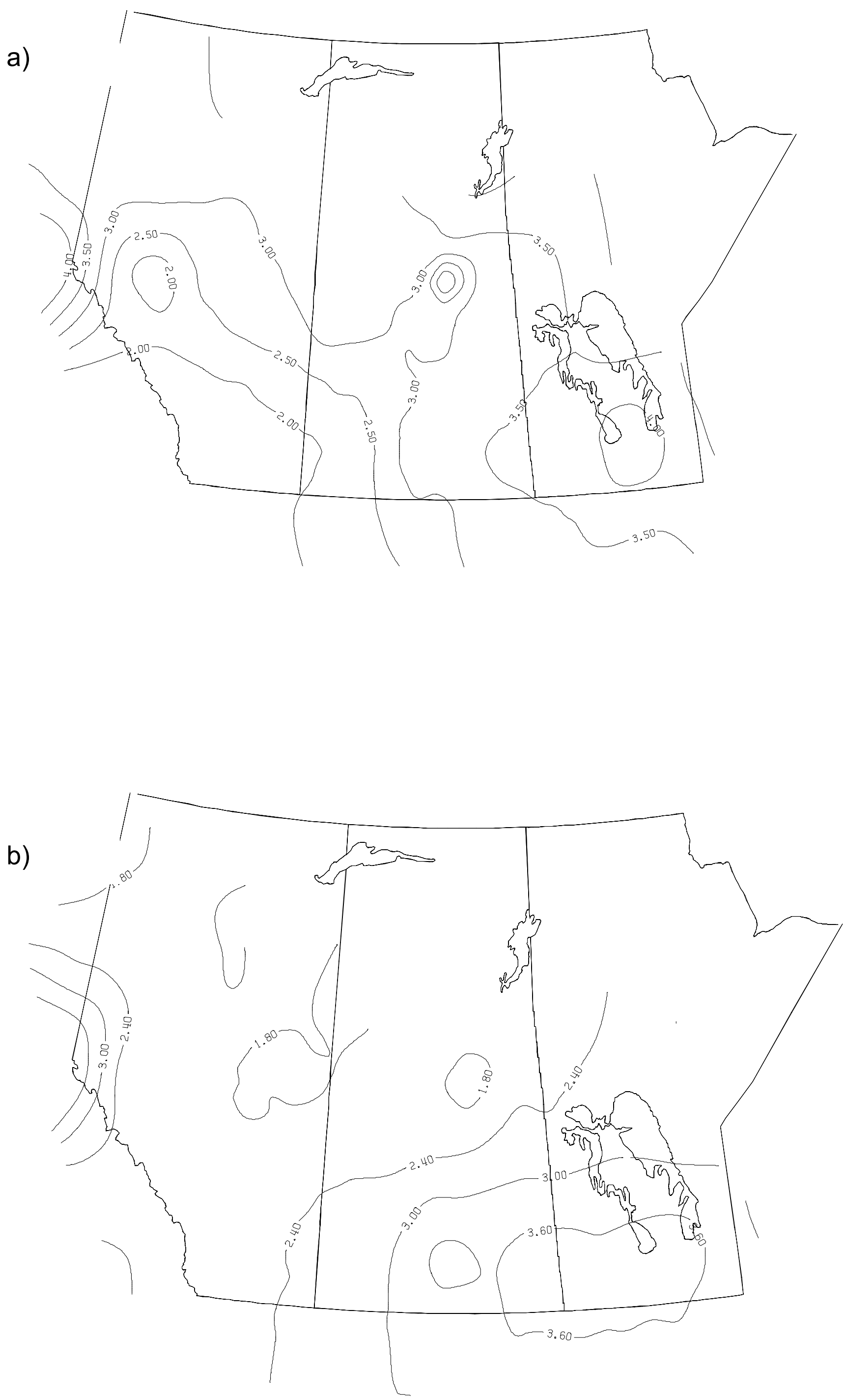
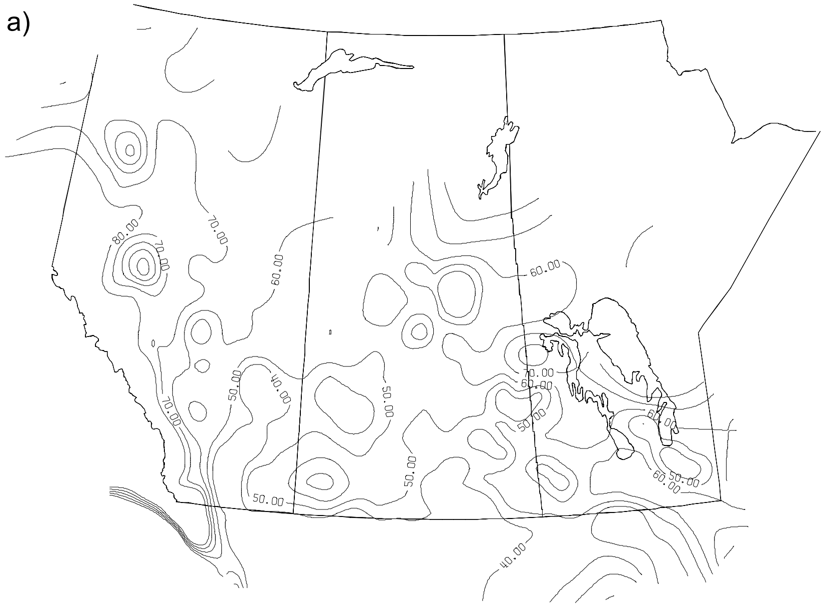


