Climate Change, Ecosystem and Water Resources: Modeling and Impact Scenarios for the South Saskatchewan River Basin, Canada: A Working Paper

V.Wittrock, E. Wheaton, S. Kulshreshtha
University of Regina
June, 2005

IACC Project Working Paper No. 25

Please do not quote or cite this publication without the permission of V.Wittrock.

Please contact V.Wittrock at sauchyn@uregina.ca.

LIMITED REPORT

Climate Change, Ecosystem and Water Resources: Modeling and Impact Scenarios for the South Saskatchewan River Basin, Canada: A Working Paper

for

Institutional Adaptation to Climate Change Project
University of Regina
Regina, Saskatchewan

by

V. Wittrock[1], E. Wheaton[1], S. Kulshreshtha[2]

[1]Saskatchewan Research Council and [2]University of Saskatchewan

SRC Publication No. 11899-1E05

June, 2005

LIMITED REPORT

Climate Change, Ecosystem and Water Resources: Modeling and Impact Scenarios for the South Saskatchewan River Basin, Canada: A Working Paper

for

Institutional Adaptation to Climate Change Project
University of Regina
Regina, Saskatchewan

by

V. Wittrock[1], E. Wheaton[1], S. Kulshreshtha[2]

[1]Saskatchewan Research Council and [2]University of Saskatchewan

Saskatchewan Research Council
15 Innovation Boulevard
Saskatoon, SK S7N 2X8
Tel: 306-933-7432
Fax: 306-933-7817

SRC Publication No. 11899-1E05

June, 2005

ABSTRACT

This paper describes the climate modeling used to develop climate change scenarios and describes the ecosystem (vegetation and watershed) modeling used to develop ecosystem impact scenarios. The paper is divided into three main subjects. First, selected climate change models and their resulting scenarios are reviewed. It is recommended that the most recent emissions and climate scenarios should be used as they incorporate the most appropriate information available. Also, at least three different Global Climate Models, portraying different emission scenarios, should be used. Second, several main ecosystem models are described with emphasis on water and vegetation issues. The vegetation models examined include the Climate Moisture Index; the GrassGro Decision Support System; grassland regression models. A couple of hydrologic models used in Canada are WATFLOOD and SLURP. Finally, two water use models are reviewed. The models used for the South Saskatchewan River basin include the Government of Alberta's Water Resource Management Model and Environment Canada's Water Use Analysis Model. Both models provide projections of multisectoral water uses in a drainage basin context.

EXTENDED ABSTRACT

Climate change is not just an environmental problem, but is also an economic, health and social issue that will affect the livelihoods and social well-being of Canadians especially those in the South Saskatchewan River Basin. The project "Institutional Adaptations to Climate Change: Comparative Study of Dry-land River Basins in Canada and Chile" requires the development of both climatic change scenarios and impact scenarios to translate the climate information into impact and adaptation information. Since water resources are adversely affected under climate change, a particular attention is paid to this sector

The purpose of the paper is to describe the climate modeling used to develop climate change scenarios and to describe the ecosystem modeling used to develop ecosystem impact scenarios. The paper has three main subjects. First, selected climate change models and their resulting impact scenarios are reviewed. Second, several main ecosystem models and their scenarios are described with emphasis on water and vegetation issues. Finally, water use models are reviewed.

The method to achieve these objectives is through a critical literature review with emphasis on the last five years of published information.

The climate change sections include descriptions of emission scenarios, criteria for climate change scenarios, types of climate scenarios, the uncertainties of emission and climate scenarios and how well they work. The various types of scaling were also discussed.

Based on this review, it is recommended that the most recent emissions and climate scenarios should be used as they incorporate the most information available regarding global conditions. Also, at least three different Global Climate Models (GCMs), portraying three different emission scenarios, should be used. This allows the researcher to assess a range of options in the impacts and adaptations work. The three most common Special Report on Emissions Scenarios (SRES) driven GCMs utilized for the Canadian prairies appear to be the Canadian Centre for Climate Modeling and Analysis Economic Regional Simulation (CGCM2 A21), Commonwealth Scientific Industrial Organization (CSIROMk2b) and Hadley Centre Environmental Regional Focus Simulation (HadCM3 B21) with occasional utilization of CGCM2 B22 and HadCM3 A21.

Downscaling is a tool that researchers in the impacts and adaptation area utilize for a more complete regional detail. There are numerous methods to downscale, but the process that appears to have some potential is the statistical downscaling approach because it can be utilized in both Canada and Chile. Regional climate models (RCMs) are still in their infancy. There are fewer RCMs than GCMs so researchers cannot portray a range of climatic possibilities. Statistical downscaling allows researchers to use many different GCMs.

Climatic extremes are still very difficult to project using GCMs. The best information GCMs provide relates to changes in extremes that occur on a coarse spatial scale, such as temperature, but they do not provide information on a fine scale such as thunderstorms or tornadoes. One way to estimate changes in extreme events that occur with a 10 to 100 year return period, for example, is through statistics such as the Gumbel distribution.

Climate change is expected to have potentially serious consequences for plant and animal populations as well as water availability. Ecosystems tend to respond directly to short-term departures from normal climate and to extreme events but will ultimately respond to the longer-term effects of climate change.

In the Canadian Prairies, several different ecosystem models have been used to assess how ecosystems may respond to a changed climate. This study focuses on vegetation zonation and stream flow models. A few examples are described.

To analyse the potential impact of climate change on island forests in the Canadian Prairies, Henderson et al. (2002) constructed climate scenarios to derive climate moisture indices. They found that while the Climate Moisture Index (CMI) provides a good fit to boundary lines between major vegetation ensembles, the index does not provide the critical constraints that have prevented some vegetation types from growing in areas of water deficit.

Cohen et al. (2002) integrated the Canadian Climate Change model (CGCM1) into the GrassGro Decision Support System to study possible impacts on pasture growth. Thorpe et al. (2004) examined the productivity of native grasslands under climate change in the Canadian Prairies. Their main method of data analysis was multiple linear regression of grassland production using various combinations of climate or water balance variables.

In the parkland/boreal forest region of Saskatchewan, Carr et al. (2004) used a recursive partitioning statistical method for investigating what differentiates the members of one vegetative group from their subgroups. Other models include the HyLand terrestrial model which applies Monte Carlo analysis to the spatial covariance in historical and projected climate plus other parameters to produce a series of empirical models. Other researchers use a combination of emission scenarios and various climate scenarios to determine the vegetative growth, yield and zonation changes from a combination of CO_2 fertilization with the added potential stress of higher temperature and other climatic changes.

In Canada, the hydrologic models WATFLOOD and SLURP appear to be commonly used. They both estimate potential stream flows in the short and longer term. Their validation appears to be relatively good especially on the annual time scale. Currently WATFLOOD is being used to assess potential average flows under climate change but the study results (Pietroniro et al. 2003) are not yet available for inclusion in this paper.

In other parts of the world, stochastic daily weather generators have been used (Pittock 2003). In Australia, CSIRO Mark 1 model was used to estimate mean flows and extreme high runoff events (Evans and Schreider 2002).

Other researchers such as Arnell (2004), have simulated stream flow in over 1300 watersheds world-wide using six Global Climate Models run with the SRES emissions scenarios. He found that the macro-scale hydrological model simulated average annual runoff reasonably well.

Water from the South Saskatchewan River has many uses including agricultural, municipal and residential, industrial, and recreational. Several models are used to simulate water use and demand. Two major models covering either a part or whole of the South Saskatchewan River basin are the Government of Alberta's Water Resource Management Model (WRMM) and Environment Canada's Water Use Analysis Model (WUAM). The WRMM covers only the Alberta portion of the South Saskatchewan River Basin, whereas the WAUM has been developed for the Saskatchewan portion of the basin, particularly for Lake Diefenbaker. The WUAM model is currently being extended to the entire basin. Both models provide projections of multisectoral water uses in a drainage basin context.

Other models have been set up to model a specific water usage. For example Akuoko-Asibey et al. (1993) developed a statistical model to evaluate weekly water consumption in a large urban centre (Calgary). Other models have been used to assess irrigation allocation (Doll 2002). The WaterGap model is a global water usage model that examines the level of water stress of a region. Alcamo and Henrichs (2002) found that the southern Canadian Prairie has mid-stress levels while parts of Chile are under severe water stress.

Little research has been done to estimate water use changes to climate change impacts. Two particular types of information are lacking. First, there have been no attempts made, with the exception of some preliminary modeling of irrigation water use, to relate water use levels with climatic change. Second, much of the data using the present water use patterns have been based on requirements, and on some synthesis or industrial simulation, and not based on actual observations. Furthermore, a potential difficulty in determining water usage is that some of the municipal and irrigation areas are only partially metered. This results in difficulties in formulating answers to "how will the water stress situation change in the future?".

TABLE OF CONTENTS

TABLE OF CONTENTS Continued

LIST OF FIGURES

LIST OF TABLES

LIST OF ACRONYMS AND ABBREVIATIONS

AAFC-WG	Agriculture and Agri-Food Canada Weather Generator
AGCM	Atmospheric General Circulation Model
AOGCM	Atmosphere Ocean General Circulation Model
ANUSPLIN	Name of Program
C	Carbon
CCC AGCM	Canadian Climate Center, Atmospheric General Circulation Model
CCC GCM2	Canadian Climate Centre 2nd Generation General Circulation Model
CCCma	Canadian Centre for Climate Modelling and Analysis
CCM	Community Climate Model
CCSR-98	Centre for Climate Research – 98
CCSR/NIES	Center for Climate Research/National Institute for Environmental Studies
CGCM	Canadian Global Climate Model
CLASS	Canadian Land Surface Scheme
CMD IHACRES	Catchment Moisture Deficit – Identification of unit Hydrographs And Component flows from Rainfall, Evaporation and Streamflow
CMIs	climate moisture indices
CO_2	Carbon Dioxide
CRCM	Canadian Regional Climate Model
CSIRO	Commonwealth Scientific Industrial Research Organization
°C	Degrees Celsius
DPHM-RS	Semi-Distributed Physics Based Model
ECHAM	Max Planck Institute für Meteorologie
ED	Ecosystem dynamics models
EF	Ecosystem function models
FFIRM	Farm Financial Impact and Risk Model
GCMs	Global Climate Models
GFDL	Geophysical Fluid Dynamics Laboratory
GFDL-R15	Geophysical Fluid Dynamics Laboratory Rhomboidal Resolution of 15 Wave
GHG	Greenhouse Gas
GIM	Global Irrigation Model
GISS	Goddard Institute for Space Studies
GrassGro	Name of Program
GtC	Giga-tonnes of carbon equivalent
HadCM	Hadley Centre Model
HadGEM1	Hadley Centre Global Climate Model Version 1
HYCOM	Hybrid Coordinate Ocean Model

IBIS	Integrated Biosphere Simulator
IDM	Irrigation District Model
IPCC	Intergovernmental Panel on Climate Change
IS92	IPCC Alternative Scenario
Km	Kilometres
LARS-WG	Name of Program
Mk2b	Mark 2b
MOM	Modular Ocean Model
MtS	Megatonnes of Sulphur
NCAR	National Centre for Atmospheric Research
NCAR-DOE	National Centre for Atmospheric Research Model, DOE Version
NCOM	National Centre for Atmospheric Research Ocean Model
ND	No Date
PCM	Parallel Climate Model
PRISM	Name of Climate Data Set
RCMs	Regional Climate Models
SLURP	Semi-distributed Land-Use Runoff Process
SRES	Special Report on Emissions Scenarios
SSRB	South Saskatchewan River Basin
TgS	Teragrams of Sulphur
TOPAZ	Terrain Analyses Model
WaterGap	Global Model of Water Availability and Water Use
WATFLOOD	Distributed Hydrologic Model
WRMM	Water Resource Management Model
WUAM	Water Use Analysis Model

INTRODUCTION AND PURPOSE

A set of working papers are being written in support of the project "Institutional Adaptations to Climate Change: Comparative Study of Dry-land River Basins in Canada and Chile" by Diaz et al. (2003). The methodology for assessment of future adaptive capacity of institutions to deal with a changing climate requires the development of both climatic change scenarios and impact scenarios to translate the climate information into impact and adaptation information.

A scenario is defined as a "plausible and often simplified description of how the future may develop, based on a coherent and internally consistent set of assumptions about key driving forces (e.g. rate of technology change, prices) and relationships. Scenarios are neither predictions nor forecasts and sometime may be based on a "narrative storyline." (Watson et al. 2001*b*). Scenarios can be of various types, including ones for describing greenhouse gas emissions, climate changes, impacts and adaptations. Scenarios are often developed by running models of various types, including socioeconomic models, Global Climate Models, and impact and adaptation models.

The purpose of this paper is to describe the climate modelling used to develop climate change scenarios and to describe the ecosystem modelling used to develop ecosystem impact scenarios. Climate change and impact scenarios are described in order to provide an understanding of the range of possible futures faced by institutions.

This paper has three main subjects. First, climate change models and their resulting impact scenarios are described. The main climatic parameters of temperature, precipitation and their averages and variability are emphasized. Then, ecosystem models and their scenarios are described. We focus on water (surface water and soil moisture) and vegetation issues. Finally, water use and demand scenarios are reviewed.

SCOPE, METHODS AND STUDY AREA

The scope of this paper is not to develop climate change scenarios and their corresponding impact scenarios, but to describe the work already done in terms of the implications for the main project (Diaz et al. 2003) and for the study area. Therefore, the methods used include critical literature review based on recent publications and discussions with experts.

The study area is the South Saskatchewan River Basin (Figure 1), although this paper includes information for areas beyond this basin for purposes of comparison and contrast, as required. Also as the climate changes, eco-climatic regions are also changing, meaning that other eco-climates especially those to the south will be affecting this basin more frequently. Therefore, information about these eco-climates is relevant.

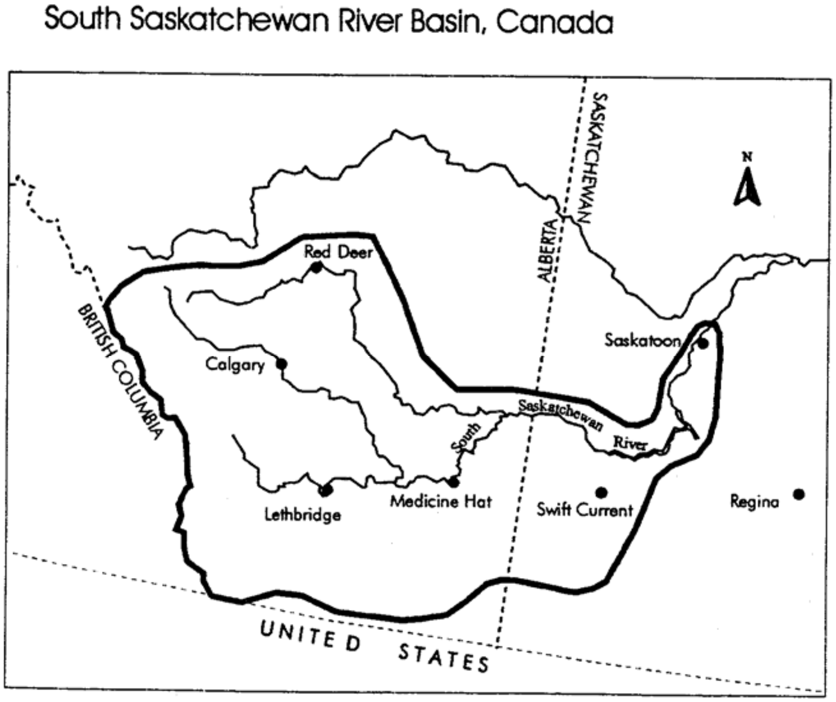

Figure 1 South Saskatchewan River Basin (Diaz et al. 2003)

CLIMATE CHANGE SCENARIOS

Overview

This section includes descriptions of the modelling and scenarios related to greenhouse gas emissions and climate change. Scenarios are often developed for quite different time and space scales than required for this paper. Global scenarios are a common spatial scale, with annual or perhaps monthly data available. Therefore, it is necessary to discuss scaling of the information.

Climate scenarios are not predictions. They are a plausible representation of the future that is consistent with assumptions about future emissions of greenhouse gases and other pollutants and with what is understood about the effect of increased atmospheric concentrations of these gases on the global climate. Other assumptions include future trends in energy demand and land use change (Carter et al. 1999 Guidelines on the use of).

Types of Climate Change Scenarios

There are several different types of scenarios that can be used in vulnerability, impact and adaptation research. The main types of climate scenarios described here are synthetic and analogue. This section documents the various types of scenarios, as well as their advantages and disadvantages.

Synthetic Scenarios

Synthetic scenarios are considered to be the simplest climate scenarios available. Generally, they are used for defining the sensitivity of an exposure unit to a plausible range of climatic variations, but they seldom present a future climate that is physically plausible (Barrow and Lee 2003). Synthetic scenarios are techniques where particular climatic or related elements are changed by a realistic but arbitrary amount, often according to a qualitative interpretation of climate model simulations for a region (Carter et al. 1999).

