LIMITED REPORT

Changing Climates: Exploring Possible Future Climates of the Canadian Prairie Provinces

by

E. Wheaton

Environment Branch

SRC Publication No. 11341-3E01

June, 2001

technology is our business

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SRC Publication No. 11341-3E01

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CLIMATE CHANGE

Much attention is increasingly focussed on climate change issues. Reasons for concern include:

- Atmospheric concentrations of "greenhouse" gases such as carbon dioxide, methane, and many others, are increasing rapidly because of human activities.
- Greenhouse gases slow the rate at which the Earth loses heat, and they contribute to global warming.
- Prevention of dangerous anthropogenic interference with the climate system (Article 2 of the Framework Convention on Climate Change).

Global and regional climates are always changing, but it is now partly a result of increasing greenhouse gases, especially those related to human activities. Global mean surface temperatures have increased by 0.7° C in the past century (WMO 2000); and according to the Intergovernmental Panel on Climate Change [IPCC], they are projected to increase much more quickly (between 1.4 and 5.8° C) in the next 100 years (Houghton et al. 2001). The IPCC second assessment report (Houghton et al. 1996) concluded that "The balance of evidence suggests a discernible human influence on global climate."

The IPCC third assessment report [TAR] (Houghton et al. 2001) made progress in assessing new evidence and in accounting for uncertainties. They conclude that most of the observed warming over the last 50 years is likely to have been due to the increase in greenhouse gas concentrations. The projected rate of warming is much larger than the observed changes during the 20th century. The rate is very likely to be without precedent during at least the last 10 000 years, based on paleoclimatic data. Emissions of long-lived greenhouse gases have a lasting effect on climate. Anthropogenic climate change will persist for many centuries.

Although Global Climate Models [GCMs] can not model all aspects of the complex climate system, confidence in their ability to model climate and to project future climates has increased. The understanding of climate processes and how to model them has improved, for example. The models have demonstrated their performance capabilities on a range of space and time scales.

Objectives and Study Area

The objectives of this paper are to describe and discuss:

- Methods for estimating possible future climates, i.e. the development of climate change scenarios.
- Selection of climate system models, termed GCMs used for a main type of climate scenario.
- Main features of possible future climates of the Prairie Provinces, including temperature, precipitation, soil moisture, and extreme events.

The study area is the Canadian Prairie Provinces of Alberta, Saskatchewan, and Manitoba, termed Prairies, here.

CLIMATE CHANGE SCENARIOS

Climate scenarios are developed to explore future possible climate changes in areas of the world. Scenarios are defined as “coherent, internally consistent and plausible descriptions of a possible future state of the world” (Parry and Carter 1998:72). One of the best ways of exploring future possible climates is by using mathematical models of the climate system called Global Climate Models, or GCMs. They are powerful computer programs that simulate the functioning of the global climate system in space and in time (Hengeveld 2000). GCMs represent physical processes in the global climate system, including the atmosphere, oceans, cryosphere, and land surfaces.

Other types of scenarios besides the GCM-based ones include:

- Temporal or spatial analogues.
- Synthetic or arbitrary.
- GCM-based.
- Hybrid types.

These types and examples for each are explained by Wheaton (1992), and more recently by Parry and Carter (1998), and by Barrow (2000). Although all of these approaches have limitations, GCM-based scenarios are the focus here, mainly because they best describe the future expected range of climates.

SELECTION OF GLOBAL CLIMATE MODELS FOR CLIMATE SCENARIOS

About Global Climate Models

During the early 1980s only a few rudimentary global climate models existed. By the late 1980s, advances in modelling techniques, computer power, and understanding of climate processes made the second generation of climate models possible. The third generation of Global Climate Models [GCMs] have considerable improvements, including coupling of atmosphere and ocean processes. Presently, there are more than 20 of these models used or being developed, including Canada’s first atmosphere-ocean coupled model from the Canadian Centre for Climate Modelling and Analysis [CGCM1] (Hengeveld 2000). Seven main atmosphere-ocean coupled GCMs [AOGCMs] and some of their characteristics are listed in Table 1.

The GCMs depict the climate system using 10 to 20 vertical layers in the atmosphere and as many as 30 layers in the oceans (Carter et al. 1999). However, their horizontal resolution is quite limited with typical resolutions of about 250 and 600 kilometres (Table 1). This is an important limitation of their use in developing climate scenarios for regional impact assessments that often require information at finer resolutions.

Several types of experiments are run with the GCMs. Older approaches were to run control simulations that assumed a constant atmospheric composition of greenhouse gases. This would be a CO_2 concentration characteristic of the 1970s or 1980s such as 300 to 330 ppm (Table 1). Equilibrium responses of the GCMs to determine the new stable state of the climate at doubled CO_2 atmospheric concentrations were used to compare the responses of the various models. These responses vary from a low of 1.3°C for ECHAM4 to a maximum of 2.7°C for the CGCM1 (Table 1).

Table 1 Characteristics of some of the main Global Climate Models (after Carter et al. 1999, IPCC Data Distribution Center [DDC] 2001)

GCM acronym	**Spatial Resolution** (over land, in degrees lat. and long.)	**CO_2 Forcing Amounts** (Transient runs, in per cent per year)	**Control CO_2** (ppmv)	**Global Warming**[1] **at CO_2 doubling** (°C)	**Organization and Country**
CGCM1	3.7x3.7	1.0 compound	295	2.7	Canadian Centre for Climate Modelling and Analysis [CCMa]
HadCM2, Had CM3	2.5x3.75	1.0 compound	323	1.7	Hadley Centre for Climate Prediction and Research, UK
ECHAM4	2.8x2.8	1.0 compound	354	1.3	German Climate Research Centre
CCSR	5.6x5.6	1.0 compound	345	2.4	Japanese Centre for Climate Research Studies
GFDL-R15	4.5x7.5	1.0 compound	300	2.3	Geophysical Fluid Dynamics Laboratory, USA
NCAR-DOE	4.5x7.5	1.0 linear	330	2.3 estimated	National Center for Climate and Atmospheric Research, USA
CSIRO-Mk2	3.2x5.6	0.9	330	2	Commonwealth Scientific and Industrial Research Organization [CSIRO], Australia

[1] More recent experiments report higher increases with a range of 1.4 to 5.8 °C (Houghton et al. 2001).

