Assessment of Climate Change on the Canadian Prairies from Downscaled GCM Data

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Assessment of Climate Change on the Canadian Prairies from Downscaled GCM Data

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ABSTRACT *Climate data were taken from the Canadian Centre for Climate Modelling and Analysis (CCCma) Second Generation Global Circulation Model (GCMII) and the more recently developed Canadian Coupled Global Circulation Model with aerosol (CGCM1-A). The GCM output difference for a current and doubling CO_2 concentration was used to modify a 30-year historic time series. Regional climate change data under a doubling of CO_2 were produced by downscaling to a grid of 50 by 50 km across Alberta, Saskatchewan and Manitoba. Two scenarios were produced containing GCM-generated temperatures and precipitation. Results show that, across all three provinces, maximum air temperature is predicted to have a mean increase of 4.0° to 5.7°C (GCMII) and 2.5° to 3.3°C (CGCM1-A) above climate normal values. Minimum air temperature is expected to have a mean increase of 5.0° to 5.6°C (GCMII) and 3.0° to 3.3°C (CGCM1-A). Precipitation is predicted to have a mean increase of 29 to 36% (GCMII) and 3 to 7% (CGCM1-A). Both the GCMII and CGCM1-A indicate that central Alberta will benefit the most during the summer and winter from increased precipitation, the eastern Prairies, however, will see little change (winter) in precipitation with smaller increases (30 mm under GCMII) or a decrease (30 mm under CGCM1-A). Overall, the CGCM1-A results are more consistent than GCMII with historic large-scale spatial patterns.*

RÉSUMÉ *[traduit par la rédaction] On a utiliséles données climatiques provenant du modèle de circulation générale de deuxième génération (GCMII) du Centre canadien de modélisation et d'analyse climatiques (CCMAC) et du modèle de circulation générale couplé canadien avec aérosol (CGCM1-A) mis au point plus récemment. On a utilisé la différence entre les sorties des GCM avec la concentration de CO_2 courante et avec la concentration double pour modifier une série chronologique historique de 30 ans. Les données des changements climatiques régionaux dans le cas d'une concentration double de CO_2 ont été produites en réduisant l'échelle à 50 par 50 km en Alberta, en Saskatchewan et au Manitoba. Deux scénarios incorporant les données de température et de précipitation issues du MCG ont été produits. Les résultats montrent que, dans les trois provinces, la température maximale de l'air devrait subir une augmentation moyenne entre 4,0 et 5,7 °C (GCMII) et entre 2,5 et 3,3 °C (CGCM1-A) par rapport aux normales climatiques. La température minimale de l'air devrait subir une augmentation moyenne entre 5,0 et 5,6 °C (GCMII) et entre 3,0 et 3,3 °C (CGCM1-A). Les précipitations devraient afficher une augmentation de 29 à 36 % (GCMII) et de 3 à 7 % (CGCM1-A). Le GCMII et le CGCM1-A indiquent tous deux que c'est le centre de l'Alberta qui bénéficiera le plus d'une hausse des précipitations en été et en hiver; l'est des Prairies, toutefois, verra peu de changement dans les précipitations (hiver), avec de plus petites augmentations (30 mm selon le GCMII) ou une diminution (30 mm selon le CGCM1-A). Dans l'ensemble, les résultats du CGCM1-A correspondent mieux aux configurations spatiales historiques à grande échelle que ceux du GCMII.*

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 any given year. Over the years agriculture production systems have evolved to minimize the constraints imposed by weather and climate. Examples of these in Canada include the reduction of summer heat units at higher latitudes that define the boundairies for corn production or the use of summer fallow in the semi-arid Prairies in response to marginal rainfall. With the possibility that North America could warm by 1° to 3°C (low emission scenarios) or by 3.5° to 7.5°C (high emission scenarios) by 2100 (IPCC, 2001), insights into regional climate change and its impact on regional sustainability of agriculture are needed. In Canada, understanding climate change for the prairie region is important because it is a grain producing region for the global community (Parry, 1990). However, drought is a common occurence in the prairie provinces, which occurs most years in some regions (Jones, 1991). Stewart (1986) noted that high latitude countries will bear the brunt of climate warming, and that the

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climate for agriculture in Canada is marginal at best. It follows that minor changes in climate could have large consequences on prairie grain production, spring wheat being the most common crop. The impact of possible climate change scenarios, outlined in our study, on soil moisture on the Canadian Prairies was reported by McGinn and Shepherd (2003).

In recent decades the surge in computing power has provided a greater opportunity for computer models to explain climate systems and predict how they behave. As part of this arsenal of models, global climate models have been developed to understand the changes in the climate system in response to projected increases in atmospheric greenhouse gases. For example, the change in December to February climate for a northern hemisphere, middle latitude location simulated by the global circulation model (GCM) second generation model (GCMII) predicted a reduction in equator-to-pole and ocean-to-land temperature gradients resulting in generally more temperate conditions (Boer, 1995).

First generation models were simplified to represent atmospheric processes but had only basic links with ocean processes, an important source of global heat transport. Processes concerning the water cycle and cloud effects were simplified and the spatial resolution was very coarse, about 800 km. By the 1980s improved computing power made the second generation of GCMs possible. These models possess increased spatial resolution and simulated interactions between ocean and atmosphere were also improved although a simplified ocean model still existed. These models simulate equilibrium climate change, that is, the stabilization of the system after a step change in greenhouse gas concentration. The GCMII features diurnal and annual solar cycles, a representation of surface geography and surface processes, cloud feedback effects and simple considerations of oceans and sea ice. The model has a spatial resolution of 400 km. The topography in the climate of the western Canadian prairies is very simple and the details of the rain shadow area of the Rockies in Alberta cannot be simulated (Saunders and Byrne, 1994).

By the 1990s third generation models were built with GCMs linked to ocean models which represented three-dimensional ocean processes. These models simulate transient climate change, that is, the behaviour of the climate system as it is adapting to an increase in greenhouse gas concentration year by year. In our study the third generation model version, Canadian Coupled Global Circulation Model with Aerosol (CGCM1-A**),** used consists of four main components (Hengeveld, 2000):

- atmospheric component with a spatial resolution of 400 km and 10 vertical levels,
- oceanic component with large-scale features of ocean circulation and water properties,
- thermodynamic sea-ice component which simulates ice growth and melt, and
- land surface component for calculating runoff and soil moisture resulting from a water balance incorporating precipitation, evaporation and the water holding capacity of the soil.

Initially, the atmospheric component is run until it reaches equilibrium and then simulates a 20-year record so that the flux of energy and water between ocean and atmosphere can be calculated. These data are used to initiate the ocean model which is run for 4500 years at which time equilibrium is reached. At this point the models are coupled and run for 80 years to stabilize interactions and generate climate change scenarios.

The limitation of a model like CGCM1-A is that the errors in the modelled flow of heat and moisture can cause the model to drift with time. The Canadian Centre for Climate Modelling and Analysis (CCCma), when running CGCM1-A, makes flux adjustments by regulating the flow of heat and water between ocean and atmosphere to combat the drift.

Hengeveld (2000) compared other global climate models with CGCM1-A and downscaled some results for southern Alberta. All show a temperature increase for the period 2040–60, i.e., timeline projection for a doubling of greenhouse gases. CGCM1-A predicts a 2°C increase, in the same range (1.4° to 2.2°C) as the increase predicted by the UK Hadley Centre, American Geophysical Fluid Dynamics Laboratory (GFDL) and the Australian Commonwealth Scientific and Industrial Research Organization (CSIRO) models. On a regional level, Hengeveld (2000) observed that there was good agreement between modelled projections of summer temperature in southern Alberta. CGCM1-A and the Hadley model predicted mean winter temperatures to be 2°C lower than the CSIRO and GFDL models. Summer precipitation change in southern Alberta was predicted, by CGCM1-A, to become slightly less than the historic value (Hengeveld's reference period of 1975–95), while the CSIRO model predicted a slight increase. CGCM1-A predicted that mean winter precipitation would remain the same while the Hadley model predicted an increase. Overall, the results closest to CGCM1-A were those of the Hadley model. Regional results must be used with caution and several scenarios from more than one model must be used when assessing the effects of climate change. Nevertheless, Hengeveld (2000) reported that CGCM1-A has accurately reproduced global climate since 1900, suggesting that predictions for the 21st century are realistic.