Carter et al. (1999) describe several advantages of scenarios such as:

- They are simple to apply for impact analysts, transparent and easily interpreted by policy makers and non-specialists.
- They capture a wide range of possible changes in climate, offering a useful tool for evaluating the sensitivity of an exposure unit to changing climate. Since individual variables can be altered independently of each other, synthetic scenarios also help to describe the relative sensitivities to changes in different climatic variables. They can assist in identifying thresholds or discontinuities of response that might occur under a given magnitude or rate of climate change.
- Different studies can readily apply the same synthetic scenarios to explore relative sensitivities of exposure units. This is potentially useful for comparing synthesizing the potential effects of climate change over different sectors and regions.

Carter et al. (1999) also indicate several disadvantages for using synthetic scenarios:

- Synthetic scenarios are arbitrary. They seldom present a realistic set of changes that are physically plausible, commonly representing adjustments as being uniform over time and space and inconsistent among variables.
- Some synthetic scenarios may be inconsistent with the uncertainty range of global changes. This limitation can be overcome if the selection of synthetic scenarios is guided by information from GCMs.

Analogue Scenarios

Analogue scenarios are constructed by identifying a recorded climate regime which may resemble the future climate anticipated for a particular site or region. These recorded climates may be identified by temporal analogues (using long observation records at a site) or by spatial analogues (from other geographical locations) (Carter et al. 1999; Barrow and Lee 2003).

There are disadvantages to analogue scenarios. The causes for the analogue climate may be different from the causes underlying future greenhouse gas induced climate change (Carter et al. 1999). Paleoclimatic changes were possibly caused by variations in the earth's orbit, for example, while instrumental period changes may be the result of or related to naturally occurring changes in atmospheric circulation (Carter et al. 1999). The assumption associated with both temporal and spatial analogue scenarios is that climate will respond in the same way to a unit change in forcing despite its source, even if boundary conditions differ (Barrow and Lee 2003).

These scenarios have the advantage of representing conditions that have been observed and experienced, rather than conditions hypothesized by models or expert judgement. The main value of analogue scenarios lies in testing and validating impact models, but it is not ordinarily recommended that they be adopted to represent the future climate in quantitative impact assessments (Carter et al. 1999; Smith et al. 1998).

The first type of analogue scenario is the temporal analogue. This analogue makes use of climatic information from the past as description of possible future climate (Carter et al. 1999). For example, the Palaeoclimatic analogue is based on information from fossil evidence, such as plant or animal remains and sedimentary deposits. Three periods have received attention – the mid-Holocene (5000 to 6000 years Before Present) – when the northern hemisphere temperatures are estimated to have been about 1°C warmer than present, the Last Interglacial (125000 Before Present) – about 2°C warmer and the Pliocene (three to four million years Before Present) – about 3 to 4°C warmer. During these periods, global temperatures relative to present conditions may have been similar to changes anticipated during the 21st century (Carter et al. 1999).

The second type of temporal analogue is the instrumentally-based analogue. This analogue selects data from the historical instrumental record usually within the 20th century. It has been used to identify past periods of observed global warmth as an analogue of a greenhouse gas induced warmer world. Scenarios are often constructed by estimating the difference between the regional climate during the warm period and that of the long term average or that of a similarly selected cold period. An alternative approach is to select the past period on the basis of using both observed climatic conditions and recorded impacts. Another method employs observed atmospheric circulation patterns as analogues (Carter et al. 1999).

Spatial analogues use regions which today have a climate that may occur in the study region in the future. The disadvantage of this approach may be the lack of correspondence between certain features (both climatic and non-climatic) of the two regions such as daylength and soils. Therefore, it is unlikely that the present-day combination of climatic and non-climatic conditions prevailing in an analogue region today would be physically plausible scenarios for conditions in the study region in the future (Carter et al. 1999).

Global Climate Models or Regional Climate Based Models Using Various Emission Scenarios

Global Climate Models (GCMs) represent physical processes in the atmosphere, ocean, cryosphere and land surface (Carter et al. 1999). GCMs depict the climate using a three dimensional grid over the planet. They have a horizontal resolution of between 250 and 600 km and between 10 and 20 vertical layers in the atmosphere and sometimes as many as 30 layers in the oceans (Carter et al. 1999; Barrow and Lee 2003).

Carter et al. (1999) state that the GCMs are the only credible tools available for simulating the response of global climate system to increasing greenhouse gas concentrations and other factors. The newer GCMs are able to distinguish between the warming effect of greenhouse gases and the regional cooling effect of sulphate aerosols (Barrow and Lee 2003). Also GCMs, possibly in conjunction with nested regional climate models, have the potential to provide geographically and physically consistent estimates of regional climates for impact analyses (Carter et al. 1999).

Since 1990, greenhouse gas emissions scenarios have been used to provide information on future atmospheric composition and the resultant effect on the radiation balance of the atmosphere. This information usually extends until 2100. These scenarios are known as ‘warm start’ experiments and are now most widely used in the construction of climate change scenarios. Previously used scenarios, known as ‘cold start’ did not include a representation of observed changes in atmospheric composition over the historical period resulting in a lag between the start of the climate change experiment in 1990 and the earth-atmosphere-ocean system response. ‘Cold start’ experiments have been superseded by ‘warm start’ experiments (Barrow and Lee 2003).

Criteria for Usage

The Intergovernmental Panel on Climate Change has developed guidelines on the use of scenario data for impact and adaptation assessments (Smith et al. 1998; Carter et al. 1999; Barrow and Lee 2003). They include:

- Consistency with global projections – scenarios should be within the broad range of climate change projections.
- Physical plausibility – scenarios should be consistent with the physical laws that govern climate. Hence changes in one region should be physically consistent with those in another region as well as with those at the global scale. Also, climate variables are often correlated with one another, so changes in one variable should be reflected by changes in the related variables.
- Applicability in impacts assessments – scenarios should describe changes in a sufficient number of climate variables at a spatial and temporal scale that allows for climate impact assessments.
- Representativeness – scenarios should be representative of the potential range of future regional climate change so as to allow a realistic assessment of possible impacts (Carter et al. 1999; Barrow and Lee 2003).
- Accessibility – scenarios should be straightforward to obtain, interpret and apply in impacts assessments and environmental assessments.

Smith et al. (1998) and Carter et al. (1999) also made recommendations for selecting model outputs for impact assessment including:

- Vintage – recent model simulations are likely to be more reliable than those of an earlier vintage (Carter et al. 1999).
- Resolution – there has been a tendency towards increased resolution. However, although higher resolution models contain more spatial detail (i.e. complex topography, better-defined land/sea boundaries, etc.) this does not necessarily guarantee a superior model performance (Carter et al. 1999).
- Validity – GCMs that simulate the present-day climate most faithfully should be used, with the assumption that these GCMs’ would also yield the most reliable representation of future climate (Carter et al. 1999). GCMs performance can depend on the size of the region, its location and on the variables being analysed. The most valuable function of a model inter-comparison study is to exclude those models whose performance is unacceptably poor, especially in estimating features of the climate that are of critical importance for the impact application. Also, models giving the best correlation

coefficients for the control simulation may not necessarily be the models providing the most reliable predictions (Carter et al. 1999).

- Representativeness of Results – it is also recommended that more than one GCM be used (Carter et al. 1999; Nakicenovic et al. 2000). The various GCMs can display large differences in estimates of regional climate change, especially for variables like precipitation, which frequently show wetter conditions in a region in some models and dryer in others. Also, it is considered to be prudent to choose models that show a range of changes in a key variable in the study region. Given the substantial inter-decadal climatic variability exhibited by most GCMs, it was often difficult to distinguish a climate change signal from the background noise. Therefore, it is recommended that at least a 30 year period is employed for averaging GCM output data to dampen the effects of interdecadal variability (Carter et al. 1999).

Emission Scenarios

Greenhouse gas emissions are the product of complex dynamic systems determined by various driving forces such as demographic development, socio-economic development and technological change (Nakicenovic et al. 2000). This section briefly examines the IPCC alternative scenarios (IS92) and examines the IPCC Special Report on Emissions Scenarios (SRES) in more details plus gives an indication of the limitations of the most recent emissions scenarios.

IS92 Emissions Scenarios

The IS92 emissions scenarios, classified as the ‘business as usual’ scenarios, were used in the Intergovernmental Panel on Climate Change Second Assessment Report (Houghton et al. 1996). Six emissions scenarios were defined (Table 1), spanning a range of assumptions concerning population growth potential, economic growth, energy use, technological changes and transfer plus responses to environmental, economic and institutional constraints. Each of the scenarios was defined to be equally likely to occur, but the IS92a scenario was generally most used by the climate modeling and impacts community (Barrow 2002; Canadian Institute for Climate Studies 2003*c*).

Table 1 IS92 Emissions Scenarios (Leggett et al. 1992)

Scenario Estimates	**IS92 Emissions Scenarios for 2100**					
	IS92a	**IS92b**	**IS92c**	**IS92d**	**IS92e**	**IS92f**
Population (billion)	11.3	11.3	6.4	6.4	11.3	17.6
CO_2 emissions per year (GtC)	20.3	19.1	4.6	10.3	35.8	26.6
SO_x emissions per year (TgS)	169	164	77	87	254	204

SRES Emission Scenarios

Quantitative emission drivers have been constructed and detailed in the IPCC Special Report on Emissions Scenarios (SRES) (Nakicenovic et al. 2000). These scenarios were constructed to explore future development of the global environment with special reference to the production of greenhouse gases and aerosol precursor emissions (Carter et al. 1999). The SRES emissions scenarios are the qualitative interpretations of these qualitative storylines (Canadian Institute for Climate Studies 2003*a*). These scenarios are reference scenarios that try to exclude the effects of climate change and climate related policies on society and the economy (categorized as non-intervention scenarios) (Carter et al. 2000). SRES emissions scenarios do not include policies explicitly designed to account emission increases. Carter et al. (2004) suggested that they should be regarded as baseline, non-intervention scenarios.

SRES scenarios include estimated emissions of carbon dioxide, nitrous oxide and sulphur dioxide. These scenarios contain higher upper limits of carbon dioxide emissions but lower sulphur dioxide levels than the IS92 scenarios (Pittock 2003). The SRES lower sulphur levels result in the projected global temperature increase to be 2.0 to 3.1°C rise compared to the 1.4 to 2.6°C rise using the IS92 scenarios. This is due to sulphate aerosols reflecting sunshine, therefore the lower sulphur levels of SRES mean less warming than the IS92 scenarios (Canadian Institute for Climate Studies ND). The resulting accumulated emission by 2100 for all of the SRES scenarios, expressed in units of thousand of millions of tonnes of carbon equivalent (GtC), range from a low of 770 GtC to about 2540 GtC. The range of IS92 scenarios was between 770 and 2140 GtC (Pittock 2003).

The SRES approach developed a set of four “scenario families” (Figure 2). SRES storylines provide a range of potential world developments. They form the basis for estimating the emissions that are used to ‘force’ the climate models (Canadian Institute for Climate Studies ND). The storylines of each of these four scenario families describes demographic, politico-economic, societal and technological futures. The four scenario families combine two sets of divergent tendencies. One set includes strong economic values and strong environmental values and the other set includes increasing globalization and regionalization (Carter et al. 2000). Within each of the families, one or more scenarios explore global energy, industry and other developments and their implications for greenhouse gas emissions and other pollutants (Carter et al. 1999).

The four storylines were developed to describe the relationships between emission driving forces and add context for the scenario quantification (Nakicenovic et al. 2000). Although the storylines do not contain explicit climate change policy measures, there are examples of indirect mitigation measures in some of the scenarios (Pittock 2003; Carter et al. 1999). The scenario quantifications of the main indicators relate to population and economic growth, energy system characteristics and the associated greenhouse gas emissions all of which fall within the range of prior studies (Carter et al. 1999).

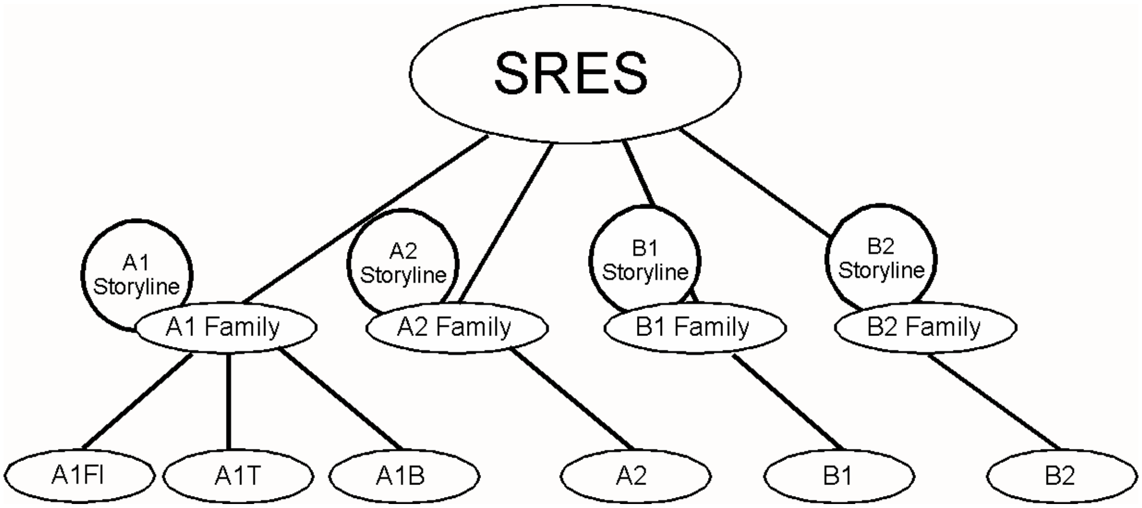

Figure 2 The Family of SRES Scenarios and Storylines (Nakicenovic et al. 2000)

Table 2 is a summary of the SRES scenarios and their estimated environmental impact (Carter et al. 1999). These scenarios are compared to the population and CO_2 concentration of 1990. The population in the A2 scenario by 2100 is projected to be three times the 1990 levels with the CO_2 concentration being equally high.

Table 2 Summary of the SRES Marker Scenarios and their Estimated Environmental Consequences (Carter et al. 1999; Carter et al. 2004)

Scenario Estimates	**1990**	**SRES Marker Scenarios for 2100**			
		A1	**A2**	**B1**	**B2**
Population (billion)	5.252	7.1	15.1	7.2	10.4
CO_2 concentration, fossil fuels (GtC/yr)	60	30.3 to 4.3	28.9	5.2	13.8
Sulfur dioxide emission (MtS/yr)	70.9	40 to 20	60	25	48
Global annual-mean temperature change (°C)		2.52	3.09	2.04	2.16
Range (°C)		1.70-3.66	2.12-4.41	1.37-2.99	1.45-3.14
Global mean sea-level rise (cm)		58	62	50	52
Range (cm)		23-101	27-107	19-90	20-93

The A1 storyline and scenario family describes a future world of rapid economic growth. This storyline indicates that the global population would peak in the mid-2000s and then decline plus a rapid introduction of new and efficient technologies. There would be a convergence among regions, capacity-building and increased cultural and social interactions with a substantial reduction in regional differences in per capita income. The A1 scenario family develops into three groups that describe alternative directions of technological changes in the energy system. This scenario has economic and cultural convergence and capacity building with a substantial reduction in regional differences in per capita income. Personal wealth would be pursued rather than environmental quality (Nakicenovic et al. 2000; Carter et al. 2000; Canadian Institute for Climate Studies 2003*a*).

The A2 storyline describes a heterogeneous, differentiated world. This family's theme is self-reliance and preservation of local identities and a strengthening of regional cultural identities. It includes projections of high population growth. Economic developments will be mostly regional and per capita economic growth and technological change will be more fragmented and slower than the other storylines (Nakicenovic et al. 2000; Canadian Institute for Climate Studies 2003*a*).

The B1 storyline describes a world with the same population growth as the A1 storyline. This storyline has rapid change in economic structures toward a service and information economy with reductions in material intensity or dematerialization. There is an introduction of resource-efficient, clean technologies. The emphasis is on global solutions to economic, social and environmental sustainability and improving equity (Nakicenovic et al. 2000; Carter et al. 2000; Canadian Institute for Climate Studies 2003*a*).

The B2 storyline emphasizes local solutions to economic, social and environmental sustainability. There will be continuously increasing global population but at a rate lower than A2, intermediate levels of economic development and less rapid and more diverse technological change than in B1 and A1. This storyline has strong emphasis on community initiative and social innovation at the local and regional levels. It is oriented towards environmental protection and social equity, but focuses on local and regional levels (Nakicenovic et al. 2000; Carter et al. 2000; Canadian Institute for Climate Studies 2003*a*).

Six illustrative scenarios have been selected by the Intergovernmental Panel on Climate Change for use from in the SRES scenarios. These scenarios were chosen because of they are representative of integrated assessment frameworks (Nakicenovic et al. 2000). They are A1F1 (fossil intensive), A1T (non-fossil energy sources), A1B (balance across all energy sources) from the A1 family and A2, B1 and B2) (Nakicenovic et al. 2000; Canadian Institute for Climate Studies 2003*a*).

SRES scenarios with their socio-economic components are important because they improve the understanding of the relationships among factors that drive future emissions. They assist in assessing the relative importance of trace gases and aerosol precursors in changing atmospheric composition and climate (Carter et al. 1999). These scenarios also offer a framework of projections that can be applied to climate change impact assessments (Carter et al. 1999).

An advantage of using a multi-model approach is that the resultant 40 SRES climate scenarios together encompass the current range of uncertainties of future emissions that arise from the SRES emissions scenarios (Nakicenovic et al. 2000).