More recent atmosphere-ocean coupled GCM runs use a "warm start approach" to simulate the current climate. This approach is the use of the historical concentrations of the greenhouse gases from about 1850 to 1990. The next question is what amounts of greenhouse gas emissions should be used to depict the future forcings of the climate system? Commonly experiments used forcings of 1% per year in equivalent carbon dioxide concentrations (Table 1). This approximates the radiative forcing expected under the "business as usual" emissions scenario or what is termed the IPCC IS92a emission scenario (Houghton et al. 1996). This type of forcing provides more realistic information depicting the behaviour of the climate system changing through time, i.e. the transient response, as contrasted to the equilibrium response at a doubled, tripled, or quadrupled amount of greenhouse gas forcing.

The most recent greenhouse gas and sulphate aerosol emission scenarios are those developed for the IPCC Third Assessment Report [TAR] and detailed in the IPCC Special Report on Emissions Scenarios [SRES] (Carter et al. 2000). Four main sets of narrative descriptions, or story lines were designed to represent different demographic, social, economic, technological and environmental developments in the future. Modelling teams produced 40 emissions scenarios.

The SRES emission scenarios are currently being used to drive the Global Climate Models. The globally averaged surface temperature increases projected using these newer emission scenarios are greater than those of the IS92 scenarios used in the IPCC Second Assessment Report, at 1.4 to 5.8°C as compared to 1.0 to 3.5°C. The higher and greater ranges of projected temperatures are mainly due to the lower projected sulphur dioxide emissions in the SRES scenarios compared to the IS92 scenarios as well as the wider range of scenarios (Houghton et al. 2001).

It is important to note that there is a time delay between the availability of emission scenarios, GCM results and impact and adaptation assessments. Therefore, most of the current impact work uses GCM-based scenarios with older emission scenarios, such as IS92 types, and not the most recent SRES scenarios. The newer impact work will be based on the greater changes of the newer GCM experiments, and more extreme results may be expected.

Which Global Climate Models?

Considering there are many GCMs to choose from and many experiments from each, researchers need to apply selection criteria to help decide which ones to use for scenario creation for their specific impacts and adaptation projects. Climate change scenarios are **not predictions** of the future, but as their definition indicates, they are descriptions of possible climatic futures or projections. As a result, it is wise to select scenarios that give a range of results in order to explore the sensitivities of possible impacts and adaptations. The Intergovernmental Panel on Climate Change guidelines on the use of scenario data recommends using multiple scenarios spanning a range of possible future climates for such reasons (Carter et al. 1999). This is one of the guidelines most important recommendations for several reasons including the point that each scenario is considered equally likely and therefore a wide range of future possibilities needs to be considered, at this early stage.

Several criteria should be used to choose the set of GCMs to create the climate scenarios (Smith and Hulme 1998). For example the newest models are preferred because of their improvements in simulation, in spatial resolution, in ability to simulate the observed climate, and in representativeness of the greenhouse signal. Results should be at an adequate spatial scale, accessible, and valid as compared with observed climates. The IPCC Data Distribution Centre (IPCC DDC 2001) and the Canadian Climate Impact Scenarios Project (CCIS 2001) are among the recommended websites for obtaining data from GCM runs and relevant information.

The Canadian CGCM1 is commonly selected for use in impact and adaptation assessments as it is one of the best of the coupled models tested under inter-comparison programs (Hengeveld 2000:6). Another advantage of using this GCM's results is that data and documentation are readily available and the output consists of many variables. Its spatial resolution is about mid-range compared with the other models of Table 1.

How well do Global Climate Models work?

Comparisons of observed and simulated climates show that the GCMs perform reasonably well. Model estimates of natural variability are quite similar to observations, especially for some regions and periods (Tett et al. 1997). Simulations are also similar to climate fluctuations reconstructed from proxy records over the past millennium (Jones et al. 1998). The GCMs largely agree on the expected large area patterns of climatic change even though important uncertainties remain in regional projections (Carter et al. 1999).

Simulating the climate system is a very difficult task considering that GCMs are very simplified approximations of an extremely complex system. GCMs are tested in two main ways: 1) their ability to reproduce past and present climates through space and time, and 2) comparisons with other models. For example, the CGCM1 successfully reproduces the general spatial characteristics of the global climate. This indicates that the modelling of climate processes is mostly correct.

Other ways to assess GCMs' ability to model the climate system include:

- Modelling of biophysical and chemical processes.
- Global patterns through space. Regional climate patterns are much more difficult to simulate. Regional climate models [RCMs] are often used for this task, however, they depend on the GCM for their lateral boundary conditions.
- Global patterns through time, including the past century, previous centuries, and recent years.
- Comparison with other model results. Each model is different. If the various models give similar results, more confidence can be placed in both the modelling process and their results.

Comparison of Global Climate Model Experiments

GCM results for a number of experiments are run to determine the range of possible climatic futures for regions. The experiments consist of different forcing factors, i.e. different rates of increase of greenhouse gases, greenhouse gas plus aerosols, as well as experiments with different initial conditions. The results also are useful to check the level of agreement of estimates for different regions. A higher level of agreement indicates higher confidence in the projections, and vice versa.

The CGCM1, for example, has been run for a series of experiments. These include a control run to provide a baseline for comparison with the other experiments. The control is forced with constant greenhouse gases and other external forces. A second experiment was run with only increases in greenhouse gas concentrations [GG], converted to an equivalent carbon dioxide amount. Also, a set of three independent experiments was undertaken with increases in greenhouse gases and sulphate aerosols [GGA]. These last three experiments differ in their initial conditions in order to approximate natural variability and noise (Hengeveld 2000). The results from the GGA experiments are also averaged to provide an ensemble mean, which can be considered an approximation to the climate change signal (Barrow et al. 2000).

Barrow et al. (2000) compared results from 25 experiments from several GCMs. The example for winter of the 2020s shows that all the experiments agree on an increase of winter mean temperature for land areas of Canada. Agreement of the amounts of change was also explored. An agreement of 60 to 90% of the experiments exists for the Canadian Prairies for a greater or equal to 2°C increase in winter mean temperatures. The agreement level indicates that summer warming for the 2020s is likely to be greater than 1°C, but less than 2°C for the Prairies. Comparisons of agreement of experiment results for precipitation show much more spatial variability than for temperature, as expected. More than 50% of the experiments indicate an increase in precipitation in all seasons, except summer for the Prairies. Much more variable results occur for summer.

As described in the first section, the latest estimates of global temperature increases are greater than those reported earlier mostly because of the reduced effect of the sulphate aerosols. This means that the range of GCM experiments used to drive impact models should reflect this effect by considering the higher temperature changes by using the experiments run with greenhouse gases only as part of the set of experiments selected. Updated impact assessments should be run based on the latest emission scenarios because of the greater change from earlier GCM experiments.