Downscaling GCM data to a regional scale was reported by Laprise et al. (1998) who worked with the Canadian Regional Climate Model (CRCM) data. Laprise et al. (1998) attributed differences in results from GCMII and the regional climate model (45-km resolution) to a number of factors including a simplified land surface in the GCM, excessive ground water and little seasonal change in groundwater, plus the radiative balance in the models.

The use of climate scenario data to drive agronomic models is common when assessing the potential impact on agriculture. However, the spatial and temporal resolution of these data need to be sufficiently sensitive to changes in agronomic factors. The second (GCMII) and third (CGCM1-A) generation GCMs consisted of 23 grid locations distributed across the Canadian Prairies (a 3.71° by 3.75° grid). This scale for weather data is too coarse relative to other agronomic variables (i.e., soil types and topography). A more reasonable scale is 50 km which still reflects large-scale GCM output locations yet is also sensitive to major soil and topography features of the landscape. Work on developing a fine resolution climate database was 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, on the order of 50 by 50 km intervals, to allow the comparison of output with agriculture models. Our objective was to produce two climate change datasets based on CGCM1-A and GCMII for Alberta, Saskatchewan and Manitoba scaled to agricultural needs and compare these to historic baseline data at this same scale.

2 Materials and methods

Maximum and minimum air temperature, and precipitation data were obtained at a daily timestep from GCMII and CGCM1-A for 23 grid points across the agricultural regions of Alberta, Saskatchewan and Manitoba (Canada). Each GCM was sampled at a current (1x) and double (2x) atmospheric CO_2 concentration (i.e., a 20-year period in the future corresponding to 2040–60).

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 each GCM's 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 one current climate scenario and two climate change scenarios (GCMII and CGCM1-A). All climate scenarios were scaled to a regional level consisting of 368 points across the agricultural region of the Canadian Prairies at approximately 50 by 50 km grid intervals.

a *Historic 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 station data across the three prairie provinces, British Columbia and the Northwest Territories (Environment Canada archive) were screened for the quality and record length of data. Missing maximum and minimum air temperatures and total precipitation data were estimated as a weighted average of the nearest stations at locations where less than 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 north-west United States were also incorporated into the weather archive. Missing data were estimated 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 and the missing value was estimated (T_e). The actual temperature 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.

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. The interpolated data of air temperature 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 were used. The fine-scaled dataset consisted of 30 years of daily data ending in 1989.

b *GCM Grid Statistics*

For each grid point of the GCMII and CGCM1-A models, the difference in the temperature means (ΔT) and ratio of precipitation means (ΔP) were calculated from their respective 1x and 2x CO_2 GCM data, for the years 1960–89 and 2040–60, respectively. The difference in temperature means between 1x and 2x CO_2 was calculated daily and the 30-year average taken, the ratio of precipitation means was calculated monthly and the 30-year average taken.

$$\Delta T = \overline{T}_{2x} - \overline{T}_{1x} \quad (1)$$

$$\Delta P = \overline{P}_{2x} / \overline{P}_{1x}. \quad (2)$$

In addition, the ratio of the variance (δ) for temperature and precipitation at each grid point was calculated for each month as the ratio variances of 2x CO_2 to 1x CO_2 data.

c *Downscaling GCM Statistics*

The Δ values (Eqs (1) and (2)) and δ derived from GCM data, and the GCM daily maximum and minimum air temperatures and the total precipitation amounts were downscaled to match the historic climate data locations. This was accomplished by weighting each neighbouring value by the separation distance (inverse-distance-squared method; McGinn et al., 1999). For example, to calculate the temperature at grid point x (T_x), the nearest seven GCM grid point temperatures were divided by their respective distances squared and the sum taken. In a similar fashion, the precipitation at each grid point (P_x) was also determined.

d *Generating Climate Change Scenarios*

The climate change scenarios were created by imposing change from the GCM statistics (δ, Δ, 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:

$$T_{new} = [\overline{T} + \sqrt{\delta}\,(T - \overline{T})] + \Delta T \quad (3)$$

where $\overline{T}$ is the mean daily temperature obtained from a 30-year normal record, T is the historic temperature for the day in question and ΔT is the difference in temperature means between the 2x and 1x CO_2 temperature. Only the variance ratio (δ) was based on a monthly time step, with the value for a month applied to all days in that month. The discontinuity caused by the monthly variance ratios is minimal compared to the daily variance in temperature.

The precipitation data used in generating the climate change scenario were first transformed using a natural logarithm due to the skewed nature of precipitation data. The log-transformed monthly precipitation χ^* was calculated in a similar way to Eq. (3) as:

$$\chi^* = [\,\overline{\chi} + \sqrt{\delta}\,(\chi - \overline{\chi})\,] \qquad (4)$$

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

$$P^* = \exp(\chi^*) \cdot \Delta P. \qquad (5)$$

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):

$$P_{new} = P_d\,(P^*/P_m). \qquad (6)$$

Equations (4) to (6) change the amount of monthly precipitation but not the frequency of monthly precipitation.

The sensitivity of the variance ratios was tested on temperature and precipitation using variances ratios of 0.5, 1.0, 2.0 and the variance ratio δ from the GCM. Very little difference was observed in the resulting test grid temperature and precipitation values indicating that the step change due to CO_2 doubling predominated. For example, Fig. 1 shows the effects on CGCM1-A maximum temperature when changing variance for a single grid point in southern Alberta. As a result, the variance ratio from the GCM (close to unity, hence results from each superimpose) was used in generating all climate change scenarios.

3 Results and discussion

All GCM scenarios referred to are for a doubling of CO_2.

a *Minimum Air Temperature*

Annual historic values of minimum air temperature (T_{mn}) averaged between –4.0° (Alberta) to –4.2°C (Saskatchewan and Manitoba) (Table 1a). However, the Canadian Prairies experienced considerable seasonal variability in air temperature. For T_{mn}, the average summer temperature was about 28°C higher than that in winter. During winter across the Prairies, a well-defined gradient existed in T_{mn}, extending from a high of around –14.5°C in southern Alberta and decreasing to the east and north to less than0 –20.5°C (Fig. 2a). This pattern reflects both a latitudinal effect and the effect of a cold continental air mass in winter. The pattern of T_{mn} over the Prairies during summer was less distinct, although an elevation effect of cooler air to the west was evident (Fig. 2b). In summer, the highest T_{mn} (>10.5°C) existed just north of the Canada–US border, in south-eastern Saskatchewan and southern Manitoba. The higher winter minimum temperature in southern Alberta coincides with a region known for the frequency of warm Chinook winds, which have a moderating effect on the average winter temperature.

The GCMII scenario for the winter period projected a T_{mn} pattern with a similar south-west (–4°C) to north-east (–12°C) gradient across the Prairies as existed historically. The greatest warming in T_{mn} in winter (Fig. 3a) was found in southern Saskatchewan (increases of about 9°C). The warming decreased concentrically with distance from this region, where warming of between 7° and 7.5°C was projected in the northern prairie region. During the summer months (Fig. 3b), the changes simulated by GCMII are much less than in winter, where T_{mn} increased by 4.6°C in south-eastern Saskatchewan and south-western 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.

For the CGCM1-A scenario, T_{mn} increased more in the winter (4.0°C) than in summer (2.4°C) relative to the historic T_{mn}. In winter (Fig. 4a), the greatest increase in T_{mn} over the historic values was found in southern Manitoba and south-eastern Saskatchewan, which warmed by approximately 5.2°C. The smallest increase in T_{mn} was found in Alberta, which warmed by between 3.8° and 4.5°C. In summer (Fig. 4b), there was also an east–west gradient in the magnitude of warming where T_{mn} in the eastern Prairie was projected to increase by 2.6°C while in the west the increase was 2.2°C.

b *Maximum Air Temperature*

The mean historical maximum air temperature (T_{mx}) for the agricultural regions of Alberta, Saskatchewan and Manitoba throughout the year was 8.4°, 8.3° and 7.6°C, respectively (Table 1b). The seasonal effect results in T_{mx} values that were 22°C higher in summer than in winter over most of the Prairies. In winter, T_{mx} decreased from about –2.5°C in south-western Alberta to less than –10.5°C as depicted by the isotherm (Fig. 5a) 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, plus the effect of the Chinook winds along the east slope of the mountains. In summer, the southern Canadian Prairies experienced T_{mx} values in the order of 25.5°C, which decreased concentrically to the east, north (latitude effect) and west (elevation effect) (Fig. 5b). Low values of 19.5°C were found in the northern agricultural region of Alberta.