Global Climate Models

As stated in the introduction of this report, Global Climate Models (GCMs) offer the most credible tools for estimating the future response of climate to radiative forcing (Carter et al. 1999). The models largely agree on the expected large-scale pattern of climate change, but there are uncertainties in regional projections (Carter et al. 1999).

Global Climate Model Definition

GCMs have been described by many researchers including Ahmad et al. (2001), Hengeveld (2000), Barrow and Lee (2003), Barrow et al. (2004*b*) plus many others. GCMs are numerical models representing the physical processes of and the known feedbacks between the atmosphere, ocean, cryosphere and land surface. The models are used for simulating past, present and future climate. Most GCMs have a horizontal resolution of 250 to 600 km and 10 to 20 vertical layers in the atmosphere and up to 30 ocean layers.

The most advanced GCMs are coupled atmosphere-ocean models. These models can be used to simulate the climate response to changing atmospheric greenhouse gas and aerosol concentrations and provide information about the rate and magnitude of climate change (Barrow et al. 2004*b*).

Global Climate Model Uncertainties

GCMs have many uncertainties and areas of concern associated with them. These uncertainties have been documented in many pieces of literature (Barrow 2002; Barrow and Lee 2003; Carter et al. 1999). Researchers (e.g., Barrow 2002; Barrow and Lee 2003; Carter et al. 1999) also brought forward suggestions to deal with the uncertainties. These suggestions are discussed in the Criteria for Usage Section of this document.

There are several uncertainties with many physical processes, such as those related to clouds, occur at smaller scales and cannot be properly modeled. Therefore, their known properties must be averaged over the coarser scale using a parameterization technique. Other uncertainties relate to the simulation of various feedback mechanisms in models concerning water vapour and warming, clouds and radiation, ocean circulation and ice and snow albedo, for example. Therefore, GCMs may simulate different responses to the same forcing, because of the way certain processes and feedbacks are modeled (Carter et al. 1999).

Uncertainties in the future projections of climate partly stem from uncertainties in defining the factors that affect future emissions scenarios (Barrow and Lee 2003). Future emission scenarios are dependent upon the rate of human emissions of greenhouse gases; population growth, economic growth, energy efficiency, type of energy used and land-use change (Hengeveld 2004). While these variables are not independent of each other, their evolution will vary geographically and have the potential to have dramatic changes.

Giorgi et al. (2001) have found through analysis of AOGCM simulations for sub-continental scale regions that there are biases in the simulation of present day regionally and seasonally averaged surface climate variables. They found high variability across regions and models, but these more recent simulations were generally better than the previous generation models. They also found that the performance of models in reproducing observed inter-annual variability varies across regions and models.

Natural forcing of the climate occurs through volcanic eruptions and changes in solar radiation, for example, which are not always included in the GCMs (Hengeveld 2004). However it is believed that these natural forcings do not significantly add to the uncertainty in the longer, i.e., decadal, time period involved in GCM projections (Ramaswamy et al. 2001; Hengeveld 2004).

Ocean circulation is an uncertainty in climate variability over the decadal- and longer- time periods (Hengeveld 2004). Oceanic oscillations have significant influence on global atmospheric circulation and therefore on regional climate. While GCMs capture some of these oscillations, they may not fully capture changes in the variability (Hengeveld 2004).

Uncertainties also pertain to the complexity and/or highly variable state of the real climate system. Many of the linkages in this system are poorly understood (Hengeveld 2004). Also, computing power to run the GCM is a significant limitation. It only allows a certain amount of detail to be included in describing these processes within the models and simulating them with adequate geographic resolution (Hengeveld 2004).

Mearns et al. (2003) developed a table of scenario types, the description and use of the scenarios and advantages and disadvantages of each type (Table 3). The advantages and disadvantages are based on the five criteria from the Intergovernmental Panel on Climate Change (Smith et al. 1998; Carter et al. 1999; Barrow and Lee 2003).

In summary, climate change forecasting includes many uncertainties (Allen et al. 2004). These include uncertainty in anthropogenic forcing due to different emission paths (scenario uncertainty); uncertainty due to natural variability encompassing internal chaotic climate variability and externally driven (e.g., solar, volcanic) natural climate change (natural variability). The third uncertainty deals with climate system's response to external forcing due to incomplete knowledge of feedbacks and timescales in the system (response uncertainty).

Global Climate Model Progress

Many developments to the GCMs are currently taking place. In the summer of 2004, the IPCC Working Group I had a meeting that explained how the various GCMs around the world were changing (Table 4).

Table 3 Climate Scenario Types and an Evaluation of their Advantages and Disadvantages According to the Five Criteria (Mearns et al. 2003)

Scenario Type or Tool	Description/Use	Advantages*	Disadvantages*
-Climate model based: Direct AOGCM outputs	-Starting point for most climate scenarios -Coarse spatial resolution response to anthropogenic forcing	-Information derived from the most comprehensive, physically-based models (1,2) -Long integrations (1) -Data readily available (5) -Many variables (potentially) available (3)	-Spatial information is poorly resolved (3) -Daily characteristics may be unrealistic except for very large regions (3) -Computationally expensive to derive multiple scenarios (4, 5) -Large control run biases may be a concern for use in certain regions (2)
-High resolution/stretched grid (AGCM)	-Providing high resolution information at global/continental scales	-Provides highly resolved information (3) -Information is derived from physically-based models (2) -Many variables available (3) -Globally consistent and allows for feedbacks (1, 2)	-Computationally expensive to derive multiple scenarios (4, 5) -Problems in maintaining viable parameterizations across scales (1, 2) -High resolution is dependent on sea surface temperature and sea ice margins for driving model (AOGCM) (2) -Dependent on (usually biased) inputs from driving AOGCM (2)
-Regional models	-Providing high spatial/temporal resolution information	-Provides very highly resolved information (spatial and temporal) (3) -Information is derived from physically based models (2) -Many variables available (3) -Better representation of some weather extremes than in GCMs (2, 4)	-Computationally expensive to derive multiple scenarios (4, 5) -Lack of two-way nesting may raise concern regarding completeness (2) -Dependent on (usually biased) inputs from driving AOGCM (2)
-Statistical Downscaling	-Providing point/high spatial resolution information	-Can generate information on high resolution grids, or non-uniform regions (3) -Potential for some techniques to address a diverse range of variables(3) -Variables are (probably) internally consistent (2) -Computationally (relatively) inexpensive (5) -Suitable for locations with limited computational resources (5) -Rapid application to multiple GCMs (4)	-Assumes constancy of empirical relationships in the future (1, 2) -Demands access to daily observational surface and/or upper air data that spans range of variability (5) -Not many variables produced for some techniques (3, 5) -Dependent on (usually biased) inputs from driving AOGCM (2)

* number in parentheses refers to criteria below

Criteria of evaluation:

1) Consistency at regional level with global projections
2) Physically plausibility and realism, such that changes in different climatic variables are mutually consistent and credible and spatial and temporal patterns of change are realistic
3) Appropriateness of information for impact assessments (i.e., resolution in time and space, variables)
4) Representativeness of the potential range of future regional climate change
5) Accessibility for use in impact assessments

Table 4 Specific Improvements to the Models (IPCC Working Group I 2004)

Model Source Agency	**Model Developments**
NCAR	-Improved prognostic cloud liquid water scheme and mid-level cloud amount compares better with observations (raised low sensitivity)
GFDL	-Improved boundary layer scheme
CCCma	-Improved cloud optical properties (raised hydrological sensitivity)
CCSR/NIES	-Improved and better tuned cloud physics – e.g., cloud ice to cloud water conversion
HadGEM1	-New dynamical core, new boundary layer, new convection scheme and many other changes (slightly higher sensitivity)
GISS	-Model E AGCM has been coupled to two oceans models HYCOM and Russell; many model changes and difficult to attribute sensitivity change to any particular change

Participants at the IPCC Paris Workshop believed that they could strengthen the traditional Charney range at least at the low end (Kerr 2004). In 1979 Charney estimated the global mean climate sensitivity for doubled CO_2 to be between 1.5° and 4.5°C (Hansen et al. 1984). Workshop participants thought improvement unlikely at the high end (4.5°C) of climate sensitivity. This is because the calculation of sensitivity probabilities is nonlinear at the high end, producing a small but statistically real chance of an extreme warming (Kerr 2004). Kerr does not state what that extreme warming could be.

The participants generally agreed on the most probable climate sensitivity would be around 3°C. This estimate is based on three approaches – a collection of expert designed independent models, a thoroughly varied single model and paleoclimates over a range of time scales. All of these approaches point to sensitivities in the same temperature range, with the middle of the canonical range appearing to be most likely (Kerr 2004).

In Canada (Zwiers 2005), development will focus on uncertainties. This includes increased resolution of atmosphere and oceans, clouds and aerosols, ocean mixing and variability, interactions with the biosphere, and improving sulphur cycle in AGCM4.

A third generation Canadian atmospheric model (CCC AGCM3) has become operational. It operates at higher horizontal (a 47 wave triangularly truncated spherical harmonic expansion) and vertical resolution (extends from the surface to the stratopause region) than the AGCM2 and includes improved boundary layer, convection, cloud and radiation parameterizations, an optimized representation of the earth's topography and a land surface module (CLASS) (Canadian Centre for Climate Modelling and Analysis 2003).

Hengeveld and Francis (2000) and Hengeveld (2000) stated that CGCM3 would have improvements to the ocean and sea-ice components, as well as include an improved atmosphere-terrestrial system from CGCM1 and CGCM2. They projected that the atmospheric GCM2 will be replaced with GCM3 which continues to use a physical resolution of 3.7° x 3.7° longitude but simulates the dynamical behaviour within the body of the atmosphere at an improved horizontal resolution of about 2.8° latitude by 2.8° longitude and at 32 layers in an atmosphere now extending to an altitude of 50 km. CGCM3 will also include a new method for describing land surface flux processes and land-air interactions. Known as CLASS, this land surface scheme is more detailed than the single soil layer scheme used in CGCM2. CLASS includes 3 soil layers, a snow layer where applicable and a vegetative canopy treatment. Soil surface properties such as surface roughness and albedos are taken to be functions of the soil and vegetation types and soil moisture conditions within a given grid element of the model. The model has improvements to its description of solar radiative heating processes; water vapour transport and convective behaviour within the atmosphere; the turbulent transfer of heat, moisture and momentum within the planetary boundary layer; high terrain topography and the effect of gravity wave drag on surface winds and pressure patterns.

A new ocean model (NCOM1.3) is used in CGCM3. This ocean model includes improvements in the representation of ocean physical processes. An improved sea ice model now includes prognostic values for ice concentration (i.e., the fraction of each grid cell covered by ice).

Extreme Climatic Events

Climate change does not behave in a linear fashion. The climate regime can have sudden changes occurring over wide areas, apparently resulting in the shifting of global circulation patterns or vice versa. The mathematical theory of such changes is still being developed (Palmer 1999; Crommelin 2002; Stewart 2003; Pittock 2003). However, changes in climate extremes are expected with anthropogenic-induced climate change (Easterling et al. 2000). Decadal changes from flood to droughts have been found in climate model simulations (Yonetani and Gordon 2001). These changes may not be predictable because they occur as part of the natural climate variability on a multi-decadal time-scale. The climatic extremes may also be precipitated by gradual changes that slowly move the climate to a critical threshold when a climatic shift occurs (Pittock 2003).

GCM simulations are able to produce extreme scenarios on different temporal scales such as daily, monthly or seasonally (Zhang and Barrow 2004). This can be done by using a change in threshold such as defining a ‘hot’ summer for the 2020s, 2050s and 2080s relative to the 1961-1990 baseline (Zhang and Barrow 2004). Other options are return periods or the probability of the baseline threshold values being exceeding in the future (Zhang and Barrow 2004). Extreme precipitation, such as droughts or floods can be projected using the percentile method (Zhang and Barrow 2004).

Climate extremes can be placed into two groupings (Easterling et al. 2000; Watson et al. 2001*b*). The first is based on simple climate statistics which include extremes of climatic variables such as extreme daily temperatures and extreme daily or monthly precipitation amounts. The second grouping is based on more complex extremes such as droughts, floods or hurricanes.

Developments in recent climate models have enhanced the ability to simulate many aspects of climate variability and extremes, but they still have systematic errors and limitations in simulating regional climatic conditions (Easterling et al. 2000). GCMs do not simulate extremes as well as averages and they only give partial answers to questions about extreme events (Zwiers 2005 and Hengeveld 2000). The best information about extremes GCMs are able to provide relates to large area events such as temperature or wind speeds. GCMs provide information about the direction of change in extremes of other climate variables (Hengeveld 2000). GCMs do not provide information on small scale phenomena such as thunderstorms, tornadoes plus others (Barrow and Lee 2003). Because extremes occur infrequently, very long simulation periods are needed before enough of these events are available for reliable statistical analysis. Similarly, very long record of observations of real events is needed to provide the reference base against which the models results can be compared. As a result, validating the model's performance in simulating extremes can be difficult (Hengeveld 2000).

It is believed that there will be a change in 'waiting time' from present day extreme events. For example, a 20 year event may become a 10 year event due to a projected increase in extreme precipitation events (Zwiers 2005; Hengeveld 2000; Barrow and Lee 2003).

It is often possible to estimate changes in infrequent extremes, such as those that might occur once every 10 to 100 years, without detailed knowledge of the parent distributions. Statistics provides an asymptotic theory for extreme values which predicts that the largest observation in a large sample, such as the annual maximum temperature or 24-h precipitation amount, will tend to have one of only three extreme value distributions depending upon the shape of the upper tail of the parent distribution. One of these distributions is the Gumbel. This approach to extreme value analysis, together with related techniques based on the study of the crossing of high thresholds, has been used extensively in meteorology, climatology and hydrology to predict precipitation, streamflow, temperature and wind speed extremes (Meehl et al. 2000*b*).

GCMs do indicate an increased temperature variance which adds to the probability of extreme high-temperature events over and above simply what could be expected from increases of mean alone. Simulations suggest that both mean and variance are likely to change with a changed climate, and the relative contribution of the mean and variance changes depends on how much each variable changes (Meehl et al. 2000*a*). It was found that with the CCC GCM2 under CO_2 doubling, precipitation extremes are projected to increase more than the mean. For example, the mean would increase by 4%, but the 20 year extreme precipitation event return may increase by up to 11%. This change would decrease the return period for the 20-year extreme precipitation from 20 years to 10 years over North America, for example (Meehl et al. 2000*a*).

The first Hadley Centre time-dependent climate change experiment and three extreme statistics were used to define drought to determine if drought conditions will increase or decrease in the future (Gregory et al. 1997). They found an increased chance of summer drought in certain parts of the world which is generally attributed to a combination of increased temperature and evaporation along with decreased precipitation (Gregory et al. 1997; Meehl et al. 2000*a*).

Another way to estimate climate variability is to apply GCM-derived changes in both the mean and variability to an observed time series (Barrow and Lee 2003). Also, a stochastic weather generator may be used to synthesize daily time series which incorporate changes in both these statistical parameters (Barrow and Lee 2003).

Palutikof (ND) believes that if used appropriately, GCM data can be applied without having to use statistical downscaling to estimate extremes. This allows for preservation of the relationships in spatial and temporal fields and consideration of whether or not all of the contributing forcing factors have been taken into account. The techniques to do this include extreme value analysis and storm tracking algorithms.

Regional Climate Models

One of the disadvantages of applying GCM results to regional impact assessments is the coarse spatial scale of the gridded estimates in relation to the variables being used in impact assessment research (Mearns 2004; Carter et al. 1999; Barrow et al. 2004*b*). Downscaling of the GCMs would allow for more complete regional impact assessments.

Types of Downscaling

Downscaling techniques have been designed to bridge the gap between the information that the climate modelling community can currently provide and that required by the impacts research community (Barrow and Lee 2003). The end product of downscaling is a set of scenarios which describe the range of possible future conditions derived from weather stations and from the GCMs. The information can be manipulated at the station level or summarized and interpolated to make maps (Carr et al. 2004).

If downscaling is considered to be necessary, it is important to be aware of the limitations of the methodologies and to ask the question "does the cost of downscaling add sufficient value to the coarse-scale scenarios?" (Barrow 2002). A problem with using downscaling methods that are atmospheric circulation based is that these scenarios would be insensitive to future climate forcing (Carter et al. 1999).

There are two main types of downscaling: dynamical (regional climate modelling) and statistical. Dynamical or spatial downscaling techniques are used to derive finer resolution climate information from coarser resolution GCM output (Barrow and Lee 2003) and can be combined to produce very high resolution climate scenarios and land-atmosphere feedbacks (Carter et al. 1999).

Dynamical Scaling

Regional climate models (RCM) are high resolution numerical models that are similar to global climate models, but contain a better representation of the underlying topography within the model domain. The approach is to nest an RCM within the GCM so that the high resolution model simulates the climate features and physical processes in greater detail for selected area of the world. Information about initial conditions, time-dependent meteorological conditions and surface boundary conditions is obtained from the GCM (Mearns 2004; Barrow et al. 2004*b*; Barrow and Lee 2003; Hengeveld 2000).

The nesting procedure is a complex process. Nesting is a one way process, with information flowing from the global model to the regional model but not vice versa (Canadian Centre for Climate Modelling and Analysis 2003; Hengeveld 2000).