Creating Global Climate Model-Based Climate Scenarios

The Classic Method

Although climate models are rapidly improving, their results are still not considered to be of adequate reliability or resolution to be used directly for impacts and adaptation assessments. Another reason for scenario development is that some impacts and adaptation studies may require data that GCM modelling centres may not provide.

One of the first climate change impact assessments to develop and use GCM-based climate scenarios was led by Parry et al. (1988). A "classic" climate scenario formation technique was developed by this group in the mid-1980s (Williams et al. 1988); it became a standard method for later and current scenario creation (e.g. Smith and Tirpak 1988, Mearns et al. 1997, Canadian Climate Impacts Scenarios Project [CCIS] 2000).

Basically, the classical method is that of determining the anomalies of GCM experiments for the future as compared to a baseline period. The baseline is the GCM simulation for a present climate normal period, i.e., 1961-1990. This period is suggested by the IPCC guidelines for many reasons (Carter et al. 1999). The anomalies are differences for temperature and similar variables, or ratios for precipitation and similar variables. The anomalies (or termed change fields) are then applied to the averages from the record of observed climate, for the same baseline period. This method was selected as the problem is similar to that of adjusting shorter term averages to be comparable to the thirty year normal period. The differences or ratios of the averages are more stable than the averages themselves (Conrad and Pollak 1950) and they are more representative of the expected changes. An advantage of using both the change fields and the observed baseline values is that the richness of the observed data is preserved for representing regional climates. The effect of local variations of topography and land cover, for example, is not well simulated by GCMs and is much better reflected in the observed baseline data.

Other methods have been and are being considered for creating climate scenarios. The method used needs to be carefully documented, as it can strongly affect the climate changes used for impact and adaptation assessment, and therefore the impact and adaptation assessment results. The development of climate change scenarios is a relatively recent research topic and rapid development is occurring. The next topics are those of dealing with both time and space scales of climate scenario development.

Time Scales

Time periods of the climate scenarios can vary from daily to monthly, often as averages. Usually, averages for 10 to 30 years are calculated from the GCM experiments (e.g. monthly averages for

2040 to 2069). The anomalies are then applied to the 1961 to 1990 averages, or in some cases the monthly anomalies are used with the 1961-1990 monthly time series (as done by Williams et al. 1988 for example) or even daily observational time series (as done by Mearns et al. 1997 for example).

Spatial Scales

GCM results are available for very coarse spatial resolution as grid-box data. For example, the Canadian coupled model [CGCM1] has a horizontal resolution of about 3.7 degrees of latitude and longitude (about 400 kilometres). The UK Hadley Centre coupled model's [HadCM2] resolution is 2.5 by 3.75 degrees (Table 1). Various methods, called downscaling or regionalisation, are used to provide sub-grid size results for impact assessments. These methods include (Barrow 2000):

- Using the nearest grid-box to the study station or area.
- Interpolating grid-box results.
- Downscaling using empirical/statistical methods.
- Applying weather typing.
- Using weather generators.
- Using regional climate models [RCMs].

Again, each of these methods has their advantages and disadvantages. For many purposes, the simplest approaches such as the first two methods may be appropriate, especially if a main objective of the project is to determine the sensitivity of impact and adaptation results to a range of climate parameters. Then, researchers would have more time for using more climate scenarios in their analyses.

In summary, one of the simplest and classic methods for climate change scenario creation is:

- Obtain the anomaly data from the GCM experiments for each grid-box within and surrounding the study area. Anomalies are the differences or ratios between the mean values for a future time period and the simulations for the current baseline period of 1961-1990.
- Select the grid-box anomaly closest to each study area station location.
- Apply the anomaly (i.e. add, for temperature and similar variables, or multiply, for precipitation and similar variables) to the observed values (e.g. monthly or daily time scales) for the 1961 to 1990 period.
- Use the new climate scenario data as inputs to the impact and adaptation models (e.g. simulation of vegetation growth and management).

CLIMATE CHANGES PROJECTED FOR THE PRAIRIE PROVINCES

The past, present, and future changing climates of the Prairies are related to the context of global changes. The considerable global climate change that is already proceeding is mentioned in the introductory section and in a companion paper regarding past climate changes (with emphasis on the Prairies) (Wheaton 2001). Small changes in mean global climates can produce relatively large changes in regional climates and the frequency of extreme events (Houghton et al. 1996). Therefore, the future changes for the Prairies are likely to be even more extreme than the global averages.

This section overviews the types of global climate changes that have occurred and are estimated for the future. Then future estimated changes in climate variables such as temperature and precipitation are discussed, followed by discussions of other phenomenon such as snow-cover, soil moisture and extremes.

Observed past and possible future changes in some global weather and climate phenomenon are listed in Table 2 with estimates of the confidence in the changes. The assessment and confidence ratings are based on observational and modelling studies, as well as the physical plausibility of future projections for many commonly used climate scenarios. The descriptions of the confidence level are described as "likely" to "very likely." "Very likely" indicates that the change is physically plausible and that several models have been analysed for such a change and all the models show it in most regions. The category "likely" indicates that theoretical studies and those models analysed show such a change, but only a few current climate models are configured in such a way as to reasonably represent such changes.

Table 2 Observed and projected changes in weather and climate events and the confidence in these estimates (after Houghton et al. 2001)

Changes in Weather and Climate Events	Confidence in Observed Changes over the past 50 Years[3]	Confidence in Projected Changes during the 2000s[3]
Higher **maximum temperatures** and more hot days over nearly all land areas[1]	Likely	Very likely
Higher **minimum temperatures**, fewer cold days and frost days over nearly all land areas	Very likely	Very likely
Reduced diurnal **temperature range** over most land areas	Very likely	Very likely
Increase of **heat index** over land areas[2]	Likely, over many areas	Very likely, over many areas
More **intense precipitation** events	Likely, over many Northern Hemisphere mid- to high- latitude land areas	Very likely, over many areas
Increased summer continental drying and associated risk of **drought**	Likely, in a few areas	Likely, over most mid-continental interiors.

[1] "Hot days" refers to a day whose maximum temperature reaches or exceeds a critical threshold for impacts on human and natural systems. Thresholds vary regionally, but typical values include 32°C, 35°C or 40°C.
[2] Heat index refers to a combination of temperature and humidity that measures effects on human comfort.
[3] These terms are used to indicate judgmental estimates of confidence: very likely (90-99% chance) and likely (66-90% chance).