In comparison to the historic values, the annual GCMII T_{mx} increased across Alberta, Saskatchewan and Manitoba by 4.0°, 5.2° and 5.7°C, respectively (Table 1b). In the summer T_{mx} displayed a more irregular pattern with isolated cooler spots

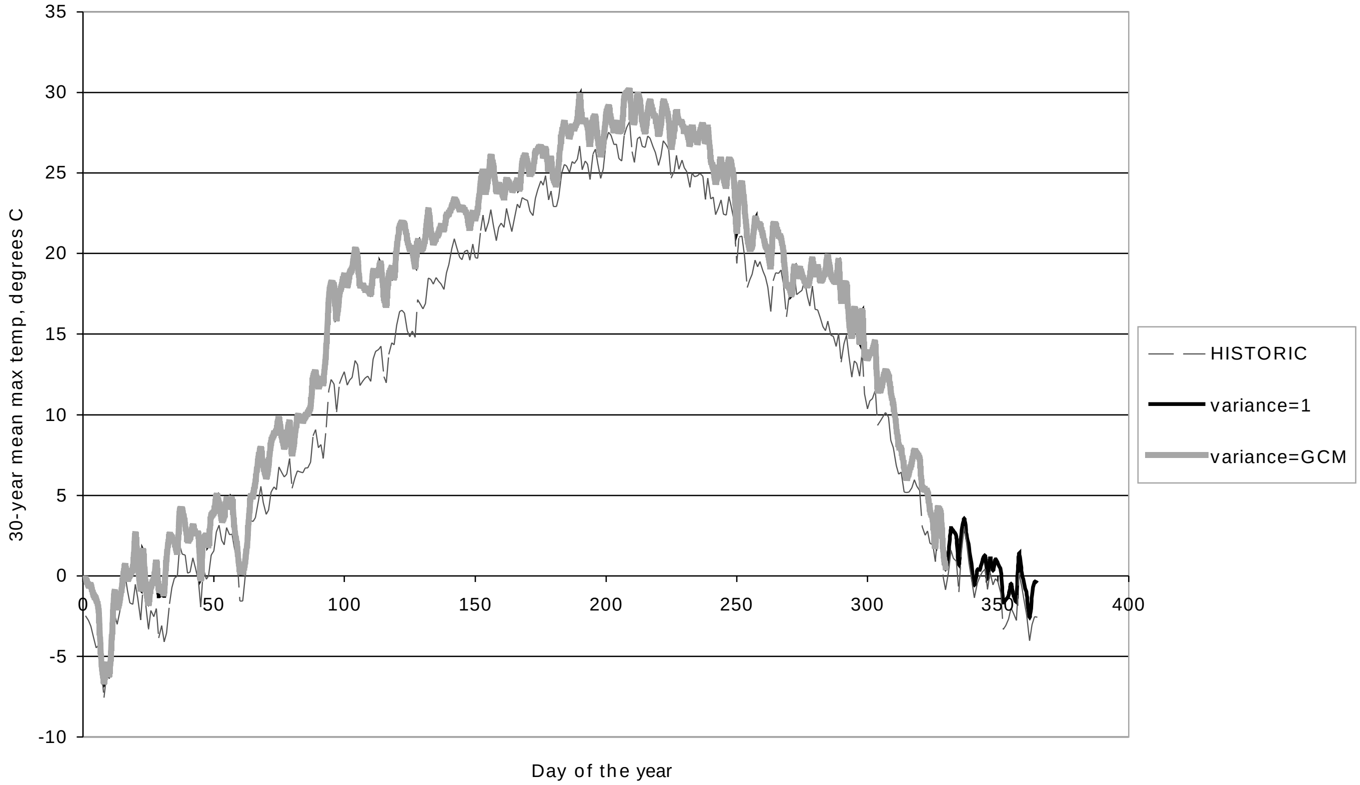


Fig. 1 Climate change scenarios from CGCM1-A, 30-yr. mean maximum temperature, for a single gridpoint, variance = 1, GCM and historic (note: GCM and 1 overlay).

TABLE 1. (a) Averaged annual minimum air temperature for the climate scenarios across the three prairie provinces of Canada. Bracketed values are the differences (°C) between historic and climate change values. (b) Averaged annual maximum air temperature for the climate scenarios across the three prairie provinces of Canada.

(a)	Minimum Air Temperature (°C)		
Scenario	Alberta	Saskatchewan	Manitoba
Historic	–4.0	–4.2	–4.2
GCMII	1.0 (5.0)	1.4 (5.6)	1.2 (5.4)
CGCM1-A	–1.0 (3.0)	–1.0 (3.2)	–0.9 (3.3)

(b)	Maximum Air Temperature (°C)		
Scenario	Alberta	Saskatchewan	Manitoba
Historic	8.4	8.3	7.6
GCMII	12.4 (4.0)	13.5 (5.2)	13.3 (5.7)
CGCM1-A	10.9 (2.5)	11.2 (2.9)	10.9 (3.3)

along the Alberta–Saskatchewan border. Winter predictions of T_{mx} are more evenly distributed, displaying the same south-west–north-east gradient pattern as found in the historic data. The GCMII predictions show the greatest increase in T_{mx} in southern Manitoba (5.5°C increase in summer, 6.0°C increase in winter; Fig. 6). In both the summer and winter, GCMII predicted that the temperature increase would be smaller in the west, between 3.5° and 4.0°C, respectively.

CGCM1-A predictions indicated a smaller increase in T_{mx} compared to GCMII values. Averaged over the year, T_{mx} increased by 2.5°, 2.9° and 3.3°C across Alberta, Saskatchewan and Manitoba, respectively (Table 1b). Not only was the magnitude of change smaller than in GCMII predictions, but the differences between averages across the three provinces were also less (0.8°C versus 1.7°C), i.e., the change in T_{mx} was spatially more uniform for CGCM1-A compared to GCMII.

In CGCM1-A, the greatest increases in T_{mx} were 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 was centred on southern Manitoba (Fig. 7). The region showing the smallest increase in T_{mx} in winter was south-western Alberta (2°C) and in summer central Alberta and central Saskatchewan (1.8°C). Overall, both climate change scenarios indicated that T_{mx} will increase the most in southern Saskatchewan and Manitoba. The increase was greater for GCMII compared to CGCM1-A in both winter and summer.

c *Comparison between Models*

The CRCM of Laprise et al. (1998) uses GCMII for the initial input values and then has a separate atmospheric model to downscale to a fine grid. However, our method of downscaling does not change the GCM atmospheric processes, but downscales statistics describing the change of GCM from a 1x CO_2 regime to a 2x CO_2 regime. These statistics are then applied to historical data to generate downscaled climate change data. We cannot compare our model directly to the CRCM, however, we can compare the results of the different downscaled GCMII scenarios.