Regional models have their own errors, plus the errors incurred from the GCMs. Therefore, regional models should be compared to historic climate (Caya 2005).

The Canadian RCM, can be used over any part of the globe (Canadian Centre for Climate Modelling and Analysis 2003). However, this data may not always be available (Caya 2005). The Canadian RCM has been used to simulate current and future climate for Western Canada (Barrow and Lee 2003). Using a spatial resolution of 45 km, the CRCM simulations showed increased spatial variability and detail in the near surface climate variables because of the greater topographic details in the RCMs (Hengeveld and Francis 2000). However, there is little difference in the variability of the free atmosphere well above the earth's surface between the GCM and the CRCM (Hengeveld and Francis 2000). The Canadian RCM appears to have a cool bias over the prairie provinces and like the GCMs, summer precipitation is the most difficult to project (Caya 2005).

Statistical Downscaling

Statistical downscaling models calculate statistical relationships, based on multiple linear regression techniques between large-scale (predictors) and local (predictand) climate. These relationships are developed using observed weather data and can be used to obtain downscaled local information for some future period by driving the relationships with GCM-derived predictors (Canadian Institute for Climate Studies 2003*b*). Regional or location climate information may be determined by using a statistical downscaling model which relates large scale climate variables to regional and local variables (Barrow et al. 2004*b*). Techniques for downscaling include regression analysis and artificial neural networks (Barrow et al. 2004*b*). The five steps of statistical downscaling are the screening of variables to identify useful variables, the calibration of the model, the generation of historical scenario data, the comparison of the source and scenario data, and the generation of future scenario data (Carr et al. 2004).

Statistical downscaling is much less computationally demanding than physical downscaling using numerical models and offers an opportunity to produce ensembles of high resolution climate scenarios (Barrow et al. 2004*b*; Carter et al. 1999). However, statistical downscaling requires large amounts of observational data to establish statistical relationships for the present-day climate and a high degree of specialist knowledge and skill is needed to apply statistically downscaled results sensibly in impact assessments (Barrow et al. 2004*b*; Carter et al. 1999). Statistical downscaling has disadvantages relating to the assumption of empirical relationships in the future, and the analysis does not include many variables (Gachon 2005). Statistical downscaling is dependent on potentially biased inputs from GCMs (Gachon 2005).

An example of a statistical downscaling model is LARS-WG. LARS-WG, a readily available stochastic weather generator (Barrow and Lee 2003), enables production of daily weather data from monthly scenario information. This ability allows for daily weather generation from any GCM for which monthly data is available (Barrow and Wilby 2001).

Qian et al. (2004) compared LARS-WG and Agriculture and Agri-Food Canada Weather Generator (AAFC-WG) to gauge the capabilities of reproducing probability distributions, means and variances of observed daily precipitation, maximum and minimum temperature for various Canadian cities. They found that AAFC-WG was better at simulating temperature related statistics. LARS-WG and AAFC-WG had similar results for statistics associated with daily temperature. Both weather generators underestimated inter-annual variability, especially temperatures (Qian et al. 2004).

Regional Climate Model Uncertainties

One major difficulty with RCMs is that while they provide higher resolution climate information, the cost of running climate experiments with these models means that there is a much smaller set of results available for scenario construction and only a single experiment may be available from a single RCM for a particular region. This means that it may be impossible to explore a range of plausible future climates and researchers may place too much emphasis on the results of a single higher resolution experiment (Barrow et al. 2004*b*). Other disadvantages of RCMs is a lack of two way nesting and like statistical downscaling, RCMs are dependent on potentially biased inputs from GCMs (Gachon 2005).

Regional Climate Model Progress

Several enhancements have been implemented in CRCM2. The large computational domain, extending farther west, north and south, allows for a better spin-up of weather systems as they enter the regional domain. The increased length of the simulations from 5 to 10 years strengthens the statistical robustness of the results. The improvements to the physical parameterization, notably the moist convection scheme and the diagnostic cloud formulation, overcome the excessive cloud cover problem present in the CRCMI as noted in Laprise et al (1998), reduce the warm surface bias and prevent the occurrence of grid-point precipitation storms that occurred with CRCMI in summer. The dynamical ocean and sea-ice components of CGCM2 that are used to provide atmospheric lateral and surface boundary conditions to CRCM2 also increase the realism of the climate change simulation (Laprise et al. 2003).

Laprise et al. (2003) showed that the CRCM II has been used in time-slice simulations over north-western North America, nested in the coupled Canadian GCM (CGCM2). Both GCM’s and RCM’s were integrated in an emission scenario of transient greenhouse gases and aerosols. The time slices span three decades that were chosen to correspond roughly to single, double and triple the current GHG concentration levels.

The North American Regional Climate Assessment Program (Anderson ND) is currently investigating the uncertainties in regional scale projections of future climate and are producing high resolution climate change scenarios using multiple regional climate models and multiple global model responses to future emissions scenarios. This is being accomplished by nesting the RCMs within multiple atmosphere ocean general circulation models forced with the A2 and A1B emission scenarios. Areas cover the lower 48 States and most of Canada.

CRCM 3.6 data is available. Its main difference from CRCM 3.5 is the cumulus convection scheme. Also, CRCM3.6 is able to perform spectral nudging of large scale winds within the regional domain and can be coupled with the lake model for the Great Lakes (Environment Canada 2005). The Canadian Regional Climate Model Network is making developments in the fourth generation of the CRCM simulator. The main improvement of the new CRCM will be a more sophisticated land-surface scheme (Barrow et al. 2004*b*). It is believed that CRCM4.0 beta (with CLASS) should be completed early in 2005 (Caya 2005).

There are several other RCMs available. One is the National Center for Atmospheric Research Community Climate Model version 3.6.6 (CCM3) that has been used to expand on modelling experiments of future climate change in California to address issues of timing and length of the growing season as well as the frequency and intensity of extreme temperatures and precipitation (Bell et al. 2004). The comparison between modern-day regional model results and weather station data is very good. The regional model adequately captures seasonal as well as annual changes in temperature. While the model simulates too few extreme events, it does not overestimate the intensity of simulated extreme events. The growing season starts earlier and ends later due to the use of proxy minimum temperature. The model simulates one day too many per year of moderate precipitation and only 0.2 too many days per year of heavy precipitation. The biggest weakness found was the RCM's dependence on lateral boundary input either via GCM, reanalysis or observational data (Bell et al. 2004).

Extremes

Many extreme events occur at a finer spatial scale than what GCMs are able to provide. Therefore, statistical and dynamical downscaling techniques are utilized. Zhang and Barrow (2004) state the spatial downscaling using RCMs are likely to produce more robust information at finer spatial and temporal scales. However, RCM's scale may still be too coarse of scale for some extreme events such as tornadoes. Statistical downscaling where fine-scale local extremes are related to larger scale atmospheric circulation also has potential for developing extremes scenarios (Zhang and Barrow 2004).

There are potential problems regarding downscaling and projecting future extreme events. Regional relationships between large-scale atmospheric circulation and regional extremes that currently exist are assumed to continue to do so. This may not be the case (Zhang and Barrow 2004). Also, the assumptions made in the large-scale atmospheric patterns might be amplified in the RCMs (Zhang and Barrow 2004).

Global Climate Model and Regional Climate Model Based Climate Change Scenarios

Many SRES driven climate change experiments are available to researchers (Table 5). Many have several different runs taking into account at least two of the SRES scenario families. Each of these experiments also has many different variables that are available for use in vulnerability, impacts and adaptation research (Table 6). These variables are available on various time scales including daily, monthly, seasonally and yearly to the 2100s.

Table 5 Availability of SRES Climate Change Experiments for use in Scenario Construction

GCM	Organization	Country	Grid Size	SRES Emission Scenarios			
				A1	**A2**	**B1**	**B2**
CGCM2	Canadian Centre for Climate Modelling and Analysis	Canada	3.8 X 3.8°		3		3
GFDL R30	Geophysical Fluid Dynamics Laboratory	USA	2.2 X 3.8°		1		1
ECHAM 4	Max Planck Institute für Meteorologie	Germany	2.8 X 2.8°		1		1
CSIRO-Mk2b	Commonwealth Scientific Industrial Research Organization	Australia	3.2 X 5.6°	FI	1	1	1
CCSR/NIES	Center for Climate Research – National Institute for Environmental Studies	Japan	5.6 X 5.6°	T, F1	1	1	1
HadCM3	Hadley Centre	United Kingdom	2.5 X 3.8°	FI	3	1	2
NCAR PCM	National Centre for Atmospheric Research	USA	2.8 X 2.8°		1		1

Source: Canadian Institute for Climate Studies 2003*c*; Ruosteenoja et al. 2003

A1 = Economic Global Focus Simulation
FI = Fossil Fuel Intensive Simulation
T = Non-Fossil-Fuel Transition Simulation
A2 = Economic Regional Focus Simulation
B1 = Environmental Global Focus Simulation
B2 = Environmental Regional Focus Simulation

Table 6 Variables Available from the SRES Global Climate Model Simulations

	CGCM 2	GFDL R30	ECHAM 4	CSIROMk2b	CCSRNIES	HadCM3	NCAR PCM
Maximum Temperature	✓			✓	✓	✓	✓
Minimum Temperature	✓			✓	✓	✓	✓
Mean Temperature	✓	✓	✓	✓	✓	✓	✓
Precipitation	✓	✓	✓	✓	✓	✓	✓
Solar Radiation	Incident	Surface Shortwave	Incident	Incident	Incident	Incident	Incident
Mean Sea Level Pressure	✓	✓	✓	✓	✓	✓	✓
Relative Humidity	Derived	✓	Derived		Derived	✓	
Specific Humidity	✓				✓		
Vapour Pressure	Derived	✓	✓		Derived	Derived	
Diurnal Temperature Range	Derived			Derived	Derived	Derived	Derived
Wind Speed	✓		✓	✓	✓	✓	
Cloud						✓	
Evaporation	✓						
Soil Moisture	✓	✓		✓	✓	✓	
Snow Water Equivalent	✓			✓		✓	
Surface Temperature	✓	✓		✓	✓	✓	
Geopotential Height	✓				✓		
Sea Ice	✓						
Snow Depth		✓		✓			
Snow Melt		✓					

Source: Canadian Institute for Climate Studies 2003*d*

Scenario Results

Many researchers have analysed how well the various GCMs simulate climatic trends. More analysis has been carried out to determine how well the IS92 driven GCMs portray climatic trends than the SRES GCMs. This section examines both IS92 and SRES driven GCMs, but the analysis of the SRES GCMs is limited due to the lack of available information. When determining which types of models to use, Barrow and Lee (2003) recommended that it should be determined that there is an actual physical reason (e.g., improved spatial resolution or use of a superior algorithm describing a particular process) for the improved model performance.

Barrow and Lee (2003) examined results from three GCMs based on IS92 emission scenarios. In an experiment, examining Saskatoon, Saskatchewan's climate where it is known to be sensitive to summer precipitation, they found the ECHAM greenhouse gas-only scenario could be used to represent hot dry conditions. The GFDL-R15 greenhouse gas plus sulphate aerosol scenario could be used to represent cool, wet conditions and the CGCM1 greenhouse gas plus sulphate aerosol ensemble mean scenario represents mid range conditions. They recommended that these three scenarios could be used to define the range of possible future climate in response to IS92a forcing (Barrow and Lee 2003).

Boer and Yu (2003) assessed IS92 driven GCMs. They found that there was an overall 10 to 20% strengthening of the negative feedback (decrease in climate sensitivity) in the CCCma model which contrasts with a weakening of negative feedback (increase in climate sensitivity) of over 20% in the Hadley Centre model under similar conditions. They believe that the different behaviour in the CCCma and Hadley Centre GCMs is due primarily to solar radiation absorption in clouds feedback with a strengthening of the negative solar radiation absorption in clouds feedback in the CCCma model contrasting with a weakening of it in the Hadley Centre model. The importance of processes which determine cloud properties and distribution is again manifest both in determining first order climate feedback/sensitivity and also in determining its second order variation with climate state (Boer and Yu 2003).

Flato et al. (2000) used a global, three-dimensional climate model, developed by coupling the CCCma second-generation atmospheric general circulation model (CGCM2) to a version of the GFDL modular ocean model (MOM1) which forms the basis for extended simulations of past, current and projected future climate. Its simulated climate was systematically compared to available observations in terms of mean climate quantities and their spatial patterns, temporal variability and regional behaviour. The comparison demonstrated a generally successful reproduction of the broad features of mean climate quantities. There were local discrepancies usually largest in the winter and over land. Variability was generally well simulated over land, but somewhat underestimated in the tropical ocean and the extratropical storm track regions. They also found that the modeled climate state shows only small trends, indicating a reasonable level of balance at the surface, which is achieved in part by the use of heat and freshwater flux adjustments (Flato et al. 2000).

Bonsal et al. (2003) assessed nine SRES driven GCMs in their ability to simulate the magnitude and spatial variability of baseline (1961-90) temperature and precipitation over the western cordillera of Canada (Bonsal et al. 2003). The nine GCMs were Canada’s CGCM1 and CGCM2, Hadley Centres HadCM2 and HadCM3, Australia’s CSIROMk2b, Germany’s ECHAM4, USA’s GFDL – R15 and NCAR-DOE and Japan’s CCSR-98. The results revealed a close correspondence among the four gridded data sets of observed climate, particularly for temperature. The gridded data sets of observed climate data were the Climate Research Unit, PRISM, ANUSPLIN and Square-grid. There was considerable variability regarding the various GCM simulations of the observed climate (Bonsal et al. 2003). They found the British, Canadian, German, Australian and US models the best of the GCMs assessed at simulating the magnitude and spatial variability of mean temperature for this region (Bonsal et al. 2003). Also, nearly all the models overestimated the magnitude of total precipitation, both on an annual and a seasonal basis. The Hadley model (HadCM3) best represented the observed magnitude and spatial variability of precipitation. CGCM2 and NCAR models had the poorest precipitation skill of the nine GCM runs (Bonsal et al. 2003).

SRES driven GCMs have been used in climate projections for Canada and the prairies. For example, Hulme and Sheard (1999) combined four preliminary SRES emission scenarios with three different values of climate sensitivity (low 1.5°C, medium 2.5°C and high 4.5°C) and used a "simple" climate model to calculate global temperature increases and for Canada from which information on the South Saskatchewan River Basin (SSRB) region could be obtained (Table 7 and Table 8). They also state that for the Canadian Prairies in the 2050s, the models suggest summers will become drier because of higher temperatures and highly variable precipitation. The scenarios show that summer precipitation changes over the prairies by the 2050s are generally not large relative to natural variability (Hulme and Sheard 1999).

Table 7 Projected Temperature Changes from the 1961-1990 baseline for the 2080s for Four Scenarios in the South Saskatchewan River Basin Region (°C) (Hulme and Sheard 1999)

Scenario	2080's Winter Temperature	2080s Summer Temperature
B1 – low (B1 emissions with 1.5°C)	1.6 to 2.3	1.8 to 1.4
B2 – mid (B2 emissions with 2.5°C)	2.6 to 3.7	2.9 to 2.3
A1 – mid (A1 emissions with 2.5°C)	3.0 to 4.2	3.3 to 2.7
A2 – high (A2 emissions with 4.5°C)	5.2 to 7.4	5.8 to 4.7

Table 8 Projected Precipitation Changes from the 1961-1990 baseline for the 2080s for Four Scenarios in the South Saskatchewan River Basin Region (%) (Hulme and Sheard 1999)

Scenario	2080's Winter Precipitation Change	2080's Summer Precipitation Change
B1 – low (B1 emissions with 1.5°C)	6 to 7%	0
B2 – mid (B2 emissions with 2.5°C)	0 to 15%	0
A1 – mid (A1 emissions with 2.5°C)	0 to 17%	0 to -4%
A2 – high (A2 emissions with 4.5°C)	6 to 30%	0 to -7%

Henderson et al. (2002) examined climate change impacts on the island forests of the Great Plains. Island forests are relatively small forests that are isolated from other wooded regions by grasslands. Their study region included the headwaters of the SSRB. They used three GCMs (HadCM3, CGCM2 and CSIROMk2b) and four emission scenarios in their research resulting in 36 climate scenarios being used. The SRES emissions scenarios and GCMs were chosen because of availability at the time the research was undertaken and suitability. They focused on three of the scenarios because they stated these scenarios encompassed the range of probable future values. The three scenarios were the HadCM3 B21 which is a cool-wet marker, the CGCM2 A21 a warm-dry marker and the CSIROMK2b B11 as the mid-range marker (Figure 3). Most of the scenarios exhibit increases in both mean annual temperature and precipitation for all three future time periods (2020s, 2050s and 2080s). The seasonal breakdown indicates that the summer season will have substantial decreases in precipitation by between 4 and 10 percent in the 2020s, between 9 and 11 percent in the 2050s and 1.6 to 18 percent decrease in the 2080s, depending on the GCM.