Changes are presented as anomalies or differences from the 1961 to 1990 baseline simulations for ease of presentation. Mean anomalies for the thirty year periods centred on the 2020s (i.e. 2010 to 2039), 2050s (2040 to 2069), and the 2080s (2070 to 2099) are recommended for use by the IPCC (Carter et al. 1999). The results are presented at the original GCM grid resolution (Table 1). Results are available and mapped on an annual, seasonal, and monthly basis using data from the CCIS website (CCIS 2001).

Temperature and Precipitation Changes

Future global temperature changes in the "very likely" category include higher maximum and minimum temperature changes (Table 2). More hot days, fewer cold days, a lower daily temperature range, and increased heat indices are accompanying changes. These changes would be even more likely for mid-continental high-latitude locations such as the Prairies.

Summary graphs of temperature and precipitation changes for the Prairies and Canada using several of the main GCMs are available from the CCIS Project (Barrow et al. 2000) (Figure 1). They are useful to depict the types and ranges of expected changes, as well as to select which GCMs give a range of changes for use in impacts and adaptation analyses, for example. It is also an important first step to document and describe the precipitation and temperature changes, as well as the derived variables so that the reasons for the changes in impacts can be determined.

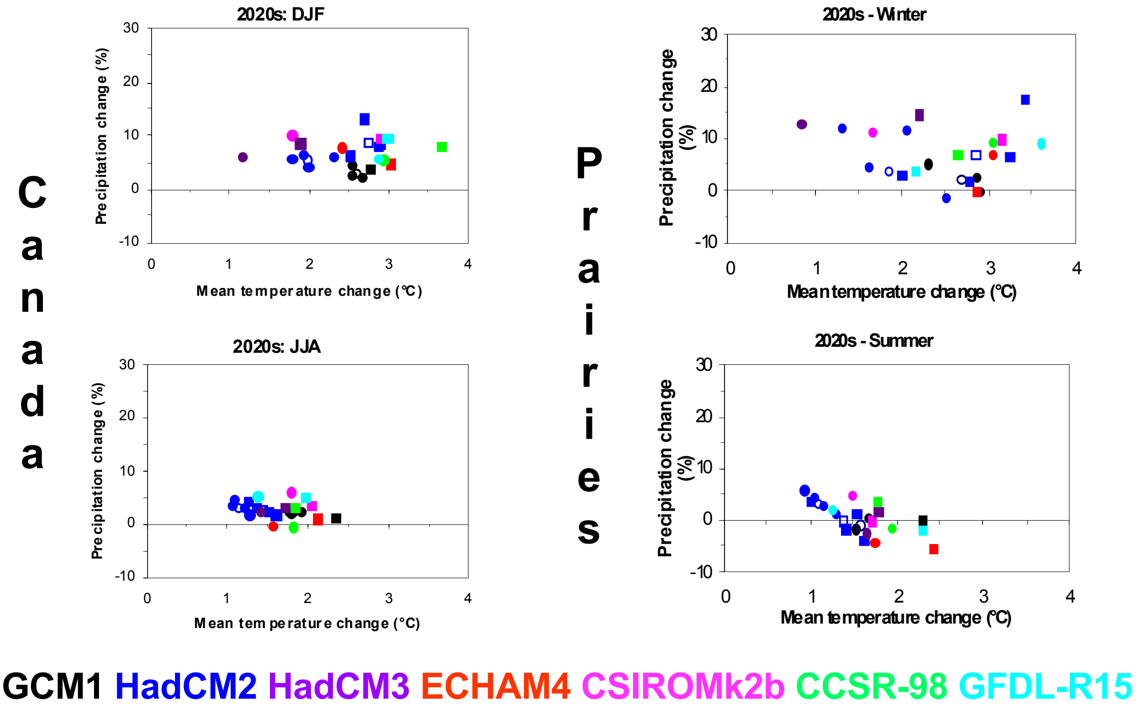

Figure 1Summary of temperature and precipitation changes for several main Global Climate Models for winter and summer as averages for the 2010 to 2039 period (2020s) for the Prairies and Canada (Barrow et al. 2000). Refer to Table 1 for the organization and country and other characteristics of each model.

First compare the Prairie temperature and precipitation changes to the Canadian changes for the 2020s (i.e. 2010 to 2030 averages) and note that the Prairie changes are more extreme, that is, they have a greater range (Figure 1). This is as expected, not only for smaller areas, but especially for high-latitude continental locations, such as the Prairies. The changes are averaged over the grid boxes comprising the Prairies.

Mean **temperature** changes for the Prairies exhibit increases from the 1961-1990 baseline simulation for all the commonly used scenarios (Figure 1). Increases for **winter** range from less than 1°C to more than 3.5°C, for the UK Hadley Centre [HadCM3] and American [GFDL-R15] GCM-based scenarios. The Canadian CGCM1 and the HADCM3 experiments both with greenhouse gases only [GG] are in the mid-range. **Summer** changes show less difference among scenarios and range from less than 1°C for the HADCM2 using the greenhouse gases and aerosols experiment [GGA] to almost 2.5°C for the German ECHAM4 and the CGCM1 with greenhouse gases only.

Mean **precipitation** changes also show more spread for winter than for summer for the 2020 time slice averages (Figure 1). Percentage changes for **winter** range from slight decreases for the UK HadCM2 with GGA and the ECHAM4 GG to 15% and greater increases for the HadCM2 GG and the HadCM3 GG. The CGCM1 GGA results were mid-range with increases at about 5% and less.

Mean precipitation changes for **summer** differ from winter and from the picture for Canada as a whole as they show both decreases as well as increases. The values range from more than -5% for ECHAM4 with GG to about 5% for HadCM2 GGA and Australian CSIROMk2b GGA. The CGCM1 GG shows negligible change. This concurrent change of large increases in average temperature and decreases in average precipitation totals indicates average soil moisture decreases.

It is much more difficult to model precipitation than temperature because precipitation is much more variable spatially and temporally, and the processes leading to precipitation formation occur at scales finer than the GCMs can resolve. Hence, precipitation is modelled using parameterisation processes, in which precipitation is inferred from other climate variables, such as atmospheric humidity, rather than being modelled directly. Simulated results show lower correspondence with observed precipitation patterns than for more stable variables such as temperature. For example CGCM1 overestimates mean precipitation rates in high latitudes and the northern extratropics (Kharin and Zwiers 2000). Therefore, more confidence is placed in temperature projections than in the precipitation projections.