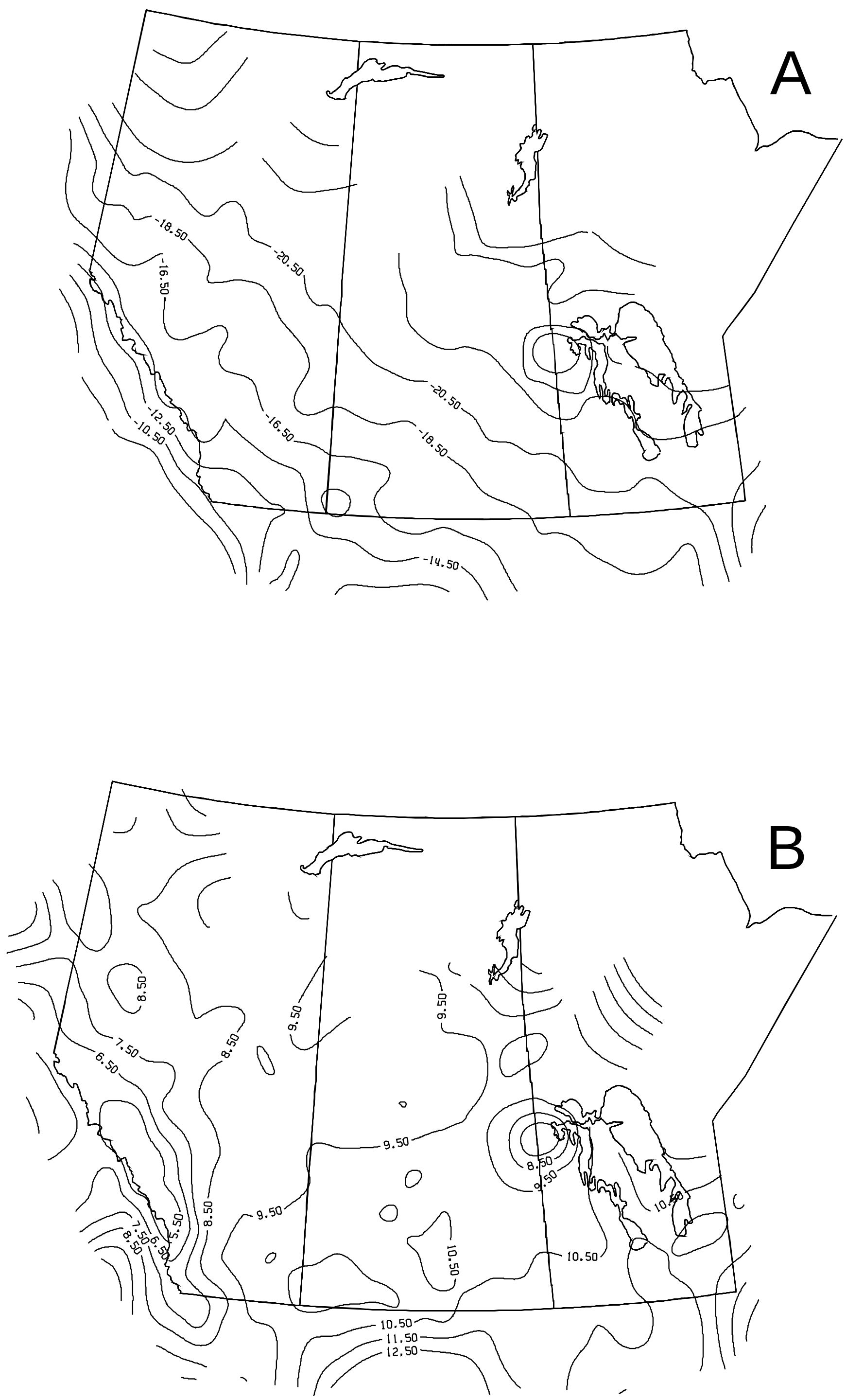


Fig. 2 Average historic minimum temperature (°C) for the periods a) December to February and b) July to August.

In our study, the change in T_{mn} in winter between historic values and a doubling of CO_2 ranged from an increase of 7.0° to 9.0°C . This appears to be consistent with Laprise et al.'s assessment of the winter increase in T_{mn} using non-downscaled data from GCMII. The CRCM simulates a similar spatial pattern of change with temperatures that are a degree or two lower than our results. The change in summer T_{mn} was smaller than that in winter, calculated to be 4.0° to 4.6°C. Laprise et al. (1998) reported a change of about 4.0°C, increasing towards Manitoba. In comparison, our results for the downscaled CGCM1-A show a greater warming in winter than summer where the winter warming is about 4°C less than GCMII, and the summer warming is about 2°C less.

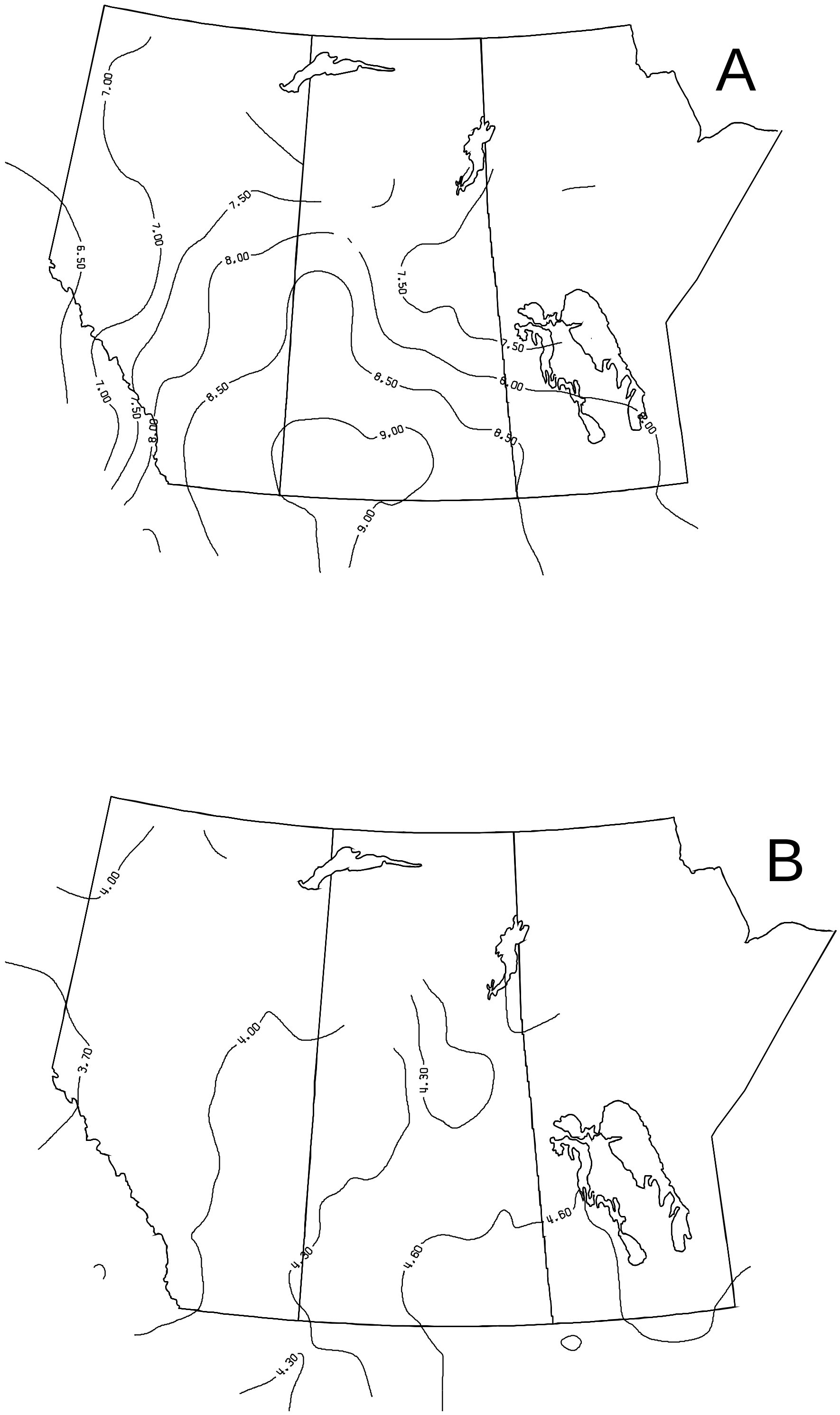


Fig. 3 Difference between GCMII and historic values for minimum temperature (°C) for the periods a) December to February and b) July to August.

Our downscaled GCMII data show an increase in winter T_{mx} of 4.0° to 6.0°C over historic values due to a doubling of CO_2 . In comparison Laprise et al.'s GCMII and CRCM values are another 2°C higher in the eastern Prairies; better agreement between data exists in Alberta. The resulting summer increase in T_{mx} of 3.5° to 5.5°C from our downscaling technique agrees with GCMII and CRCM results from Laprise et al. (1998). In comparison, our results from CGCM1-A show winter increases in T_{mx} of 2° to 2.5°C less than our downscaled GCMII increases, and summer increases 2°C less than our downscaled GCMII increases.