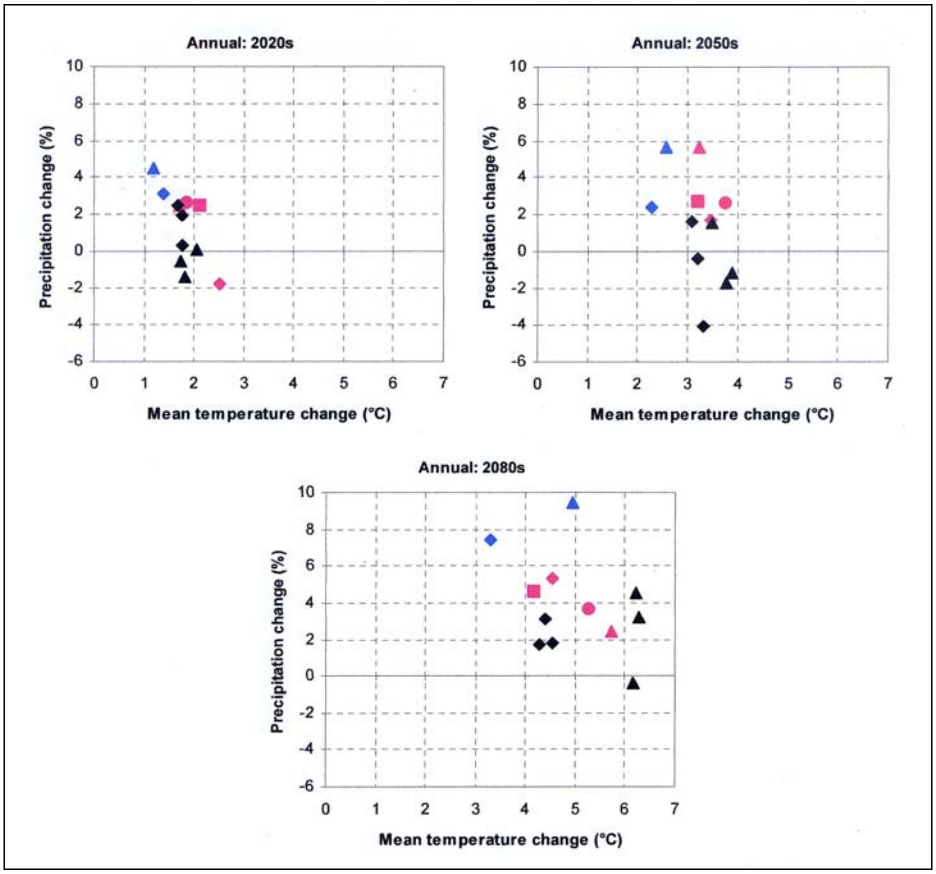

Figure 3 Scatter Plots of Annual Mean Temperature (°C) Versus Precipitation Change (%) over the Southern Canadian Prairies and Northern US Prairie States for the 2020s, 2050s and 2080s. All changes calculated with respect to the 1961-1990 averaging period. Different symbol colours show different GCMs: CGCM2 – black; HadCM3 – blue; CSIROMk2b – red. Different shapes indicate different emissions scenarios: A1 – circles; A2 – triangles; B1 – squares; B2 – diamonds. Each symbol is a single experiment (Henderson et al. 2002).

Conclusions and Recommendations

It is recommended that more than one GCM be used. Ideally, GCM results from each of the four SRES families should be used to obtain as many different emission hypothesis as possible. In the research undertaken thus far in Canada (see Ecosystem Scenario section), the HadCM3, CGCM2 and the CSIROMk2B SRES based GCMs appear to be most used in Canada.

When using downscaling methods Gachon (2005) put forward a set of recommendations for researchers. Gachon (2005) says:

- Test downscaling models using independent variables. Researchers should inter-compare several downscaling methods (both statistical and RCMs).
- Researchers should be sure they require the information derived from downscaling as compared to GCM output.
- Downscaling models should only be applied critically, not used as a “black box”.

ECOSYSTEM IMPACT SCENARIOS

Introduction

Climate change is expected to have serious consequences for plant and animal populations (Sauchyn et al. 2005). Ecological productivity and biodiversity will be altered by climate change with an increased risk of extinction of some vulnerable species (Watson et al. 2001*a*). The Intergovernmental Panel on Climate Change stated that regional climate changes, particularly temperature increases, have already affected physical and biological systems in many parts of the world including the Canadian Prairies (Ahmad et al. 2001).

Changes in the proportion of days exceeding species-specific temperature thresholds, or changes in the frequency of droughts or extreme seasonal precipitation will lead to physical and behavioural changes in species and to dramatic changes in the distribution of many other species. Despite this knowledge, there is still limited understanding on how climate change will impact regional ecosystems and the availability of natural resources (Sauchyn et al. 2005; Easterling et al. 2000). Ecosystem management relies on the process of decision-making based on society's understanding of the world and predictions of the future. Consequently, understanding ecological change is vital for ecosystem management decisions (Bennett et al. 2003). This section examines selected models used for simulating vegetation responses to climate change, plus the progress of and limitations of these models.

The global hydrological cycle appears to be intensifying with warmer temperatures (Watson et al. 2001*b*). Peak stream flow has shifted to late winter from spring in many areas of North America (Watson et al. 2001*b*). Different rivers in Canada display different trends and tendencies in streamflow, and no simple description is possible for natural rivers and streams in Canada (Whitfield et al. 2004). Currently it is not considered possible to attribute decreasing stream flows to either climate change or to natural variability (Whitfield et al. 2004).

Coupling hydrological forecasts with numerical weather prediction models provides a means to compute forecasted river flows with forecasted precipitation data (Pietroniro et al. 2004). This section examines selected models used for simulating hydrological responses to climate change, plus the progress and limitations of these models.

Hydrology Models and Scenarios

Hydrology models and their scenarios are useful for determining the amount of flow a waterway may be expected to accommodate in the short and longer term. In Canada, two models have been widely used for hydrologic forecasting, the SLURP and the WATFLOOD (Table 9).

WATFLOOD was developed at the University of Waterloo with its primary purpose to assist in forecasting floods. Figure 4 is an overview of the variables examined in the WATFLOOD model. WATFLOOD has since been used in climate change impact studies and environmental impact studies. It has been used with grid sizes from 1 to 25 km and for watershed areas from 15 to 1,700,000 km^2 (Anonymous 2000). WATFLOOD has been used in Quebec, the Prairies, Ontario, British Columbia and the Northwest Territories (Kouwen et al. 2003; Pietroniro et al. 2003; Soulis et al. 2000; Anonymous 2002).

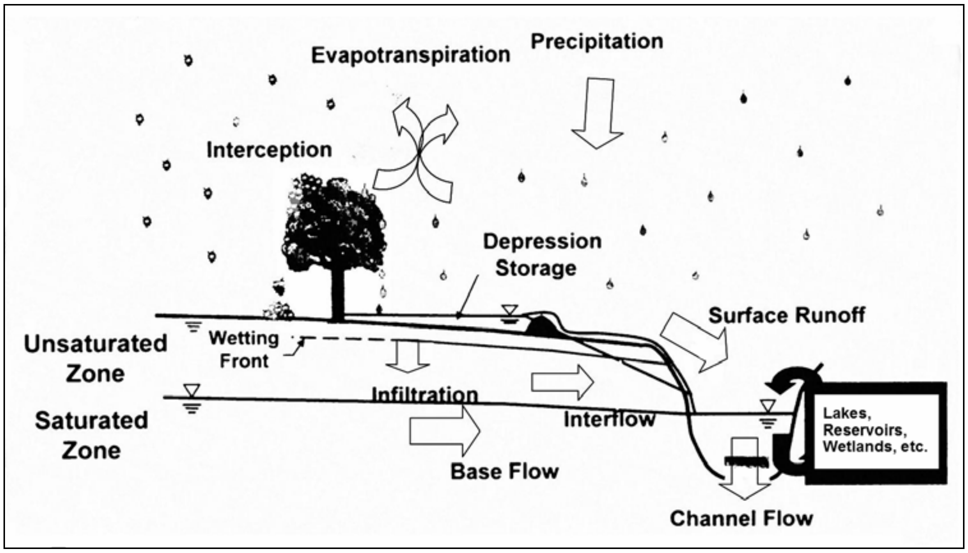

Figure 4 Overview of the WATFLOOD model (after Pietroniro et al. 2004)

The SLURP model (Semi-distributed Land-Use Runoff Process model) is a continuous simulation distributed hydrological model in which the parameters are related to land cover (vegetation type) in order to estimate runoff amounts (Figure 5). The inputs included in the model include interception coefficients, depression storage, surface roughness, infiltration coefficient, groundwater conductivity and snowmelt rates (Kite 1998). This model has been used in the Upper Columbia Watershed, British Columbia, the Upper Assiniboine River Basin, the Yukon and Quebec (Kite 1996; Oegema 2000; Lacroix et al. 2002; Romero et al. 2002).

Lacroix et al. (2002) used SLURP and TOPAZ, a terrain analysis model, to derive physiographic parameters at several different levels of detail and for numerous sub-basins. Kite (2001) states that outputs from SLURP can be used to investigate water allocations, effects of land use change, effects of climate change on water resources, evaluate effects of proposed structures on numerous environmental interest including fisheries and on the performance of irrigation schemes.

These two large area models have not been built on the understanding of physical process established through small-scale hydrological studies. Modelling streamflow conditions is a complex undertaking because beyond the hydrological conditions, accounting for human activities is also a challenge. Modeling efforts require knowledge of local intervention such as irrigation, land use changes (Whitfield et al. 2004).

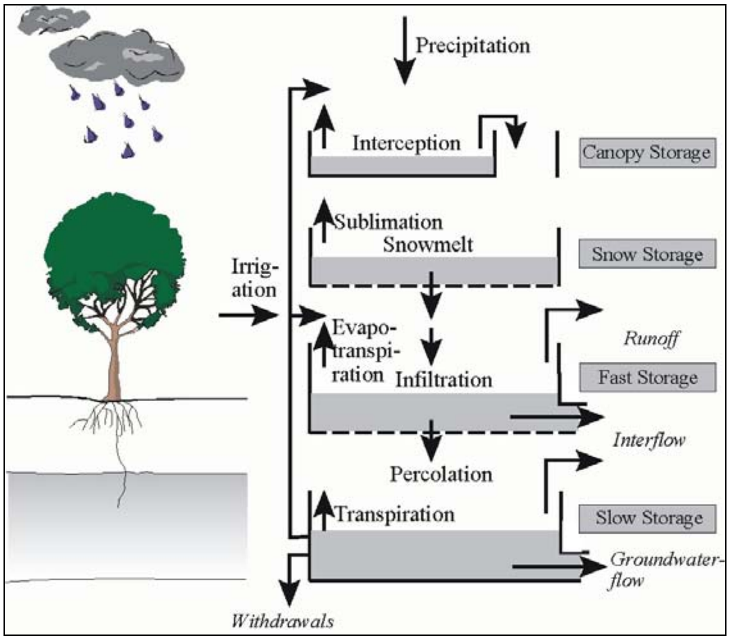

Figure 5 SLURP Model (Lacroix et al. 2002)

There are many other models used throughout the world. One example is the one used by Evans and Schreider (2002). They estimated mean flows and extreme high runoff events for three small catchments entering the Perth region using the Catchment Moisture Deficit – Identification of unit Hydrographs And Component flows from Rainfall, Evaporation and Streamflow (CMD IHACRES) rainfall-runoff model, and using a climate change scenario generated by the CSIRO Mark 1 model (Table 9). The CMD IHACRES rainfall-runoff model is based on the Instantaneous Unit Hydrograph technique. IHACRES is a non-linear loss module which converts observed rainfall into effective or excessive rainfall and a linear streamflow routing module which extends the hypothesis that the relationship between excess rainfall and total streamflow is conservative and linear (Evans 2003).

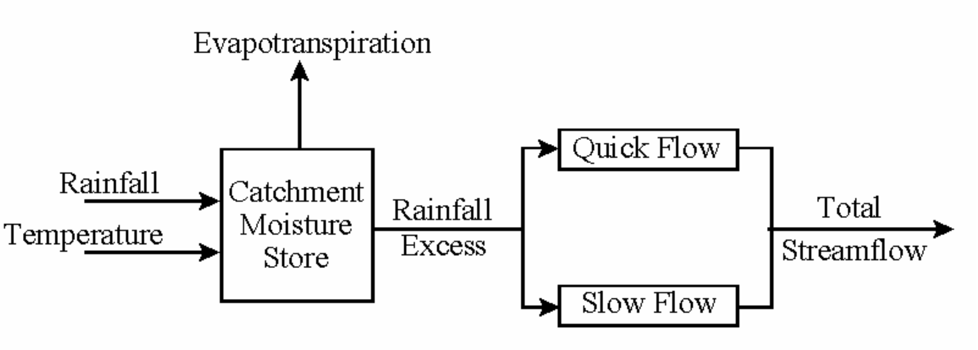

Figure 6 Structure of CMD-IHACRES (Evans and Jakeman 1998)

The CMD IHACRES method represents total streamflow response as a linear convolution of the Instantaneous Unity Hydrograph with rainfall excess or effective rainfall, which is a non-linear function of measured rainfall and temperature. As the CSIRO Mark 1 is a slab-ocean model (only 50 m deep), it is no longer considered reliable, but it is interesting that their results showed small decreases in mean runoff, and increases in rare flood events. The CSIRO Mark 1 model simulation used a stochastic daily weather generator tuned to the daily output from the model and emphasizes the importance of considering the change in the frequency distribution of daily rainfall (Pittock 2003).

Arora and Boer's (2001) research examined how runoff can be simulated using the CCCma coupled climate model (CGCM1) for the current climate routed through the river system to the river mouth and compared with results for the warmer climate simulated to occur towards the end of the 21st century in 23 major river basins around the world including the Mackenzie, Columbia, Yukon and Mississippi Rivers in North America (Table 9). They used a variable velocity algorithm designed for use in GCMs to perform flow routing and the 3.75° resolution. They also used Manning's equation to determine time-evolving channel flow velocities that depend on runoff amounts generated in the grid cell. Changes in mean discharge, in the amplitude and phase of the annual streamflow cycle, in the annual maximum discharge (the flood) and its standard deviation, and in flow duration curves were examined. They determined changes in flood magnitudes for different return periods and were estimated using extreme value analysis. Middle and high latitude rivers showed marked changes in the amplitude and phase of their annual cycle associated with a decrease in snowfall and earlier spring melt in the warmer climate (Arora and Boer 2001).

However, there were differences in the regional distribution of simulated precipitation and runoff for the control simulation which currently limits the application of this approach used by Arora and Boer (2001). The inferred hydrological changes are plausible and consistent responses to simulated changes in precipitation and evaportranspiration and indicate the kinds of hydrological changes that could occur in a warmer world. Limitations in using GCM data directly to study hydrological impacts of climate change include the coarse spatial resolution of the GCM climate simulations and the inaccuracies in the regional climate. Studying the hydrological response of large river basins partially overcomes the first limitation (Arora and Boer 2001).

Arnell (2004) simulated river runoff at a spatial resolution of 0.5 x 0.5° to estimate current and future water resource availability for 1300 watersheds and small islands around the world under the SRES population projections (Table 9). He found that climate change increases water resources stresses in some parts of the world.

The following is the methodology Arnell (2004) used in this simulation:

- Construct scenarios for climate change from climate model simulations of the climatic effects of the SRES emissions scenarios. Scenarios are constructed from six climate models run with the SRES emissions scenarios (HadCM3 (A2a), ECHAM4/OPYC, CGCM2, CSIRO MkII, GFDL_R30 and CCSR/NIES2).
- Apply these emissions scenarios to a gridded baseline climatology, describing climate over the period 1961-1990 at a spatial resolution of 0.5 x 0.5°

- Run a macro-scale hydrological model at the 0.5 x 0.5° resolution with the current and changed climates to simulate 30 year time series of monthly runoff. Calculate average annual runoff from these time series. The hydrological model is a conceptual water balance model, which calculates the evolution of the components of the water balance on a daily time-step (Arnell 1999).
- Sum the simulated runoff for the study area watersheds to estimate watershed-scale runoff volumes.
- Determine the watershed population total under each population growth scenario. This step was calculated by using national populations for 2025, 2055 and 2085 as determined by United Nations projections and regional projections. The populations were then disaggregated to 0.5 x 0.5 ° resolution using the Gridded Population of the World Version 2 data set. The assumption made was that population changes everywhere within a country at the same rate.
- Construct indicators of water resources stress for each watershed from the simulated runoff and estimated watershed population. This step includes a wide range of potential indicators of water resources stress, including measures of resources available on a per capita basis and populations living in defined stressed categories. Arnell (2004) concentrated on the numbers of people affected by water resources stress.

The macro-scale hydrological model generates streamflow from precipitation falling on the portion of the cell that is saturated and by drainage from water stored in the soil. The model parameters are not calibrated and are estimated from spatial data bases. A validation exercise has shown that the model simulates average annual runoff reasonably well (Arnell 2004).

In Australia, considerable research has examined the consequences of hydrology under a changed climate. This work has been examined in Pittock (2003). For example, Beare and Heaney (2002) examined changes in river flow and salinity levels (along with economic consequences) for two mid-range SRES scenarios (A1 mid and B1 mid) and the CSIRO Mark II global climate model (Pittock 2003). Chiew and McMahon (2002) used the CSIRO (1996) scenarios and a conceptual daily rainfall-runoff model for eight catchments distributed through different rainfall regions of Australia. They used a stochastic daily weather generator to translate changes in mean rainfall to daily rainfall (Pittock 2003). Chiew et al. (2003) examined changes in rainfall and runoff in six small catchments around Australia using an ensemble of five simulations generated by the CSIRO Mark 2 model and the SRES A2 scenario. This study accounted for the changes in daily rainfall distributions generated by the GCM, rather than simply scaling historical daily rainfall by change in mean rainfall (Pittock 2003).