The Canadian Global Climate Model [CGCM1] was chosen as the basis for further describing future possible temperatures for reasons discussed previously. The model is described in Boer et al. (2000). Average temperature and precipitation changes for two more time slices, the 2050s and 2080s as well the transitional seasons of spring and fall are provided in Tables 3 and 4. Although the grid sizes are very large, considerable spatial variation is discernible across the prairies. This variation is indicated in the ranges for the annual and seasonal values for each time period (Tables 3 and 4).

Table 3 Ranges of average temperature changes (°C) across the Prairies for the 2020s, 2050s and 2080s time slices as compared to the 1961-90 simulation. Results are from the Canadian Global Climate Model forced with greenhouse gases only [CGCM1GG] (CCIS 2000).

Season	Time Slice		
	2020s (2010-2039)	**2050s** (2040-2069)	**2080s** (2070-2099)
Annual	2 to 3	4 to 5	5 to 8
Spring	2 to 3	4 to 7	5 to 9
Summer	2 to 3	3 to 5	5 to 7
Fall	1 to 2	2 to 4	3 to 5
Winter	2 to 4	5 to 8	5 to 9

The main characteristics of these average temperature changes through these time and space scales include:

- Considerable increases with time, especially for the last period, the 2080s.
- Largest increases for the winter, then spring, and smallest increases for the fall.
- Greatest spatial variation for the winter, then for the spring and least for the fall.

Table 4 Ranges of average total precipitation changes (%) across the Prairies for the 2020s, 2050s and 2080s time slices as compared to the 1961-1990 simulation. Results are from the CGCM1GG (CCIS 2000).

Season	**Time Slice**		
	2020s (2010-2039)	**2050s** (2040-2069)	**2080s** (2070-2099)
Annual	-2 to 8	-2 to 7	0 to 15
Spring	-2 to 15	5 to 25	10 to 25
Summer	-5 to 10	-10 to 15	-25 to 7
Fall	-5 to 15	-5 to 15	5 to 25
Winter	-4 to 9	-2 to 15	-2 to 21

The main characteristics of these average precipitation changes through these time and space scales include:

- Small increases with time, in general, except for summer which shows some decreases from 2020s to 2050s and even larger decreases as much as 25% in the 2080s.
- Considerable spatial variation with both increases and decreases of about 25% for some grids in the 2080s from spring to summer.

Soil Moisture Changes

The CGCM1 indicates that most of North America would experience a decrease in available soil moisture. Summer deficits would be greater with continued warming because of the combination of possible low increases or even decreases in precipitation especially in the summer, and the considerable increases in temperature (Hengeveld 2000). Earlier impact work found that strong temperature increases (e.g. 3 to 4°C) which increase the rate of potential evapotranspiration could offset even large increases in rainfall (i.e. 20%) in terms of their effect on a precipitation effectiveness index as an indicator of soil moisture (Williams et al. 1988). The US National Assessment points to five recent modelling studies that show summer drying in mid-continental regions due to increased evaporation (National Assessment Synthesis Team 2001). Dry soils also provide a positive climatic feedback as the heat energy is used to warm the surface rather than to evaporate water. Warmer soils then tend to increase atmospheric warming.

The CGCM1 ensemble mean changes for the 2020s time slice shows generally greater soil moisture changes for summer than winter (Figure 2). The soil moisture changes are given as capacity fractions, where zero represents a dry soil, and one represents a fully saturated soil. Winter changes range from an increase of 0.1 in the forest zone to -0.15 in southeast Manitoba. The gradient of change is a decrease from northwest to southeast. Summer exhibits a similar gradient, ranging from the forest region with values near zero to values less than -0.15 in southeast Saskatchewan and southern Manitoba. Summer's spatial pattern shows greater area with a decrease in capacity fraction, indicating greater areas of drier soils and increased water deficits.

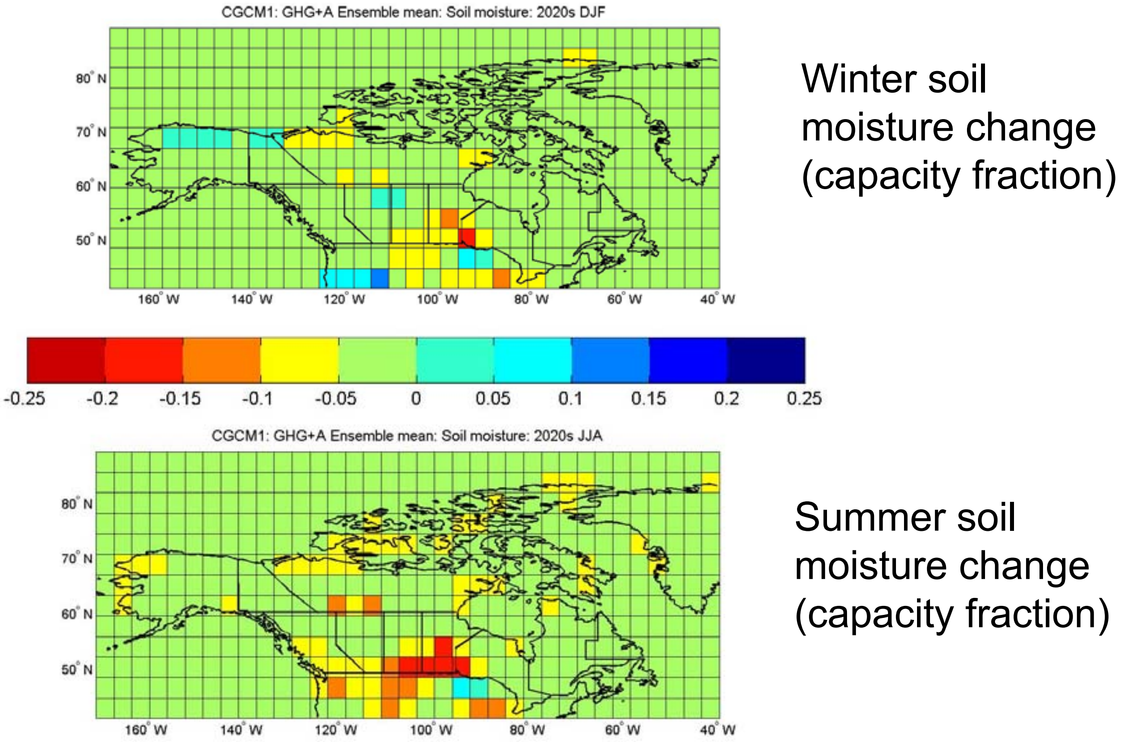

Figure 2Winter and summer average soil moisture changes (capacity fraction) for the Canadian CGCM1 GGA [greenhouse gas with aerosols] ensemble mean for 2010-2039 (Barrow et al. 2000:13). A capacity fraction of one represents a fully saturated soil, and zero represents a dry soil.