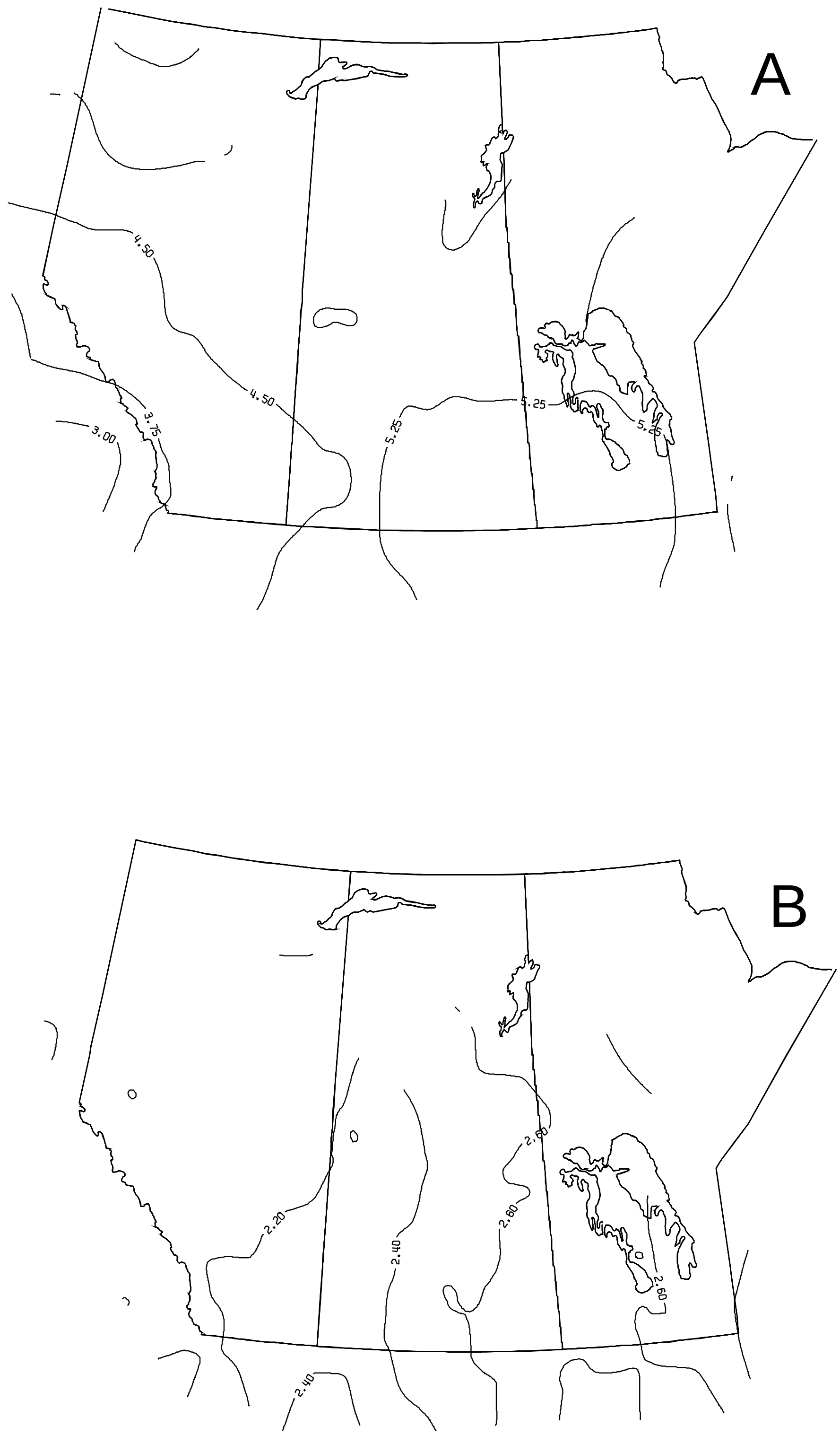


Fig. 4 Difference between CGCM1-A and historic values for minimum temperature (°C) for the periods a) December to February and b) July to August.

The increases in temperature and the spatial patterns of those increases under a doubling of CO_2 predicted by our method of downscaling for GCMII are very similar to those of Laprise et al. (1998) for non-downscaled GCMII in particular, and also for CRCM. Laprise et al. found maxima of warming generally over southern Saskatchewan and Manitoba, as well as over the Mackenzie river basin. Although the Mackenzie basin is outside our area of study, our results agree with the maxima of warming over southern Saskatchewan and Manitoba.

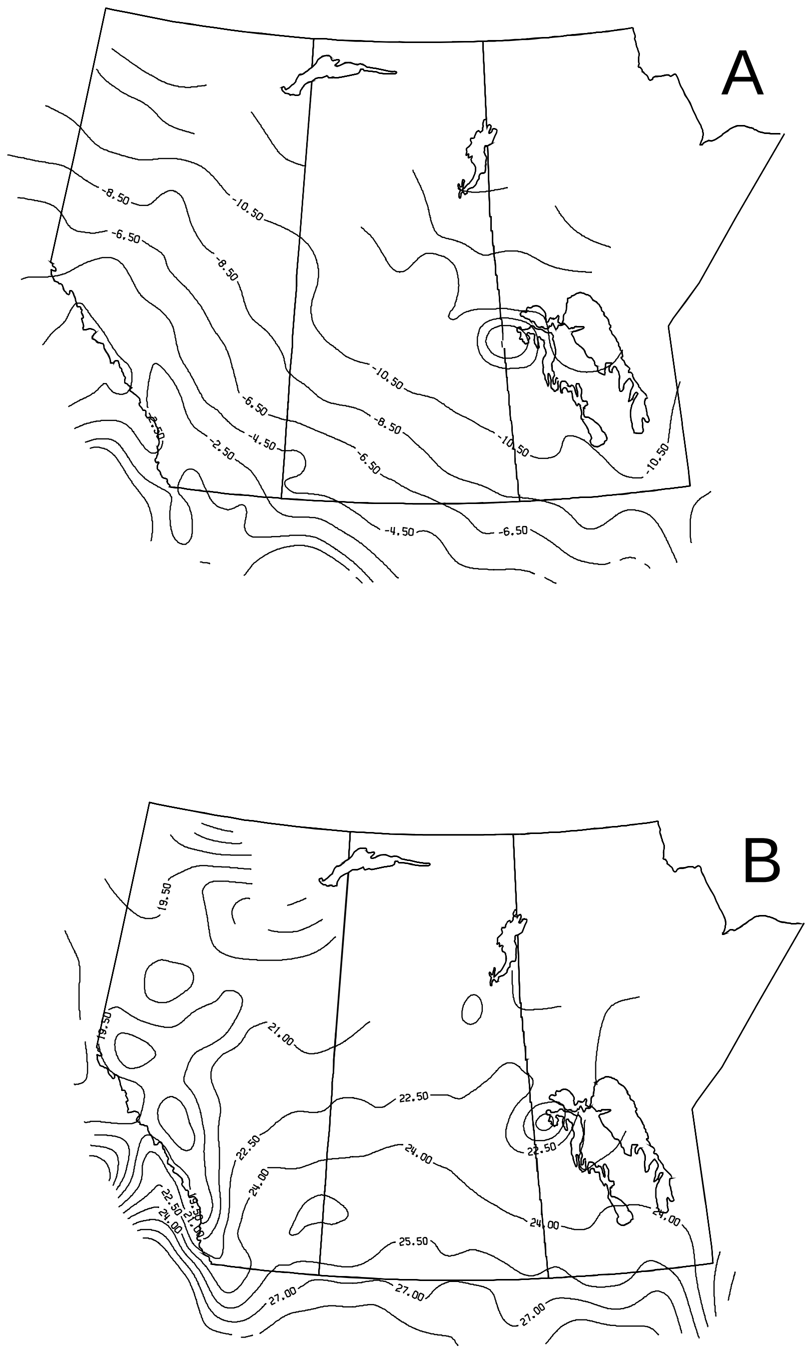
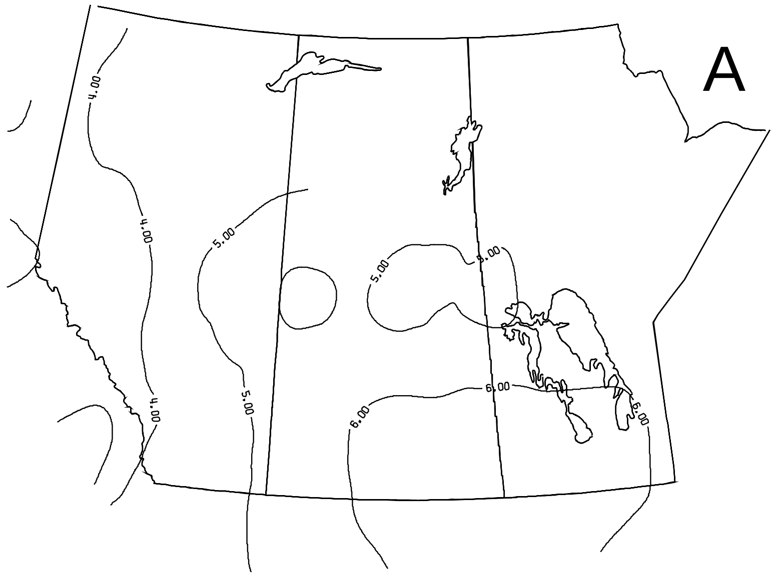


Fig. 5 Average historic maximum temperature (°C) for the periods a) December to February and b) July to August.

CRCM values for temperature differ from those generated using the same GCM coarse data. The differences may arise from the fact that our data are statistically downscaled and only reflect the environmental processes simulated in GCMII, whereas the CRCM contains simulations in addition to GCMII. A characteristic affecting global climate models is cloud cover which affects surface temperatures. The presence of more clouds in the CRCM can decrease long-wave radiation loss from the surface and increase surface temperatures. This process, in part, contributes to differences between the CRCM and our downscaled GCMII data.