Figure 7: Average historic precipitation (mm) for the period a) December to February and b) July to August.

a)




b)

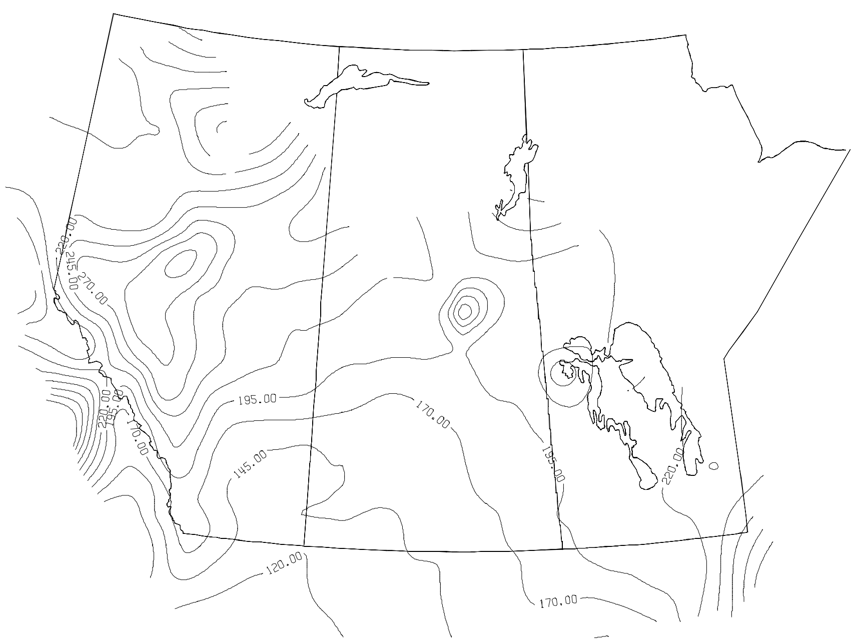
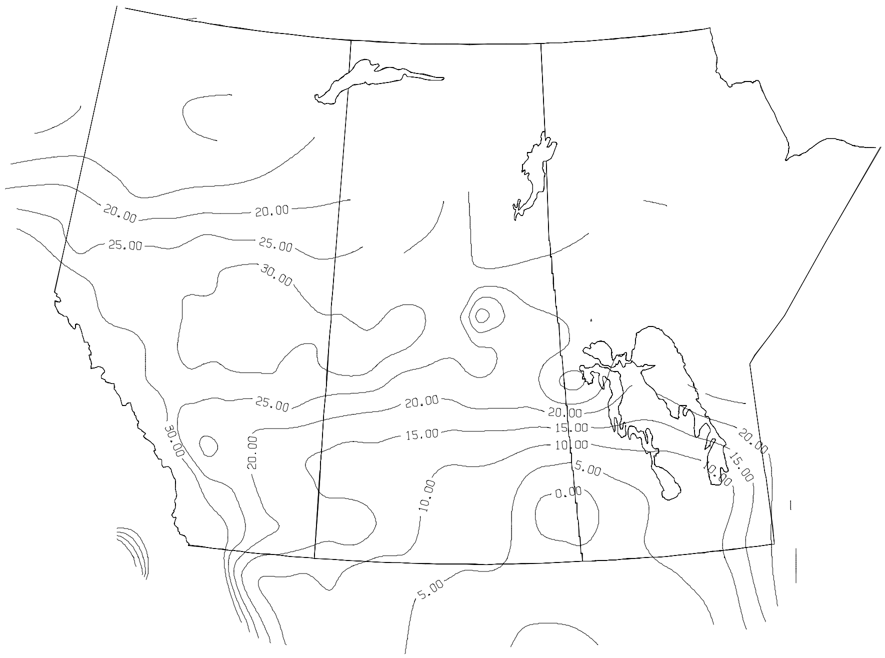