The results for soil moisture changes were also examined for the CGCM1 greenhouse gas only experiment [GG1] to explore a range of possible futures. For brevity, only results for the 2020s and the 2080s are discussed. The advantages of each period are that the earlier time is more relevant to most current impact assessments and adaptation planning processes, and the later period has stronger climate change signals.

The change in annual soil moisture values shows more drying in the 2080s (Table 5). The 2020s show little to no annual change. This small change may be related to the limitations of the sub-model used and because the largest temperature increases occur during the colder part of the year (Barrow p. comm. 2001). Summer has more drying than winter, in general for both time slices. This trend is expected because of the decreases or weak increases of precipitation in the summer. Southern Manitoba tends to show more drying than other parts of the Prairies during the summer. Winter mean changes of this soil moisture indicator have some increases which may be a result of the increased precipitation.

Table 5 Ranges of average soil moisture change (capacity fraction) across the Prairies for the 2020s and 2080s time slices as compared to the 1961-1990 simulation. Results are from the Canadian Global Climate Model forced with greenhouse gases only [CGCM1 GG] (CCIS 2001). A capacity fraction of one represents a fully saturated soil, and zero represents a dry soil.

Season	**Time Slice**	
	2020s (2010-2039)	**2080s** (2070-2099)
Annual	-0.08 in southern MB to 0 in AB and for most of SK	0 in the North to -0.11 in SE MB
Winter	0 in the south to 0.02 in the north	-0.2 in central SK to 0.1 in northern AB
Summer	-0.15 in SE MB to near 0 in the North	-0.22 in SE MB to 0.02 in SW SK

Soil moisture changes are driven by the balance among precipitation, evapo-transpiration, runoff and soil drainage. Soil moisture is difficult to determine, so more than one approach should be used. A common method is to use the difference between precipitation and evaporation as an indicator of soil moisture and to examine the sensitivity of vegetation to changes in the index (e.g. Hogg and Hurdle 1995). Future changes of this index do not appear to be readily available, except for the older work by Hogg and Hurdle (1995), so it should be determined and described. However, changes in precipitation are described earlier, and two sets of possible future evaporation changes are available from the CCIS website (CCIS 2001) and are summarized in Table 6.

Table 6 Ranges of average evaporation change (mm/d) across the Prairies for the 2020s and 2080s time slices as compared to the 1961-1990 simulation. Results are from the Canadian Global Climate Model forced with greenhouse gases only [CGCM1 GG] (CCIS 2001).

Season	**Time Slice**	
	2020s (2010-2039)	**2080s** (2070-2099)
Annual	near 0 to 0.14	0.03 to 0.33
Winter	-0.06 to 0.14	-0.08 to 0.27
Summer	-0.4 to 0.18	-0.76 to 0.28

Annual average evaporation changes show general increases across the Prairies with larger increases to the 2080s as the temperature increase accelerates (Table 6). Some grids show decreased evaporation (negative changes) in both winter and summer, with stronger decreases in the summer. This effect could be a result of moisture limitations. The method of calculation of evaporation, and potential evaporation was not documented in the CCIS website (CCIS 2001). The methods should be examined and reasons for the changes should be determined.

One of the first studies to provide information on changes in wet and dry periods with climate change is by Kharin and Zwiers (2000). They used the CGCM1 forced with greenhouse gases and aerosols to explore changes in duration of dry periods (i.e. the time between two consecutive rain days, where a rain day is a day with 1 millimetre of precipitation or more) and wet period durations (i.e. the time between two consecutive "dry" days with precipitation less than 1 millimetre). The annual average length of wet period currently in the Prairies is less than two days. The 20 year return period value for a wet period is currently about a month in western Canada. The current wet and dry period duration values are reasonably well produced by the model, although the lengths are underestimated. Regional patterns are difficult to examine as values are provided as a global scale map and as land area averages. It appears that the dry and wet period 20 year return interval for the Prairies increases by less than one day over the Prairies for 2080-2100.

The existing information about soil moisture and other aspects of the hydrological cycle is very limited. Several other variables need to be determined, especially those indices that are linked with the ecosystem, including aridity/drought/moisture indices of various types, including simpler ones such as the difference between precipitation and evapotranspiration. Information about water deficit and surpluses would also be more relevant to several applications. Moisture-driven biomass indices or process-based plant growth models would also be useful to show the sensitivity to the moisture changes for ecosystems.

Temperature Extremes

Changes in the extremes of many climatic elements, including air temperature, precipitation and wind speed, are expected and they are important aspects of climate. Extremes of storms, such as hailstorms, thunderstorms, dust storms, wind storms and tornados are also expected. Small changes in average temperatures can generate significant changes in the extremes (Houghton et al. 1996). For example, high temperatures could increase by up to 12°C by the 2050s in the Prairies (Hengeveld 2000). Changes in the extremes, in turn, can have considerable impacts on ecosystems and socio-economic sectors.

One of the first studies to consider changes in the extremes of basic climatic elements was by Kharin and Zwiers (2000). They examined changes in extremes of variables including temperature, precipitation, and wind speed on the global scale in an ensemble of three transient CGCM1 experiments with increasing greenhouse gas and aerosol concentrations. The model simulates the extremes of the contemporary climate reasonably well, considering how difficult extremes are to estimate, especially for variables such as precipitation. Changes in extreme temperatures are statistically significant over most of the globe for both the periods considered (i.e. 2040-2060 and 2080-2100). One of the regions with the greatest change in return values of daily maximum temperature include central and southeast North America, including the southeastern Prairies. The 20 year return period value for maximum temperature increases by about 4 °C in the southeastern Prairies for the 2040-60 period. The authors attribute this pattern to a reduced evaporative cooling related to the substantial decrease in summertime soil moisture content.

Extreme high temperatures are projected to become several times more frequent with global warming. High temperatures with a current 1:80 year return period would drop to a 1:10 return period projected for the 2050s (Hengeveld 2000). The Prairies currently hold the record for extreme daily maximum temperature in Canada, with a record of 45°C for stations in southeastern Saskatchewan. The average annual number of days with maximum temperature above 30°C is already more than 20 days in the southern Prairies (Phillips 1990), and this number will increase with continued warming. The temporal and spatial pattern of this potential increase must be more closely assessed, especially for temperatures relevant to critical biophysical thresholds and timing of events.