Temperature is also affected by atmospheric aerosols. The effect of increasing aerosols is to increase reflection of the incoming solar radiation. This is simulated by altering the surface albedo based on the aerosol distribution, which reduces the surface temperatures (Boer, 2000). Sulphate aerosols are the most abundant and are incorporated in the CGCM1-A model distributed around sources of industrial activity due to



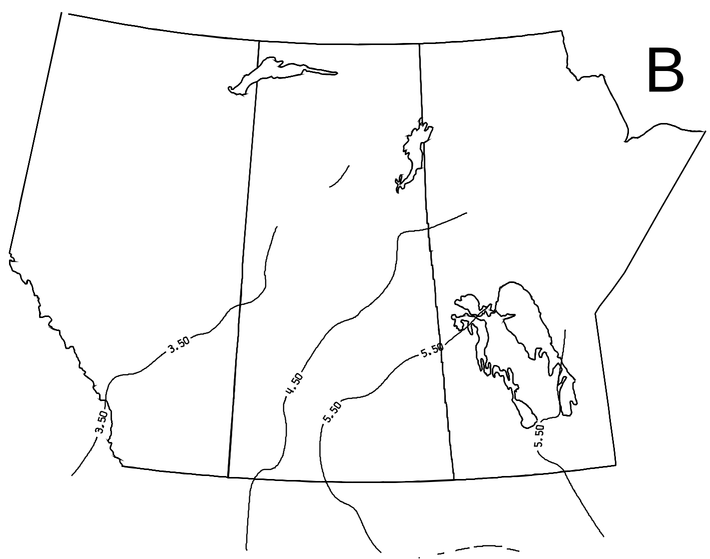


Fig. 6 Difference between GCMII and historic values for maximum temperature (°C) for the periods a) December to February and b) July to August.

their relatively short lifetime. Aerosol forcing generally decreases temperatures in CGCM1-A compared to GCMII which has no aerosol component.

d *Precipitation Amount*

Historically, the agricultural regions of Manitoba receive slightly more precipitation on average (486 mm) compared to those in Alberta (482 mm) (Table 2). The agricultural regions of Saskatchewan received the least amount of precipitation (395 mm). The pattern of winter precipitation (Fig. 8a) indicates that the southern corridor of Alberta and central Saskatchewan received 40 mm or less. The southern border of Alberta and Saskatchewan (around Cypress Hills) received more precipitation, and this is speculated to be an

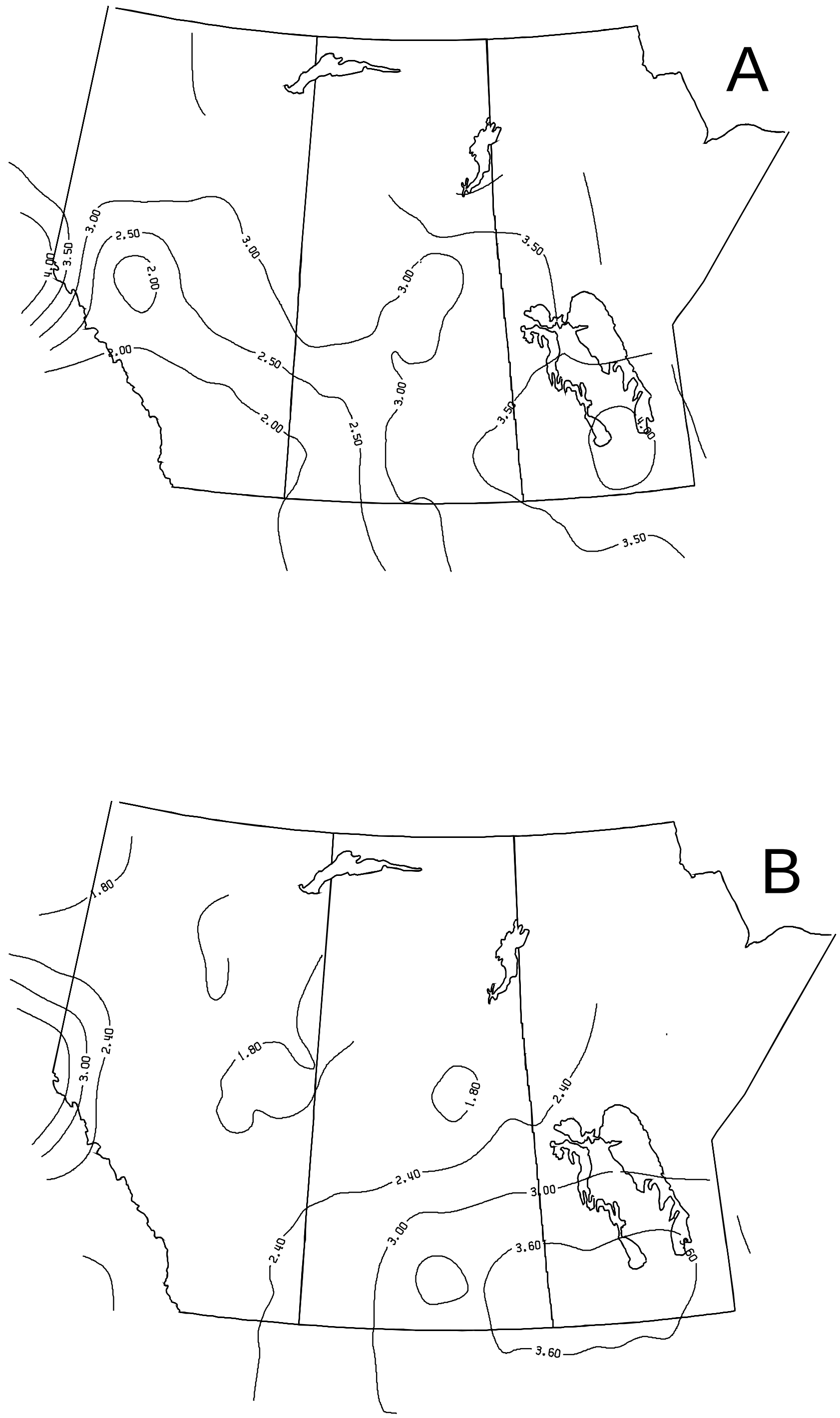


Fig. 7 Difference between CGCM1-A and historic values for maximum temperature (°C) for the periods a) December to February and b) July to August.

elevation effect. The greatest winter precipitation, greater than 60 mm, was found north of central Alberta and along the Foothills, as well as in Manitoba. In summer, between 120 and 145 mm fell in south-eastern Alberta and south-western Saskatchewan (Fig. 8b). There was a concentric pattern where summer precipitation increased to the west (foothills), north and east. The maximum average precipitation occured

TABLE 2. Averaged annual precipitation for the climate scenarios across the three prairie provinces of Canada. Bracketed values are the differences (%) between historic and climate change values.

	Precipitation (mm)		
Scenario	Alberta	Saskatchewan	Manitoba
Historic	482	395	486
GCMII	622 (29%)	514 (30%)	663 (36%)
CGCM1-A	518 (7%)	405 (3%)	503 (3%)