Uncertainties and Progress in Hydrologic Models and Scenarios

Gan (ND) feels that driving a coupled mesoscale atmospheric model-land surface scheme by the initial and boundary conditions of GCMs is better than statistical downscaling of general circulation models. This is because the atmospheric model-land surface scheme should be more reliable to estimate processed-based relationships between changes in basin-scale hydrologic responses to the combined interactive effects of climate variability and change. Also, due to scale mismatch and uncertainties involved with GCM's projected climate at the regional scale, simulating climate scenarios for the SSRB and surrounding areas should be based on a downscale approach.

There are several limitations to hydrologic modelling. For example, hydrographs are difficult to get correct because of the many variables involved such as precipitation, temperature, ecology plus others (Zwiers 2005). Direct use of GCM output results in hydrologic modelling give inaccurate hydrological simulations due to different temporal and spatial scales used in GCMs and hydrological models (Varis et al. 2004).

Hydrologic modelling also has omissions. First, some models do not simulate transmission loss along the river channel, which is common in dry regions, and it do not incorporate the evaporation of water which runs across the surface of the catchment and either infiltrates downslope or enters ponds or wetlands. The model used by Arnell (2004) tends to overestimate the river flow in dry region. Also, the model does not include a glacier component, so river flows in a cell do not include any melt from upstream glaciers. Other limitations relate to the use of average annual runoff and the 10-year return period minimum annual runoff as indicators of resource availability. Resources availability in some catchments may be determined more by the seasonal variability in resource than by the total annual volume (Arnell 2004).

Results from the South Saskatchewan River Basin project were not available at time of writing. Pietroniro et al. (2003) proposed to consider three hydrologic models of different levels of complexity and data requirements. The models are: 1) fully-distributed hydrologic model WATFLOOD; 2) Sacramento Model is a lumped parameter, conceptual rainfall-runoff model; and 3) a semi-distributed physics-based model (DPHM-RS) that was developed at the University of Alberta (ND). These models would provide an ensemble of hydrological prediction using different conceptualizations of the hydrological process in the mountains and glaciers and within the prairie environment.

Table 9 Characteristics of Selected Hydrologic Models

Model	Reference	Purpose	Uses	Inputs	Outputs	Calibration/Validation
WATFLOOD	Kouwen et al. 2003 Kouwen et al. 2002 Pietroniro et al. 2003 Soulis et al. 2000	-Assist in flood forecasting -Long term simulation system	-Climate change impact studies -Environmental impact studies -Runoff	-Digital Elevation Model (grid elevation, drainage direction, basin boundaries etc) -Landcover -Precipitation, temperature and snow cover -Stream flow	-Summary of precipitation and flow in gridded and station form -Reservoir information -Runoff information for impervious areas -Diagnostic data for snow melt routines -Water balance terms	-Validation is necessary especially when using radar for precipitation measurements (Kouwen et al. 2002) -Should be calibrated so that the simulated hydrological processes behave in a physically realistic manner (Kouwen et al. 2002)
SLURP	Kite 1996, 1998 Droogers and Kite 2001 Oegema 2000 Lacroix et al. 2002 Romero et al. 2002	-Estimate run-off process with input from land use	-Investigate water allocations -Effects of land use change on stream flow -Effects of climate change on water resources -Evaluate effects of proposed structures on environmental interest -Performance of irrigation schemes	-Interception coefficients -Depression storage -Surface roughness -Infiltration coefficient -Groundwater conductivity -Snowmelt rates	-Physiographic parameters at several levels of details and many sub-basins -Steamflow/runoff	-Required calibration when model is applied over large areas (Lacroix et al. 2002)
CMD IHACRES	Evans and Schreider 2002 Evans 2003	-Estimate effective and excessive rainfall as well as total streamflow	-Flood forecasting -Urban storm water systems -Climate change impacts on streamflow	-Rainfall, temperature -Streamflow	-Hydrographs -Component flows	-Calibration is carried out using rainfall and streamflow data
Variable Velocity Algorithm Manning's Equation	Arora and Boer 2001	-Runoff simulation of large river basins	-Estimating stream flow under climate change	-Water inflow and outflow -Manning's roughness coefficient -Hydraulic radius -Channel slope	-Surface water storage -Channel velocity	-Used 31 years of daily runoff for control simulation
Macro-Scale Hydrologic Model	Arnell 2004	-Simulate runoff at a spatial resolution of 0.5 x 0.5	-Estimate stream flow under climate change	-Precipitation	-Water balance in each 0.5 X 0.5 grid cell on a daily basis	-Model parameters were not calibrated and were estimated from spatial data bases and a validation exercise showed the model simulated average annual runoff reasonably well

Vegetation Models

Global environmental changes that involve changes in both climate and land use, require process-based predictive tools of land cover and its dynamics (Neilson and Running 1996). Two main classes of ecosystem models exist. The ecosystem function models (EF) are designed for vegetation productivity estimates and for simulating carbon, nitrogen and water cycles. These models do not simulate the location of different ecosystem types, their recruitment, disturbance and mortality dynamics and do require vegetation type as an input. The ecosystem dynamics models (ED) predict the distribution of different vegetation types under a specified climate. These models are not designed to grow vegetation or calculate carbon or nutrient fluxes (Neilson and Running 1996).

EF models simulate the processes of carbon assimilation, autotrophic and heterotrophic respiration and decomposition, based on radiation, temperature, precipitation and nutrient availability. The main outputs of EF models are net primary productivity and carbon content in above and below ground vegetation (Neilson and Running 1996).

ED models assess the abiotic constraints on what an ecosystem could become, rather than the productivity of that system. The ED models simulate temperature constraints by using degree-days or thermal thresholds, calibrated to represent physiological cold hardiness limits. Thermal constraints on vegetation roughly parallel latitudinal lines of vegetation types. Within the thermal vegetation zone there also could exist a moisture conditions range, going from wet to dry condition in the same thermal vegetation zone (Neilson and Running 1996). A vegetation water balance needs to be calculated for usage in ED model. Once the water balance is calculated, ED models generate either a water balance index used to partition vegetation into biomes or they use the water balance to directly estimate the amount of vegetation that could be supported at the site (Neilson and Running 1996).

Researchers have mainly utilized the ED model type for the Canadian Prairie, but some have used a combination of the vegetation models described above (Table 11). Carr et al. (2004) utilized an ED model for their work in the parkland/boreal forest region of Saskatchewan (Table 11). They used a recursive partitioning as a statistical technique for investigating what differentiates the members of one vegetative group into their subgroups. The process of recursive partitioning divides the data by whichever predictor best splits the data into separate groups. Species presence likelihood is the response variable in this study. The dichotomous key which is a product of recursive partitioning may be used to predict forward for new cases, or cases from a population which is not already classified (Carr et al. 2004). The predictive model uses the data from the climate model, a soils layer and existing tree range data to predict the future scenario range for individual tree species (Carr et al. 2004).

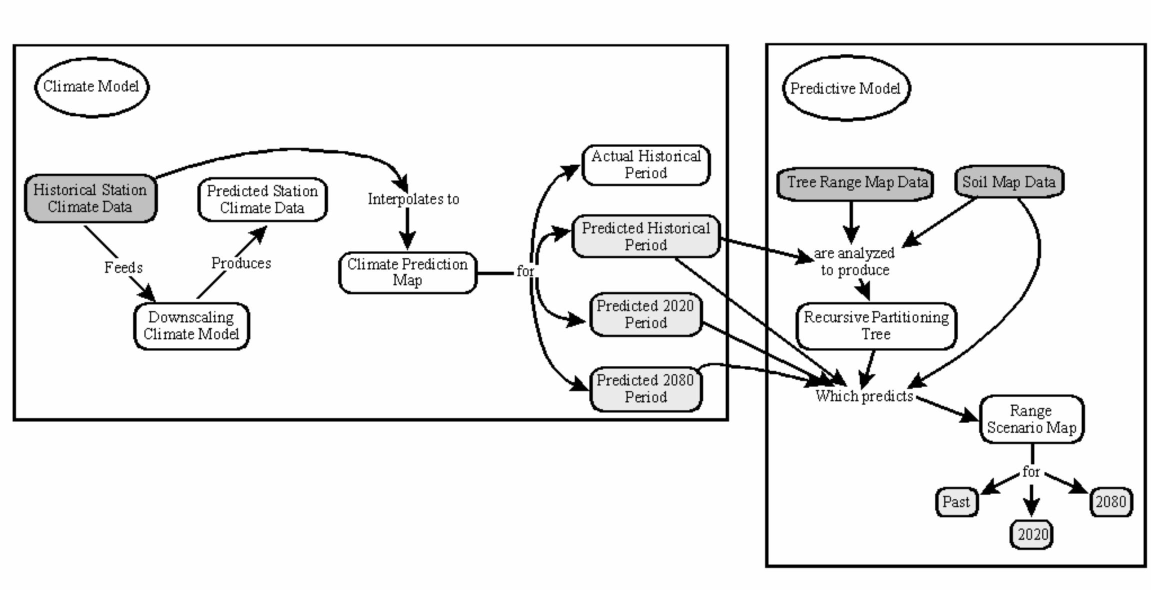

Figure 7 Conceptual Flow Diagram of the Climate and Predictive Models (Carr et al. 2004)

Henderson et al. (2002) also used an ED model (Table 11). In their research, Henderson et al. (2002) used three different global climate models (CGCM2 A21, CSIROMk2b and HadCM B21) in order to analyse the potential impact of climate change on island forests in the Canadian Prairies. They constructed climate scenarios for 2020s, 2050s and 2080s and from these scenarios they derived climate moisture indices (CMIs) based on projected precipitation, temperature and evapotranspiration in order to model moisture available plant growth. They found all of the GCM indicate declines in moisture levels over time.

CMIs are determined using only climate measurements and the slight influence of altitude on the physical process of evapotranspiration is also taken into account. CMI calculations do not require information on water holding capacity of soils. Table 10 shows the range of CMI for various vegetation types (Henderson et al. 2002).

Table 10 CMI Range Based on Vegetation Types (Hogg 1994; Henderson et al. 2002)

Range of Annual CMI	General Vegetation Type
Greater than +15	Boreal or Cordilleran (coniferous species dominant)
Zero to +15	Boreal or Cordilleran (aspen-dominated mixed woods with conifers)
-15 to zero	Parkland (mixed aspen and grassland; conifers rare)
-30 to -15	Grassland (stunted aspen in favourable sites; no conifers
Less than -30	Grassland (no trees)

Hogg (1994) found that while CMIs provide good fit to boundary lines between major vegetation ensembles, the index does not provide the critical constraint that has prevented some vegetation types such as conifers from growing in areas of water deficit or prevent aspen from growing in areas drier than -15. It is possible that the climate moisture index is a proxy measure for other factors such as fire frequency or intensity, germination success or is related to insect or other biological control (Henderson et al. 2002).

Cohen et al. (2002) used Canadian Climate Change Model (GCM1) based scenarios to drive the GrassGro Decision Support System to study possible impacts and adaptation strategies for pasture conditions in Saskatchewan. Three possible adaptation strategies to climate change at three locations and two pasture types. The results of the study demonstrated the sensitivity of present-day livestock production from pasture to specific climatic perturbations.

Thorpe et al. (2004) assessed the impacts of climate change on productivity of native grasslands in the Canadian Prairies (Table 11). They used five SRES GCMs in their analysis (CGCM2 A21, CGCM2 B22, CSIROMk2b; HadCM3 A21 and HadCM3 B21). Potential evapotranspiration was calculated by two different methods (Jensen -Haise and Baier-Robertson). They also used US grassland in portions of Montana, North Dakota, South Dakota, Wyoming, Colorado and Nebraska as analogues for the warmer future climate of the Canadian Prairies. The main method of data analysis was multiple linear regression of grassland production with various combinations of climate and water balance variables. For some of the analyses, binary variables to represent presence/absence of grazing, various range sites, or various composition types were tested. Regression models were evaluated by the coefficients and checked for patterns in the residuals. All of the regression models were fit by linear models on untransformed data with no evidence from residuals to indicate the need for data transformation or non-linear regression. They found no definitive answer regarding changes in grassland production expected under climate change over the next fifty years as results depended on the model used and there was no obvious basis for choosing one over the other (Thorpe et al. 2004).

Li et al. (2004) used the Canadian Regional Climate Model II and the IS92a emission scenario to estimate net ecosystem productivity of a semi-arid grassland (Table 11). An increase in transpiration would be caused by rising temperature. However, this would be offset by the decrease in transpiration caused by rising CO_2, thereby lengthening growing seasons and alleviating water deficits.

There are many different models used around the world. An example of one used in Australia is the HyLand terrestrial ecosystem model (Table 11). This model simulates the "natural" vegetation at each location as determined by climate and previous applications of the model assumed that present a future land cover is determined only by climate (Arnell et al. 2004). Levy et al. (2004) used the HyLand model to simulate the effects of changes in climate, CO_2 concentration and land use on natural ecosystems. Changes were prescribed by four SRES scenarios: A1F, A2, B1 and B2 and the HadCM3 GCM. Under all SRES scenarios, the terrestrial biosphere is predicted to be a net sink for carbon. As CO_2 is the dominating influence on the vegetation (by enhancing net productivity), the scenarios with high fossil fuel emissions, and thus the highest CO_2 concentrations (A1F and A2) generate the largest net terrestrial sink for carbon. This would change if these scenarios assumed continued deforestation and cropland expansion (Levy et al. 2004). They also found that without the beneficial effects of elevated CO_2, the effects of climate change are much more severe. This is of concern, as the long-term and large-scale effects of elevated CO_2 are still unknown (Levy et al. 2004).

Arnell et al. (2004) also used the HyLand model. They found that a key refinement of the terrestrial ecosystem assessment has been the inclusion of the agricultural land cover and particularly changes in agricultural land cover over time. The terrestrial ecosystem model uses data on the extent of cropland and pasture in the past and future to “over-ride” the simulated natural vegetation cover. The HyLand model simulates ecosystems at 10 different plots within each climate model grid cell, each with a discrete land cover type. At each time step, a proportion of the 10 plots is converted from the natural vegetation to cropland, via a clearcutting stage, consistent with the proportion of the grid cell covered by cropland (Arnell et al. 2004).

To determine how vegetation responds to increased CO_2 and a changed climate, some researchers use a combination of CO_2 scenarios, in particular the fossil fuel intensive simulation (F1), and various climate scenarios. Therefore, results would be a combination of CO_2 fertilization with the added potential stress of higher temperatures and other climatic changes (Table 11) (Johnston, pers. comm. 2005). When modeled yield results from cropped land include direct physiological effects of carbon dioxide, with sufficient water and nutrients are different from the research that does not take into account the CO_2 fertilization effect (Cohen et al. 2001).

Another Australian example is by Hughes (2003) who notes that a range of different modelling methods was used to investigate the potential impacts of temperature and rainfall change on vegetation (Table 11). Elevated carbon dioxide concentrations increase photosynthetic rates and water-use efficiency and may affect the temperature response. A modelling study by Rochefort and Woodward (1992) found that incorporating the effects of doubling CO_2 led to no change in Australian plant family diversity, in contrast to an earlier study with the same model that neglected carbon dioxide effects and arrived at a seriously negative impact. Results will depend on the relative changes in temperature, rainfall and carbon dioxide concentrations, which vary from one scenario to another and with location and time. Changes from increasing carbon dioxide will also be moderated by nutrient stress and other stress factors. Thus, considerable uncertainty remains as to the magnitude of CO_2 fertilization (Pittock 2003).

Higgins and Vellinga (2004) tested structural and functional ecosystem responses to the four climate boundary scenarios using IBIS 2.1 (Integrated Biosphere Simulator), a process-based dynamic global ecosystem model. IBIS takes monthly climate input for average temperature, precipitation, relative humidity, cloudiness, temperature range, wind speed and number of rainy days and uses a weather generator to produce daily variability. Monthly average temperature and precipitation are from the four climate scenarios created by HadCM3 and all others are from historical climatology. IBIS requires input data for topography, soil texture and minimum temperatures. IBIS simulations begin with a 100-year spin up under HadCM3’s control temperature and precipitation. At the end of the 100 year spin up, climate experiences a step change to each of the perturbation scenarios except the control scenario, which is held constant. IBIS then runs for an additional 100 years under each of the four perturbed climates to estimate longer term vegetation changes (Higgins and Vellinga 2004).

Uncertainties Associated with Ecosystem Models

Ecosystem models have several uncertainties associated with them. These include the use of ensemble realizations of the SRES scenarios which highlights the regional uncertainties inherent even under similar greenhouse gas emissions pathways. Members of the A2 and B2 Had CM3 ensemble climate scenarios produce moderate differences in the crop yield results in some regions and time slices. These results point to the need for agricultural managers to prepare for a range of agricultural futures at the regional level (Parry et al. 2004).