Changes in the return values of daily minimum temperature are much larger than those of daily maximum temperatures (Kharin and Zwiers 2000). The increase in the 20 year return period values for daily minimum temperatures simulated by the CGCM1 [GGA] in 2040-2060 exceed 4°C over most of the Prairies. Canadian cold extremes are expected to decrease in frequency with continued global warming. The CGCM1 projects cold extremes to increase in return period length (i.e. decrease in frequency) by eight times from an average 1:10 year return period to a 1:80 year return period in the 2050s (Hengeveld 2000).

Precipitation Extremes

An increase in the global hydrological cycle is expected with climate warming because of the greater energy in the climate system. Rainfall is projected to become more intense, suggesting that damaging extreme events may double in frequency by the 2020s (Hengeveld 2000). Kharin and Zwiers (2000) used the CGCM1 forced with greenhouse gases and aerosols to assess changes in extreme precipitation during the 2040-2060 and 2080-2100 periods. An increase in extreme precipitation occurs almost everywhere on Earth, with smaller changes over land as compared to the oceans. The changes, however, are not statistically significant until the later period. The return period for extreme precipitation events decreases by half from 20 years to 10 years by 2080-2100. The US National Assessment (National Assessment Synthesis Team 2001) lists at least five modelling studies that show an increase in the heaviest precipitation events.

The Prairies currently hold records for some of the most intense precipitation events in Canada. The record for maximum rainfall in one hour in Canada by Buffalo Gap, Saskatchewan at 250 millimetres in an hour (1961). The second highest record is also for a location in the Prairies at Porcupine Mountain, Manitoba with 96 millimetres per hour (Phillips 1993). Further work is required to determine how the temporal and spatial pattern of intense rainfall could change in the Prairies, and to compare it with the Canadian view.

Snow-cover Changes

A rapid reduction of snow-cover area has occurred in Canada especially in the 1980s and 1990s over western Canada. The largest changes have occurred during the spring with the snow-cover leaving earlier at a rate of about one to two days per year (Crysys 2001). Snow-cover is expected to continue to decrease with continued warming. Amounts of snow-cover have many implications for natural and human systems. For example, adequate snowcover protects plant roots from freezing damage.

Increased frequencies of mixed rain and snow, as well as rain-on-snow events are expected with warming (Crysys 2001). Rain-on-snow events cause severe flooding with the current climate, and therefore are cause for concern.

Spring melt-water is also an important source for spring soil moisture, and therefore germination and plant growth. A continued reduction of snow-cover means that snow-melt input to soil moisture will continue to occur earlier and may be smaller. Changes in this input to soil moisture should be carefully assessed for both past and for future trends.

CONCLUSIONS AND RECOMMENDATIONS

Considerable climatic changes and their biophysical effects have already occurred in the Prairies (Wheaton 2001), and more rapid change is expected. This paper provides an overview of methods for estimating future climates, of the Global Climate Models used as the common basis for scenario development. It describes the main features of possible future climates of the Prairie Provinces, including temperature, precipitation, soil moisture, and extreme events.

The future projected global temperature changes are greater than any during the past 125,000 years, and the rates of future change are dramatically larger than past changes (Henegeveld 2000). A summary of future possible climate changes for the Prairie Provinces is:

- Warmer and generally wetter winters and springs.
- More warm spells and fewer cold spells.
- Fall has the least warming and least variability.
- Warming in summer is generally less than winter and spring.
- Both increases and decreases in average annual precipitation with time, in general, except for summer which shows larger decreases than other seasons.
- Greater spatial variability in precipitation than in temperature and lower confidence in estimates of precipitation.
- More intense precipitation events.
- Generally decreased summer soil moisture with considerable variation, depending on the variability of precipitation.

Several specific recommendations are in the previous sections. Temperature and precipitation changes have been compared among a range of models and experiments. These comparisons have not yet been made for other variables, to the author’s knowledge, and this should be done. More general key gaps include assessments of changes in:

- Variability and other statistics of climatic elements.
- Atmospheric dynamics, including jet stream, storm tracks and activity, and blocking events, for example.
- Water surplus and deficit.
- Snow-cover amounts, season and extent.
- Growing degree-days and other heat accumulation indices.
- Heat stress.
- Growing season length.
- Climatic variables, their combinations and thresholds that are linked with key physical and biological processes, such as germination, plant growth, death, and phenology. The dynamics of daily and/or monthly time series is more relevant to biophysical effects than averages. Time series have been neglected and must be assessed. Changes affecting different land-use and environmental management operations and planning could also be developed.

Such interdisciplinary and applied work requires much improved communication and cooperation among the various researchers and decision-makers in all phases of research programs.

ACKNOWLEDGMENTS

Funding was provided by the Government of Canada's Climate Change Action Fund (Agreement A305), the Saskatchewan Research Council [SRC], Saskatchewan Environment and Resource Management, and the University of Saskatchewan. I thank V. Wittrock, SRC, and Dr. E. Barrow, Canadian Climate Impacts Scenario Project, and C. Sykes, University of Saskatchewan, for their comments. L. Crone and C. Hudym, SRC, accomplished the word processing. J. Raven and C. Macleod, SRC, assisted with the literature searches.

A companion presentation is:
Wheaton, E. and Wittrock, V. 2001. *Prairie Climate Change: Past and Future Trends*. Invited presentation to the EMAN [Ecological Monitoring and Assessment Network] National Science Conference, May 4, 2001, Calgary, Alberta. Saskatchewan Research Council [SRC] Publication No. 11299-2D01. SRC, Saskatoon, Saskatchewan.

REFERENCES

Barrow, E. 2000. *Climate Change Scenarios for Canada*. Environment Canada, Regina, Saskatchewan. On the CCIS Project Website at http://www.cics.uvic.ca/scenarios/.

Barrow, E. 2001. P. Comm. Dr. E. Barrow, Canadian Climate Impacts Scenario Project c/o Environment Canada, Regina, Saskatchewan.

Barrow, E., F. Herfst, and R. Street. 2000. *The Canadian Climate Impacts Scenarios Project.* Invited presentation to the Climate Change/Greenhouse Gas Modelling Workshop, December 10 to 11, 2000, at Saskatoon, Saskatchewan. Environment Canada, Regina, Saskatchewan.

Boer, G.J., G. Flato, M.C. Reader, and D. Ramsden. 2000. A Transient Climate Change Simulation With Greenhouse Gas and Aerosol Forcing: Experimental Design and Comparison With the Instrumental Record for the Twentieth Century. *Climate Dynamics*, **16**:405-425.