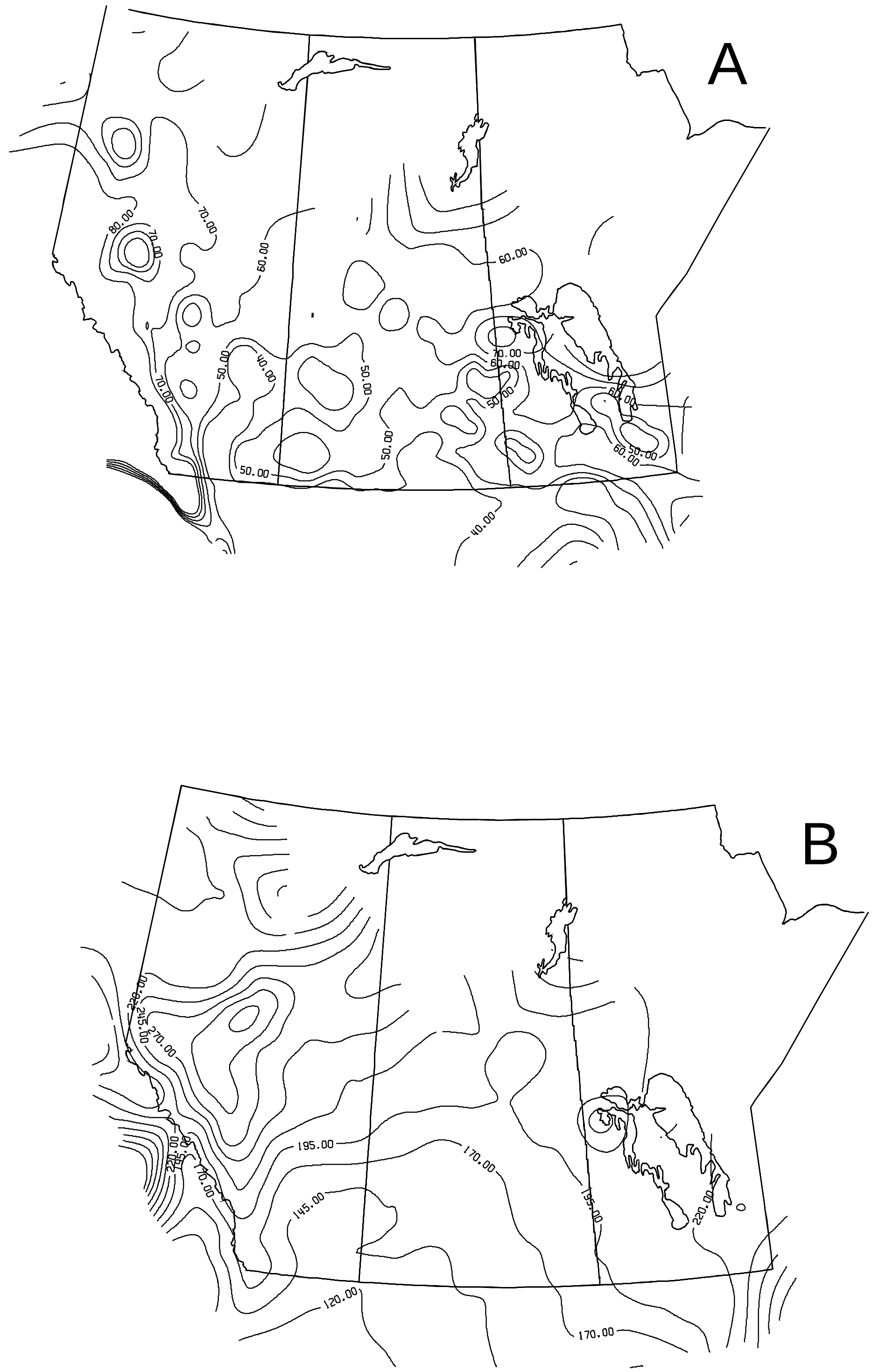


Fig. 8 Average historic precipitation (mm) for the periods a) December to February and b) July to August.

in central-northern Alberta (200 to 300 mm) and in eastern Manitoba (220 mm).

The GCMII scenario predictions indicate precipitation increases of 29 to 30% in Alberta and Saskatchewan, and as much as 36% in Manitoba (Table 2). Precipitation was predicted to increase above historic amounts during the summer (average increase of 40 mm) and winter (average increase of 20 mm) throughout the Prairies. The winter precipitation pattern (Fig. 9a) shows a concentric pattern centred on south-eastern Saskatchewan and south-western Manitoba, from an area of no change, increasing to a change of 30 mm in central Alberta. In summer, GCMII showed increased precipitation

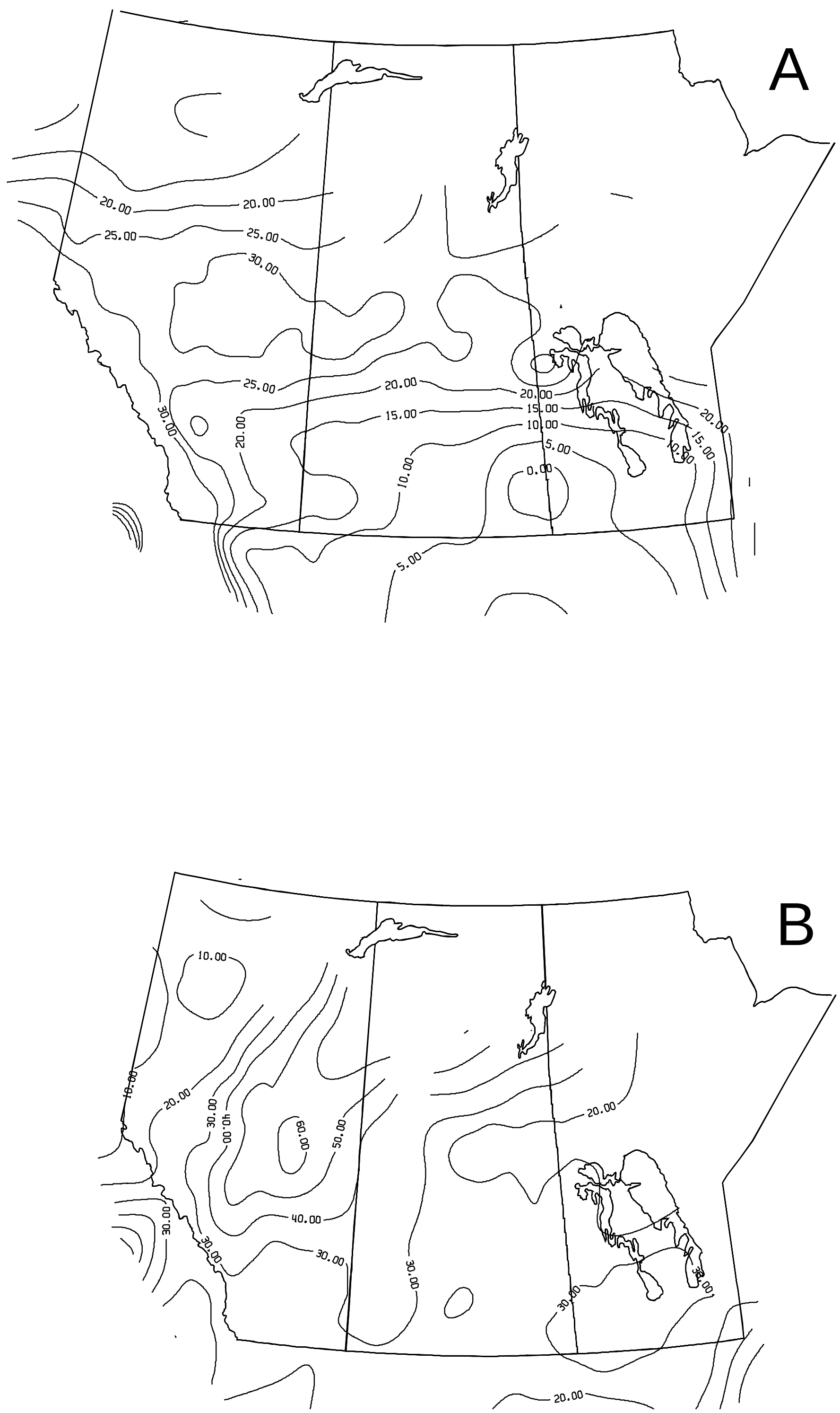


Fig. 9 Difference between GCMII and historic values for precipitation (mm) for the periods a) December to February and b) July to August.

across the Prairies (Fig. 9b) with the greatest increase in central Alberta of 60 mm (24% above historic). The smallest increase was found across Saskatchewan to Manitoba on the order of 30 mm (15% above historic). Stewart (1991), reporting on values for Saskatchewan by the Goddard Institute for Space Studies (GISS) GCM, predicted an increase in precipitation of 5–15% during the growing season. The rainfall pattern during the summer was quite different from that in winter for the GCMII prediction in south-eastern Saskatchewan and southern Manitoba, i.e., a 30-mm increase in summer compared to no change in winter. In central Alberta, GCMII precipitation was predicted to increase from 30 mm in winter to