There are issues in the application of world-region projections to estimate future land cover. First the observed area of cropland summed across each region is greater than the baseline value used in the SRES projections and second, the SRES scenarios need to be downscaled to the scale of the ecosystem model. The SRES projections were therefore used to derive regional trends in cropland change, which were then applied to all the grid cells within a region to alter over time the proportion of the 10 plots assumed covered by cropland. This avoids the discontinuity between past and future, but makes the assumption that everywhere within a major world region changes at the same rate. In practice, land cover change is likely to be greatest where population and population growth rates are greatest. The third problem is that there is a mismatch between recent trends and projected future cropland change in two of the SRES storylines. The B1 and B2 scenarios project a decrease in cropland area and an increase in forest cover – which is consistent with the assumptions behind the scenarios but inconsistent with trends over the last century – and even the A1 scenario assumes that forest cover by the end of the 21st century will be similar to 1990 (Arnell et al. 2004).

The South Saskatchewan River Basin has its own idiosyncrasies. Much of the South Saskatchewan River Basin is agricultural, crop yield as well as natural ecosystem responses to climate change need to be examined. However, crop yield change estimates include different sources of uncertainty. At the site level, the main source of uncertainty relates to the use of crop models used to derive the yield functions. The crop models embody a number of simplifications. For example, weeds, diseases, and insect pests are assumed controlled; and there are no problem soil conditions. No estimate is made of the negative effects of acid deposition or other pollutants and how this may affect yield levels. The complex and uncertain assessment of the contribution of the direct effects of CO_2 to agricultural crop remains a crucial research question (Parry et al. 2004). It has also been found that crop models simulate the effect of drought conditions relatively well, but they do not respond to flooding (Parry et al. 2004).

Extremes

Ecosystems will ultimately respond to climate change but they tend to respond directly to short-term departures from normal climate and to extreme events (Sauchyn et al. 2005). Around the world several different scenarios have been developed that examine vegetative change under climate change.

Pittock (2003) documented the modelling progress and limitations in Australia. He found that Scheffer et al. (2001) stated that abrupt changes can happen in ecological systems. Such sudden changes in system behaviour often arise from an element of the system reaching a limit or threshold at which instability sets in, and the system moves into a new stable state. When a system is close to such a threshold, even quite small random events or trends can force the system into a different state. In mathematical terms, it may take the form of a switch from a negative to a positive feedback. Distance from a threshold of this sort is a measure of system resilience or ability to cope with small variations in conditions (Scheffer et al. 2001).

Conclusions and Recommendations

Many hydrologic and terrestrial models are available for usage in the Canadian Prairies. From the literature review, it appears that the WATFLOOD and SLURP models are the hydrologic models most used. SLURP appears to have been used more in the mountainous regions of Canada, while WATFLOOD is used more in the flatter portions of Canada.

WATFLOOD is currently being used in the work being carried out by Pietroniro et al. (2003) examining the South Saskatchewan River Basin. It may be interesting to use SLURP and compare the results to determining the differences and similarities of the two models results.

Several different terrestrial models have been used in Canadian research, depending on the type of research being undertaken. The Australian HyLand terrestrial model appears to allow for both ED and EF information to be obtained. While it is more complicated than the Climate Moisture Index (Carr et al. 2004; Hogg 1994; Henderson et al. 2002), it might be worthwhile to do further research to examine its suitability for this project.

Table 11 Comparison of Vegetation Models used in Climate Impacts and Adaptation Work

Model	Reference	Purpose	Model Type (ED/EF)	Uses	Inputs	Output	Validation
-Climate Moisture Index	Henderson et al. 2002	-Potential impacts of climate change on Island Forest Sites in Canadian Prairie Region	ED	-Management decisions -Vegetation decisions	-Mean annual precipitation -Potential evapotranspiration (PET) (amount of water per year) - PET calculated using Jensen Haise method	-Climate Moisture Index	-Constructed 1961-1990 baseline climate normals -Applied Climate Change scenarios at seasonal time scale to observed normals
-Climate Moisture Index -Degree-Days	Carr et al. 2004	-Potential impacts of climate change on the range of existing local and candidate local tree species	ED	-Management decisions -Potential vegetation changes	-Tree range data -Climatic factors (daily) -Soil factors -Landuse and land cover information	-Plant Hardiness -Climate Moisture Index -Range Scenario Map	-Developed a recursive partitioning tree for each tree species -Climate data was validated using a predicted historical period dataset -Statistical model was tested using the historical range of the species based on different random subset of the training area
-GrassGro	Cohen et al. 2002	-Potential impacts and possible adaptation strategies for livestock production under climate change	ED	-Ecosystem management -Livestock management -Adaptation strategies	-Climate data -Economics -Plant species -Soil types	-Grazing simulations	-Baseline simulation was 1961-1990 -Effects of predicted climate change for the four scenarios were run and compared to the baseline
-Water Balance Models (WATBAL) -Multiple linear regression models of grassland production with various combinations of climate and water balance models -Grasslands in U.S. were used as analogues for Canadian Prairies	Thorpe et al. 2004	-Relate climate to the control of grassland production by moisture availability	ED	-Impacts of climate change on grazing capacity -Livestock and grassland management	-Temperature -Precipitation -Snowmelt -Evapotranspiration -Soil moisture -Water surplus (runoff/deep drainage)	-Grassland production	-Baseline simulation was 1961-1990 and compared to climate data in particular years

Model	Reference	Purpose	Model Type (ED/EF)	Uses	Inputs	Output	Validation
-HyLand Terrestrial Ecosystem Model	Arnell et al. 2004 Levy et al. 2004	-Simulate natural vegetation at each location as determined by climate -Simulate transient effects of changes in land use on vegetation and carbon stock	ED & EF	-Document potential land cover changes	-Land use data -SRES scenarios -Climate data CO_2 concentration data	-Cropland production -Net ecosystem production -Land use change -Net Biome productivity	-Run for a 400 year period with pre-industrial conditions specified as inputs
-CO_2 Fertilization	Pittock 2003 Hughes 2003 Rochefort and Woodward 1992 Johnston 2005	-Determine vegetation response with increased CO_2 and potential stress of increased temperature	EF	-Grassland management -Cropland management			

ED = ecosystem dynamics model
ET = ecosystem function model

WATER USE AND DEMAND[1] SCENARIOS

Water from the South Saskatchewan River Basin, that is comprised of the Red Deer, Bow, Oldman and South Saskatchewan Rivers has many uses including agricultural, municipal and residential, industrial and recreational. Wittrock (2004) examined each of the main users in terms of current water usage, how each would likely deal with future water issues and indicated knowledge gaps. This section overviews relevant models for simulating water supply, and what scenarios are available.

Water supply systems in water-scarce regions and in regions with high streamflow variability, such as the Canadian prairies, tend to be vulnerable to droughts and floods. Other factors also contribute to the uncertainties of water resources in Canadian prairies, such as 1) changes over a lengthy horizon in social values, technological progress, resource depletion, economy, population growth, and their interactions that are too complex to forecast, 2) optimal system operations derived from historical data are altered by changing hydrologic conditions and 3) uncertainties in water demand and long term climate forecasts (Gan ND).

The current water rights within the Alberta portion of the SSRB are already at or close to full allocation (Gan ND). In Alberta, the apportionment law means that the most senior water right must be satisfied in any given year before the more junior rights are satisfied (Bruce et al. 2003). In Saskatchewan, water allocation gives precedence to municipal usage. The priorities are then industrial, residential and finally irrigation. Riparian zones and fisheries are also protected (Wiebe, pers. comm. 2004).

Determination of the effects of extreme weather events is also important for water resources management and design. Climate change will have effects on the occurrence of floods and droughts (Varis et al. 2004; Watson et al. 2001*b*). Defining credible scenarios for flooding is difficult. This is due to the inability of GCMs to simulate accurately short-duration, high intensity and localized heavy rainfall (Varis et al. 2004).

Although the impact of climate change could be serious, its actual impact on water scarcity (and thereby on the society) will depend on how water resources are managed in the future (Arnell 2004).

Water Use and Demand Models

Area-specific models exist for simulating water supply, use and/or demand. Some of these models are international in scope, while others are more regionally focussed. For example, for the SSRB and its sub-basins, two models have been in use: the Water Use Analysis Model (WUAM) and the Water Resource Management Model (WRMM). The WAUM provides projections of multi-sectoral water uses in a drainage basin context (Kassem et al. 1994). This model also has the ability to compare projected water uses with available supplies and produces statistics about

---

[1] In the studies reviewed in this section, ‘water use’ and ‘water demand’ terms are almost used interchangeably. However, demand is an economic term, referring to a relationship between the quantity of a product and its price. In most studies, such a distinction is not made. It would be appropriate to state that most studies address water use and not water demand.

severity and frequency of water shortages. The only water-use portion that requires climatic information is the irrigation water use component which requires historical precipitation and evapotranspiration data (Kassem et al. 1994). Kassem et al. (1994) state that the WUAM model allowed for detailed analysis of water use and allowed for consideration of water supplies, on-stream and off-stream storage, water diversions plus other things making it suitable for river basin planning.

Figure 8 illustrates the conceptual overview of the Water Use Analysis Model. The WUAM model was used in 1993 to present preliminary assessments of future water uses in the Saskatchewan portion of the South Saskatchewan River basin and the impacts of these uses, together with Alberta uses, on Lake Diefenbaker (Kassem et al. 1994).

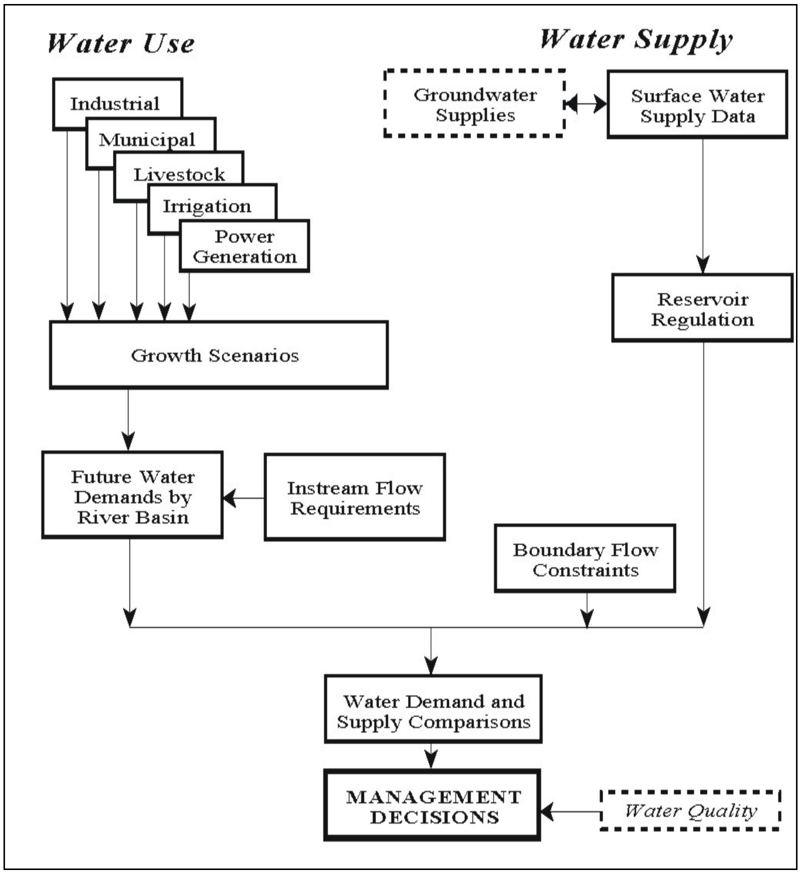

Figure 8 Water Use Analysis Model Conceptualization
(Kassem et al. 1994)

Alberta Environment uses the Water Resource Management Model (WRMM) (Figure 9). It was developed originally as a planning tool for surface water resources utilization. It has evolved to being utilized in basin planning and operational planning. Basin planning uses historical supply and demand data to project future conditions, allowing for assessment of long term water use alternatives. Operational planning allows for evaluating the shorter term future (days to weeks) of the basin, and thus has consequences for different short term operational strategies. The model has been used by Alberta Environmental Protection's decisions relating to irrigation licensing, instream flow allocations, reservoir operation and project feasibility. It has been used as a seasonal operational tool to predict the consequences of different operational strategies in dry years (Alberta Environment 2003; Alberta Environment 2002).

This model is able to simulate many physical processes including (Alberta Environment 2002):

1. water supply from reservoirs, headwater, local runoff or diversion waters
2. reservoir storage and release, precipitation and evaporation
3. natural streams and diversion channels
4. irrigation consumption with or without return flows
5. hydropower production
6. consumption demands with return flows (cities and industry)
7. consumption demands without return flows (rural, small municipal and industry).

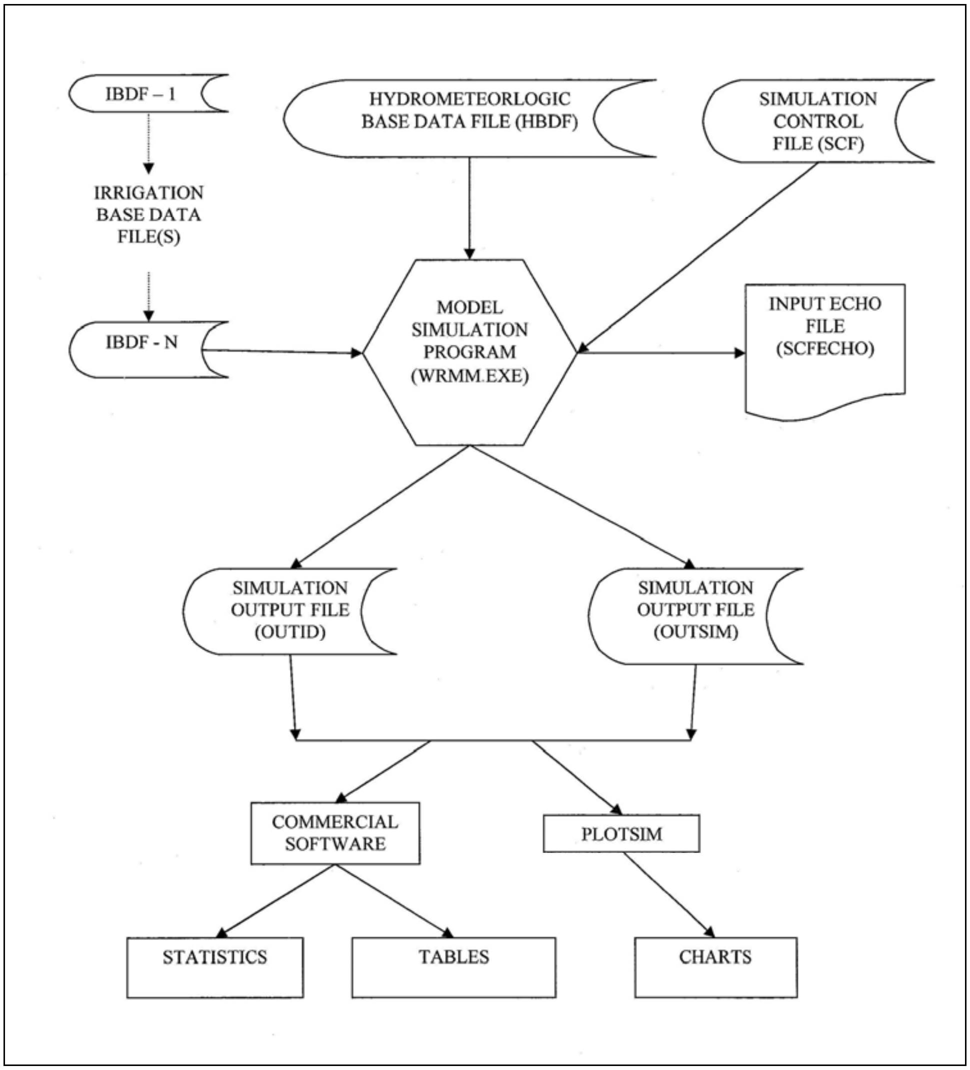

Figure 9 Water Resource Management Model - System Schematic
(Alberta Environment 2002)

In addition to the models for the SSRB, a few other attempts have been made to model water use. A statistical model was developed by Akuoko-Asibey et al. (1993) to predict spring and summer water use for Calgary, Alberta. The model's inputs include the number of days in a week with measurable precipitation, mean maximum weekly temperature and heating degree days above 16°C. The model explains only 53% of the variation in weekly water consumption per capita. Other variables (e.g., population, swimming pools) are also important in the determining weekly water consumption.

In the South Saskatchewan River Basin, computer simulation modeling of water demand and supply is considered an essential analytical technique for assessing water management options and optimizing the performance of water management systems (Irrigation Water Management Study 2002). Model outputs from the Irrigation District Model (IDM), the WRMM and the Farm Financial Impact and Risk Model (FFIRM) include water demands, water deliveries required to meet demands, stream flows, canal flows, losses, reservoir levels, irrigation deficits, and impacts of deficits on farm financial viability. Each of these models is calibrated against monitored data to ensure that the models are representative of actual field conditions. The implications for using these models for climate change research are that the modeling of water supply levels is carried out using the historic period. This could be a problem in that it could represent an overly optimistic picture of long-term water supply and demand (Irrigation Water Management Study 2002).