Figure 8: Difference between GCMII and historic values for precipitation (mm) for the period a) December to February and b) July to August.

a)




b)

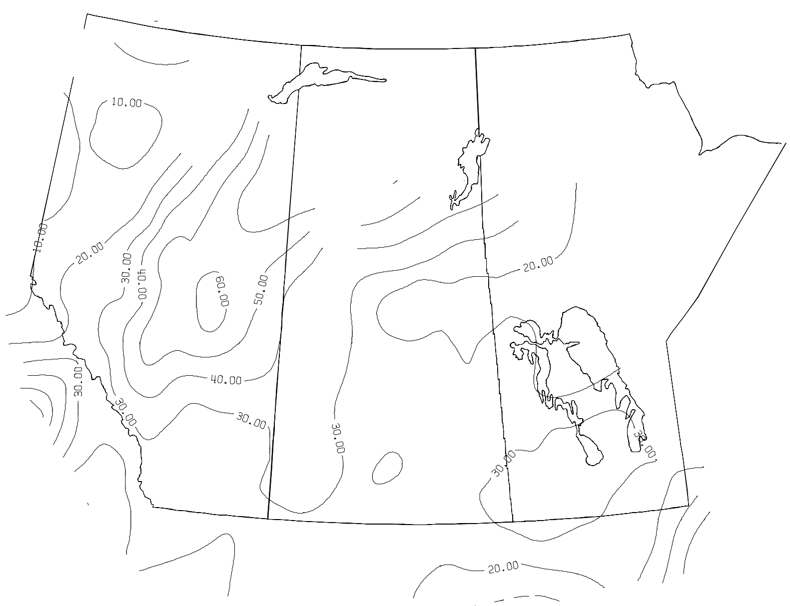
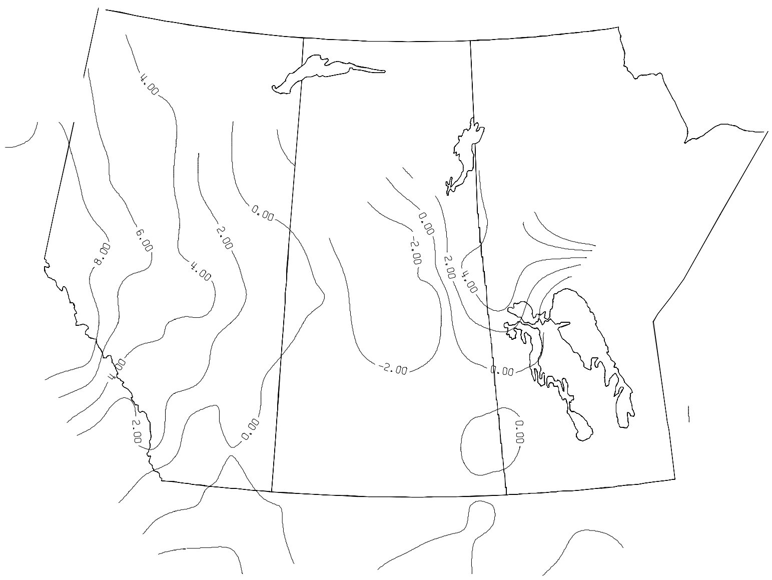


Figure 9: Difference between CGCMI-A and historic values for precipitation (mm) for the period a) December and February and b) July to August.

a)




b)