Canadian Climate Impacts Scenarios Project [CCIS]. 2001. *Web Page*. Accessed 2001. Available at: http://www.cics.uvic.ca/scenarios/.

Canadian Climate Impacts Scenarios Project [CCIS]. 2000. *Web Page*. Accessed 2000. Available at: http://www.cics.uvic.ca/scenarios/.

Carter, T., M. Hulme, and M. Lal. 1999. *Guidelines on the Use of Scenario Data for Climate Impact and Adaptation Assessment*. Prepared by the Intergovernmental Panel on Climate Change, Task Group on Scenarios for Climate Impact Assessment [IPCC-TGCIA]. Intergovernmental Panel on Climate Change, Geneva, Switzerland. 69 pp.

Carter, T.R., M. Hulme, J.F. Crossley, S. Malyshev, M.G. New, M.E. Schlesinger, and H. Tuomenvirta. 2000. *Climate Change in the 21st Century - Interim Characterizations Based on the New IPCC Emissions Scenarios.* Finnish Environment Institute, Helsinki, Finland. 148 pp.

Conrad, V. and L. Pollak. 1950. *Methods in Climatology*. Harvard University Press, Cambridge, Massachusetts. 317 pp.

Crysys. 2001. *Web Page*. Accessed 2001. Available at: http://www.crysys.uwaterloo.ca/science/documents/snow_variability.html.

Feenstra, J., I. Burton, J.B. Smith, and R.S.J. Tol (Editors). *Handbook on Methods of Climate Change Impacts Assessment and Adaptation Strategies*. United Nations Environment Program, Amsterdam, The Netherlands. 464 pp.

Hengeveld, H. 2000. Projections for Canada's Climate Future. *Climate Change Digest* CCD 00-01. Environment Canada, Downsview, ON.

Hogg, E.H. and P.A. Hurdle. 1995. The Aspen Parkland in Western Canada: A Dry-Climate Analogue for the Future Boreal Forest? *Water, Air and Soil Pollution*, **82**(1/2):391-400.

Houghton, J.T., L.G. Meira Filho, B.A Callander, N. Harris, A. Kattenberg, and K. Maskell (Editors). 1996. *Climate Change 1995: The Science of Climate Change*. Intergovernmental Panel on Climate Change [IPCC] Working Group I. Cambridge University Press, New York, New York. 572 pp.

Houghton, J.T., Y. Ding, D.J. Griggs, M. Noguer, P.J. van der Linden, X. Dai, K. Maskell, and C.A. Johnson (Editors). 2001. *Climate Change 2001: The Scientific Basis*. Intergovernmental Panel on Climate Change [IPCC] Working Group I. Cambridge University Press, New York, New York. 881 pp.

Intergovernmental Panel on Climate Change [IPCC]. 2001. *Data Distribution Centre [DDC]* [Web Page]. Available at: http://ipcc-ddc.cru.uea.ac.uk/.

Jones, P.D., K.R. Briffa, T.P. Barnett, and S.F.B. Tett. 1998. High-resolution Palaeoclimatic Records for the Last Millennium: Interpretation, Integration and Comparison with GCM Control-Run Temperatures. *The Holocene*, **8**:455-471.

Kharin, V.V. and F.W. Zwiers. 2000. Changes in the Extremes in an Ensemble of Transient Climate Simulations With a Coupled Atmosphere-Ocean GCM. *Journal of Climate*, **13**:3760-3788.

Mearns, L.O., C. Rosenzweig, and R. Goldberg. 1997. Mean and Variance Change in Climate Scenarios: Methods, Agricultural Applications, and Measures of Uncertainty. *Climate Change* **35**:367-396.

National Assessment Synthesis Team. 2001. *Climate Change Impacts on the United States: The Potential Consequences of Climate Variability and Change*. Report for the US Global Change Research Program. Cambridge University Press, Cambridge, United Kingdom. 620 pp.

Parry, M. and T. Carter. 1998. *Climate Impact and Adaptation Assessment*. Earthscan Publications, London, England. 166 pp.

Parry, M.L., T.R. Carter, and N.T. Konijin (Editors). 1988. *The Impact of Climatic Variations on Agriculture, Vol. 1: Assessments in Cool Temperate and Cold Regions*. Kluwer Academic Publishers, Dordrecht, The Netherlands. 876 pp.

Phillips, D. 1993. *The Day Niagra Falls Ran Dry! Canadian Weather Facts and Trivia*. Key Porter Books, Toronto, Ontario.

Phillips, D. 1990. *The Climates of Canada*. Canadian Government Publishing Centre, Ottawa, Ontario.

Smith, J.B. and M. Hulme. 1998. Climate Change Scenarios (Chapter 3). *In*: Feenstra, J., I. Burton, J.B. Smith, and R.S.J. Tol (Editors). *Handbook on Methods of Climate Change Impacts Assessment and Adaptation Strategies*, pp. 3-1-3-40. United Nations Environment Programme, Amsterdam, The Netherlands.

Smith, J.B. and D.A. Tirpak. 1988. *Potential Effects of Global Climate Change on the United States: Volume 1, Regional Studies*. United States Environmental Protection Agency, Washington, District of Columbia.

Tett, S.F.B., T.C. Johns, and J.F.B. Mitchell. 1997. Global and Regional Variability in a Coupled AOGCM. *Climate Dynamics* **13**:303-323.

Wheaton, E. 2001. *Past Climate Changes of the Canadian Prairie Provinces*. Prepared for the Government of Canada's Climate Change Action Fund (A305). Saskatchewan Research Council [SRC] Publication No. 11341-1E01. SRC, Saskatoon, Saskatchewan.

Wheaton, E. 1992. Using Climatic Change Scenarios to Estimate Ecoclimatic Impacts. *The Canadian Geographer* **36**(1):67-69.

Williams, G.D.V., R.A. Fautley, K.H. Jones, R.B. Stewart and E.E. Wheaton. 1988. Estimating Effects of Climatic Change on Agriculture in Saskatchewan, Canada. *In*: Parry, M.L., T.R. Carter, and N.T. Konijin (Editors), *The Impact of Climatic Variations on Agriculture, Vol. 1: Assessments in Cool Temperate and Cold Regions*, pp. 219-379. Kluwer Academic Publishers, Dordrecht, The Netherlands.

World Meteorological Organization. 2000. *WMO Statement on the Status of the Global Climate in 1999.* World Meteorological Organization, Geneva, Switzerland. 12 pp.