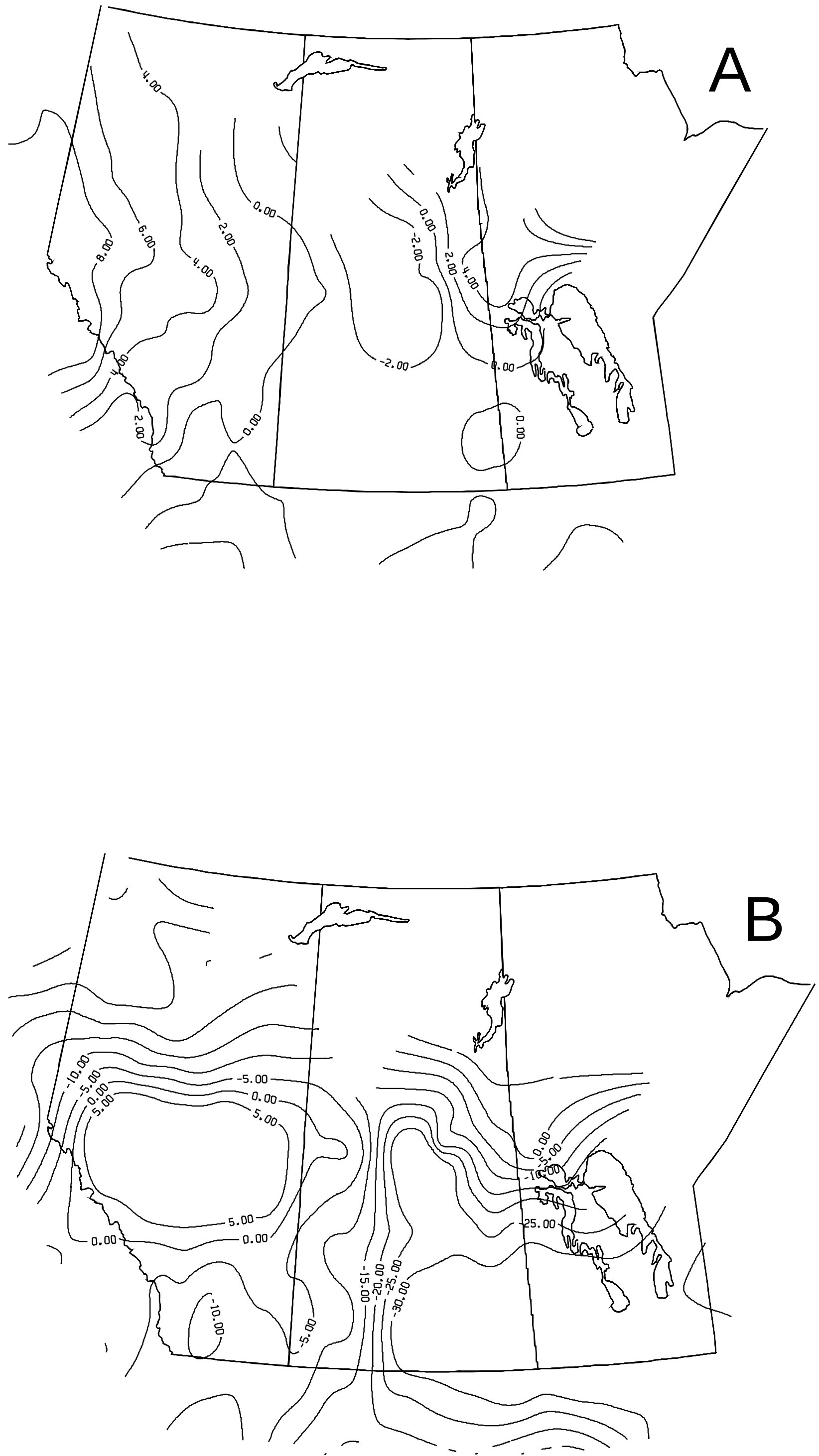


Fig. 10 Difference between CGCM1-A and historic values for precipitation (mm) for the periods a) December and February and b) July to August.

60 mm in summer. This agrees with the upper end of precipitation increase reported by Laprise et al. (1998) of 25–50%.

CGCM1-A predicted minimal changes in precipitation during winter (2-mm increase) with Alberta receiving a small precipitation increase (up to 8 mm) in the central mountains (Fig. 10a). In summer, a general decrease of 10 mm in CGCM1-A accumulated precipitation is found across the Prairies. CGCM1-A predicted that central Alberta in summer will become slightly wetter (5 mm) while the south will become drier (–10 mm, a decrease of 7%) (Fig. 10b). Southern Saskatchewan was predicted to become progressively drier from west (–5 mm) to east (–30 mm, a decrease of 17%). Manitoba was predicted to be progressively drier from north (0 mm) to south (–30 mm, a decrease of 15%).

Both GCMII and CGCM1-A indicated that, overall, central Alberta will benefit the most during the summer and winter from increased precipitation, whereas the eastern Prairies will see little change (winter), moderate increases (30 mm under GCMII) or a moderate decrease (30 mm under CGCM1-A).

During all seasons, the predicted increase in precipitation in both the GCMII and CGCM1-A data suggests a general intensification of the hydrological cycle resulting from global warming (more evaporation and atmospheric water). Akinremi et al. (2001) reported that, across the Canadian Prairies, significant increases in rainfall of 16% occurred between 1956–95, attributed to an earlier spring and summer period. They indicated that the smallest increase in rainfall occured in southern Manitoba. This finding coincides with the CGCM1-A data in the eastern Prairies showing a 30-mm decrease in south-eastern Saskatchewan and southern Manitoba in summer. Further investigation is warranted to see if linkages exist between the historic trends and those responsible for CGCM1-A results (i.e., climate change).

Cutforth et al. (1999) reported that less snow will fall on the Prairies as a result of the positive feedback of an earlier spring. With less snow, less radiation is needed to melt the snow cover and thus a larger proportion of energy is available to warm the ground. Accordingly, this may cause further reductions in snowfall. The decrease in snowfall will affect the soil water recharge necessary to buffer plants growing during a dry spell.

e *Precipitation Variability*

In addition to precipitation amount, changes to the variability in precipitation are important in climate change impact studies. In the semi-arid Prairies, precipitation variability in time (season) and location can have enormous influences on the success of crop production. It follows that in evaluating climate change, identifying spatial changes in precipitation variability should be considered.

Historically, there was 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 that ranged from 145 to 300 mm. Considerable spatial variability is expected in summer precipitation amounts related to convective (locally generated) activity. Raddatz (1998) reported that during rapid foliage expansion evapotranspiration rates are higher than if the Prairies were a natural grassland. Thus, the potential for deep convection and thunderstorms is enhanced during the growing season. Conversely, prior to crop emergence and at crop senescence the potential for deep convection and thunderstorm activity is reduced.

The standard error of the spatial accumulated annual precipitation (Table 3) is lowest for historic data compared to climate change data in each province. GCMII data have the highest standard error indicating a greater spatial range within each province. CGCM1-A data have a more intermediate range of spatial values. Comparing provinces, Alberta has the largest standard error under all scenarios. This probably reflects the large change in precipitation between the more arid south and the central region, the location of the highest precipitation predictions on the Prairies.

TABLE 3. Standard error of the averaged annual precipitation (n is the number of grid points used to calculate standard error).

Scenario	Standard Error of Means of Precipitation (mm)		
	Alberta (n = 160)	Saskatchewan (n = 149)	Manitoba (n = 59)
Historic	7.75	4.32	3.92
GCMII	9.93	5.24	7.66
CGCM1-A	8.80	4.35	3.79

In order to account for the effect of natural variability Boer (2000) has calculated the observed and CGCM1-A simulated trend in precipitation at each latitude and plotted a shaded area around the observed values accounting for 95% of the natural variability, the shaded area then cannot be statistically separated from the simulated precipitation.

4 Conclusions

Both GCM scenarios investigated in our study predict an increase in annual minimum (3° to 5.6°C) and maximum (2.5° to 5.7°C) air temperature across the Prairies. The greatest annual warming was predicted by the GCMII model (4° to 5.7°C) whereas the CGCM1-A model predicted an increase of 2.5° to 3.3°C. The GCMII downscaled model compared well to the results of previous studies. The CGCM1-A model gave more consistent spatial patterns relative to the historic temperature pattern and for this reason, may reflect the spatial pattern of future climate better. This was also the more advanced model that included a greater understanding of climate change forcing factors with respect to ocean coupling and aerosol effects. The increase in annual precipitation across the three prairie provinces was much greater for GCMII (29 to 36% increase) compared to the CGCM1-A model (3 to 7% increase).

The overall annual increase in precipitation is consistent with the global ‘intensification’ theory which predicts that, with global surface warming, greater surface evaporation will result and therefore greater precipitation is expected. The greater spatial variability of climate change predictions is reflected in a higher spatial standard error. This is also reflected in greater extreme precipitation values from GCMII than CGCM1-A. The smaller increase in precipitation over the eastern Prairies coincides with historic rainfall trends suggesting that the climate change rainfall pattern may already be evident.

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