Nielsen (2003) assessed SaskPower's hydro-management plan to determine if the supply planning process of SaskPower's electricity plants to global climate changes were adequate. The adaptive capacity of SaskPower's electricity planning processes and supply system were adequate to cope with near future climate change impacts on demand, peak demand, and thermal and gas generating plants. However, the volume of future water resources for hydroelectric generation is unclear. It is likely that the future water volumes will not be the same as past volumes and that they will likely be less. Peak flow times have already changed and the amount of flow from glaciers is diminishing. Another unknown is the degree of pressures from other resources sectors on the water supply (Nielsen 2003).

On an international scale, attempts have been made to model various types of water uses. A model specifically developed for use in irrigation management, called Global Irrigation Model (GIM) was reported by Doll (2002). The GIM is a module of WaterGAP, which is a global model of water availability and water use that has been developed to assess the impact of global change on the problem of water scarcity (Doll 2002).

GIM computes net and gross irrigation requirements with a spatial resolution of 0.5 by 0.5°. Gross irrigation requirement is the total amount of water that must be applied by irrigation such that evapotranspiration may occur at the potential rate and optimal crop productivity may be achieved. The ratio of the net irrigation water requirement and the total amount of water that needs to be withdrawn from the source, the gross irrigation requirement, is called 'irrigation water use efficiency' (Doll 2002). The model computes change in long-term average irrigation requirements under the climatic conditions of the 2020s and the 2070s as provided by climate models. These changes were related to the variations in irrigation requirements caused by long-term and inter-annual climate variability in the 20th century (Doll 2002). The accuracy of GIM has not been fully assessed due to limited independent data available at the scale of the model (Doll 2002).

WaterGap is a global water model that examines the level of 'water stress' which is used as a measure of increasing sensitivity of watershed to global change. WaterGap is a top-down approach to calculate water stress. Water stress is a measure of the degree of pressure put on water resources, both quantity and ecosystems by users of the resource. The users include municipalities, industries, power plants and agricultural users. The authors of the paper assumed that the greater the increase in water stress, the greater the sensitivity of water resources to global change. Water stress increases when either water withdrawals increase or water availability decreases. Water stress can be divided into low, medium and severe classes using conventional thresholds (Alcamo and Henrichs 2002). When the long-term average annual withdrawals is availability ratio is

- Greater than 0.4, then water stress is severe
- Between 0.2 and 0.4, then water stress is medium
- Less than 0.2, then water stress is low

There are four sets of criteria for determining critical regions in terms of levels of water stress (Alcamo and Henrichs 2002):

- Critical set #1
    - Watersheds must currently be under severe water stress and
    - The increase in water stress because of global change must be greater than zero
- Critical set #2
    - Watershed must currently be under 'severe water stress' and
    - Water stress must increase by at least one percent per year because of global change. It is assumed that society and ecosystems can adapt to a rate of increase of water stress of up to one percent per year without disruption.
- Critical set #3
    - Watersheds must currently be under 'medium water stress' and
    - Water stress must increase by at least one percent per year because of global change
- Critical set #4
    - Watersheds must currently be under 'medium water stress'
    - Water stress must increase by at least one percent because of global change; and
    - Watersheds must be located in countries in the 'higher susceptibility' category. The higher susceptibility is determined through using the Human-Development Index to give a broad indication of the state of human well-being. Much of the world is categorized as being in the higher susceptibility range, except Argentina, Australia, Canada, the United States and Western Europe which are categorized as being in the lower susceptibility range.

Alcamo and Henrichs (2002) calculated water stress levels in the southern Canadian prairies to be mid-stress and in parts of Chile to have severe water stress. This is based on the water withdrawals situation in 1995 compared to the 1961-1990 climate normal.

The use of threshold-based indicators of water stress is important because small changes in climate or population can result in some large and populous watersheds being unable to adapt to the added pressures (Arnell 2004).

Population is an important consideration when determining water usage and demand. Arnell (2004) describes an assessment of the relative effect of climate change and population growth on future global and regional water resources stresses. He does this by using SRES socio-economic scenarios and climate projections made using six climate models driven by SRES emission scenarios (Arnell 2004). The population estimates used had several assumptions. The first was that beyond 2050 population in every country in a region changes at the same regional rate, and the second is that every grid cell within a country grows at the same rate (Arnell 2004).

Water Use Information

One of the characteristics of water use modeling in Canada is that it is based on very few actual observations of water use. In most cases, particularly for irrigation and other agricultural uses, it is based on some synthesized water requirements. Data on actual measurement of water use are rarely found. For municipal water use this can be attributed to several factors. For example, the cities and towns located along the South Saskatchewan River monitor the water usage of their residents differently (Table 12). For example, only part of the residential area of Calgary is metered for water usage, while all of Regina and Saskatoon are metered (Roach et al. 2004).

Table 12 Water and Wastewater Rate Structures in Three Cities Using Water from the South Saskatchewan River Basin (Roach et al. 2004)

City	Rate Structure
Calgary	• Partially metered • Flat rate for residential – minimum monthly rate plus aggregate monthly rate, charging per thousand square feet • Constant block rate structure for metered residential • Declining block rate structure for multi-residential • Higher constant block rate structure for irrigation use • Wastewater charges based on percentage of water used (differs by customer class).
Regina	• Fully metered (replacement of all meters installed before 1992) • Constant block rate structure • Wastewater charges based on percentage of water use (differs by customer class) • Eliminated minimum water consumption charge.
Saskatoon	• Fully metered • Declining block rate structure; sewer charge for residential uses • Constant block rate structure; sewer charge for commercial uses • Wastewater charge based on metered water rate • Minimum water and sewer monthly charge.

The provincial and federal governments have daily, monthly information for streamflow, water level, suspended sediment concentration, sediment particle size and sediment load sampling sites set up along the South Saskatchewan River basin for varying periods of record (Water Survey of

Canada 2005), but details on similar jurisdictions for water use are not routinely collected by water management agencies in the basin. Some aggregate values are, however reported. Sobool and Kulshreshtha (2003) provide per capita water use values for each community situated along the South Saskatchewan River for various years between 1961 and 2001. That document may help with projections under a potentially changed water availability regime.

Recommendations

Although water use modeling for the SSRB has been the focus of a few studies in the past, several areas require further attention. One of these is the lack of investigations on relationship between climate change and water use levels. In the present models, such relationships are either assumed to be unchanging (i.e., water use or requirement under climate change would be the same as at present) or the issue is totally ignored. In other words, little research exists to relate water demand/usage models to climate change.

The second major issue in modeling water use under climate change is the potential difficulties in determining water usage/demand. For municipal water use, this stems from the fact that some of the municipal areas are only partially metered. This results in difficulties in determining how much the water stress situation will change in the future. On the agricultural front, data on major factors affecting water use are at best poor. For example, in some jurisdictions, there exists a large difference between provincial estimate of irrigated area and that reported by Statistics Canada. Reasons for such a large discrepancy are seldom investigated.

A third area that requires further attention is the change in human behaviour under climate change, particularly under the state of short supply of water. These changes would result in further adaptation to the future climate, and would result in impacting future water use in the basin.

CONCLUSIONS AND RECOMMENDATIONS

Climate change is an environmental, economic and social issue that will affect the livelihoods and social well-being of Canadians especially in the South Saskatchewan River Basin. This report has attempted to synthesize information on GCMs and GCM downscaling, ecosystem modeling and water supply and usage modeling. Several conclusions and recommendations are made by the author as well as other researchers.

The climate change models examined here included several features, such as emission scenarios, various criteria climate change scenarios should conform to, types of climate scenarios, the nature of uncertainties of emission and climate scenarios and how well they work. Various types of scaling were also examined.

It has been recommended that the most recent emissions and climate scenarios be used as they incorporate the most information available regarding global conditions. Also at least three different GCMs should be used. This allows the researcher to portray the uncertainty in projections and develop a range of options in the impacts and adaptations work. The most common three GCMs and SRES scenarios utilized on the Canadian prairies appear to be the

CGCM2 A21, CSIROMk2b, and HadCM3 B21 with occasional utilization of CGCM2 B22 and HadCM3 A21.

Downscaling is a tool that researchers in the impacts and adaptation area would like to utilize. Numerous methods and ways exist, but the process that appears to have the most potential for this project is the statistical downscaling approach because it can be utilized in both Canada and Chile and can produce more climate change scenarios. Regional climate models are still in their infancy and not as many exist as compared with GCMs, thus not allowing researchers to portray a range of climatic possibilities.

Future climatic extremes are still very difficult to project. The best information GCMs provide relates to changes in extremes that occur on a large area such as temperature, but they do not provide information on small area such as thunderstorms, tornadoes plus others. One way to estimate changes in extreme events that occur every 10 to 100 years is through statistics.

Climate change is expected to have potentially serious consequences for plant and animal populations as well as water availability. Ecosystems tend to respond directly to short-term departures from normal climate and to extreme events and will ultimately respond to the effects of longer term climatic changes.

In the Canadian Prairies, several different ecosystem models have been used to assess how ecosystems will respond to a changed climate.

Study of water use has also been undertaken by several studies, some even for the SSRB or its sub-basins. In most of these models, water use is based on some synthetic requirements or on gross diversions adjusted for system efficiency. In the context of climate change, these models suffer from three major limitations: One, lack of consideration for the relationships between climate change and water use levels for various users; Two, Lack of reliable information on water use even under current climate regimes; and Three, lack of knowledge for the nature of adaptations that could be undertaken, thereby affecting the future water use.

ACKNOWLEDGMENTS

Funding was provided by the University of Regina through the Social Sciences and Humanities Research Council of Canada's (SSHRC) Major Collaborative Research Initiatives (MCRI). This project was a part of the Institutional Adaptation to Climate Change Project. In-kind funding was provided by the Saskatchewan Research Council and the University of Saskatchewan. We thank Dr. Dave Sauchyn, Professor of Geography, University of Regina and Research Coordinator for the Prairie Adaptation Research Collaborative for his guidance and comments. L. Crone and C. Hudym, SRC, accomplished the word processing. J. Raven and C. Marshall, SRC, assisted with the literature searches.

REFERENCES

Ahmad, Q.K., O. Anisimov, N. Arnell, S. Brown, I. Burton, M. Campos, O. Canziani, T. Carter, S.J. Cohen, P. Desanker, W. Easterling, B.B. Fitzharris, D. Forbes, H. Gitay, A. Githeko, P. Gonzalez, D. Gubler, S. Gupta, A. Haines, H. Harasawa, J.I. Holten, B. Pateh Jallow, R. Jones, Z. Kundzewicz, M. Lal, E.L. La Rovere, N. Leary, R. Leemans, C. Liu, C. Magadza, M. Manning, L. Jose Mata, J. McCarthy, R. McLean, A. McMichael, K. Miller, E. Mills, M. Monirul Qader Mirza, D. Murdiyarso, L. Nurse, C. Parmesan, M. Parry, J. Patz, M. Petit, O. Pilifosova, B. Pittock, J. Price, T. Root, C. Rosenzweig, J. Sarukhan, J. Schellnhuber, S. Schneider, R. Scholes, M. Scott, G. Sem, B. Smit, J. Smith, B. Sohngen, A. Tsyban, J. van Ypersele, P. Vellinga, R. Warrick, T. Wilbanks, A. Woodward, and D. Wratt. 2001. Summary for Policymakers. *In*: McCarthy, J.J., O.F. Canziani, N.A. Leary, D.J. Dokken, and K.S. White (Editors), *Climate Change 2001: Impacts, Adaptation, and Vulnerability*, pp. 1-17. Cambridge University Press, New York, New York. Intergovernmental Panel on Climate Change [IPCC] Working Group II.

Akuoko-Asibey, A., L.C. Nkemdirim, and D.L. Draper. 1993. The Impacts of Climatic Variables on Seasonal Water Consumption in Calgary, Alberta. *Canadian Water Resources Journal*, **18**(2):107-116.

Alberta Environment. 2003. *Water Resources Management Model* [Web Page]. Accessed April 11, 2005. Available at: http://www3.gov.ab.ca/env/water/regions/ssrb/wrmmoutput/WRMM/index.asp.

Alberta Environment. 2002. *Water Resources Management Model: Computer Program Description.* Alberta Environment, Calgary, Alberta. 111 pp.

Alcamo, J. and T. Henrichs. 2002. Critical Regions: A Model-Based Estimation of World Water Resources Sensitive to Global Changes. *Aquatic Sciences*, **64**:352-362.

Allen, M.R., B.B.B. Booth, D.J. Frame, J.M. Gregory, J.A. Kettleborough, L.A. Smith, D.A. Stainforth, and P.A. Stott. 2004. Observational Constraints on Future Climate: Distinguishing Robust from Model-Dependent Statements of Uncertainty in Climate Forecasting. Contribution to the *IPCC Workshop on Communicating Uncertainty and Risk*, May, 2004.

Anderson, C. No Date. *North American Regional Climate Change Assessment Program - Program Abstract* [Web Page]. Accessed January 7, 2005. Available at: www.narccap.ucar.edu/abstract.html.

Anonymous. 2002. *Introduction to WATFLOOD* [Web Page]. Accessed March 30, 2005. Available at: www.civil.uwaterloo.ca/watflood/intro/intro1.htm.

Arnell, N.W. 1999. Climate Change and Global Water Resources. *Global Environmental Change*, **9**:S31-S49.

Arnell, N.W. 2004. Climate Change and Global Water Resources: SRES Emissions and Socio-Economic Scenarios. *Global Environmental Change*, **14**:31-52.

Arnell, N.W., M.J.L. Livermore, S. Kovats, P.E. Levy, R. Nicholls, M.L. Parry, and S.R. Gaffin. 2004. Climate and Socio-Economics Scenarios for Global-Scale Climate Change Impacts Assessments: Characterising the SRES Storylines. *Global Environmental Change*, **14**:3-20.

Arora, V.K. and G.J. Boer. 2001. Effects of Simulated Climate Change on the Hydrology of Major River Basins. *Journal of Geophysical Research - Atmospheres*, **106**(D4):3335-3348.

Barrow, E. 2002. Scenarios of Climate Change. *In*: Kulshreshtha, S.N., R. Herrington, and D. Sauchyn (Editors), *Climate Change and Water Resources in the South Saskatchewan River*. *Proceedings of the Workshop*, January 26 to 27, 2002, Calgary, Alberta, pp. 22-44.

Barrow, E., B. Maxwell, and P. Gachon (Editors). 2004. *Climate Variability and Change in Canada: Past, Present and Future*. Meteorological Service of Canada, Toronto, Ontario. 114 pp.

Barrow, E., P. Gachon, and D. Caya. 2004. Creating Climate Change Scenarios for Canada. *In*: Barrow, E., B. Maxwell, and P. Gachon (Editors), *Climate Variability and Change in Canada: Past, Present and Future*, pp. 10-18. Meteorological Service of Canada, Toronto, Ontario.

Barrow, E.M. and R.J. Lee. 2003. *Climate Change and Environmental Assessment - Part 2: Climate Change Guidance for Environmental Assessments.* The Canadian Institute for Climate Studies, Victoria, British Columbia. 111 pp.

Barrow, E.M. and R.L. Wilby. 2001. *Using SDSM - A Decision Support Tool for the Assessment of Regional Climate Change Impacts: Version 2.1 User Manual.* University of Derby, Derby, United Kingdom. 29 pp.

Barth, M.C. and J.G. Titus (Editors). 1984. *Greenhouse Effect and Sea Level Rise: A Challenge for This Generation*. Van Nostrand Reinhold Company Inc.

Beare, S. and A. Heaney. 2002. Climate Change and Water Resources in the Murray Darling Basin, Australia: Impacts and Possible Adaptation. *2002 World Congress of Environmental and Resource Economists,* June 24 to 27, 2002, Monterey, California.

Bell, J.L., L.C. Sloan, and M.A. Snyder. 2004. Regional Changes in Extreme Climatic Events: A Future Climate Scenario. *Journal of Climate*, **17**:81-87.

Bennett, A. and J. Radford. 2003. Know your Ecological Thresholds. *Thinking Bush*, (2):1-3. *Cited in*: Pittock, B. 2003. *Climate Change: An Australian Guide to the Science and Potential Impacts.* Australian Greenhouse Office, Canberra, Australia. 239 pp.

Bennett, E.M., S.R. Carpenter, G.D. Peterson, G.S. Cumming, M. Zurek, and P. Pingali. 2003. Why Global Scenarios Need Ecology. *Front Ecol Environ*, **1**(6):322-329.

Boer, G.J. and B. Yu. 2003. Climate Sensitivity and Climate State. *Climate Dynamics*, **21**:167-176.

Bonsal, B.R., T.D. Prowse, and A. Pietroniro. 2003. An Assessment of Global Climate Model-Simulated Climate for the Western Cordillera of Canada (1961-90). *Hydrological Processes*, **17**(18):3703-3716.

Bruce, J.P., H. Martin, P. Colucci, G. McBean, J. McDougall, D. Shrubsole, J. Whalley, R. Halliday, M. Alden, L. Mortsch, and B. Mills. 2003. *Climate Change Impacts on Boundary and Transboundary Water Management*. A Climate Change Action Fund Project – Natural Resources Canada (Project A458/402). 161 pp. + Appendices.

Canadian Centre for Climate Modelling and Analysis. 2003. *Overview: An Overview of Our Research Activities and Programs* [Web Page]. Accessed August 11, 2004. Available at: http://www.cccma.bc.ec.gc.ca/research/research.shtml.

Canadian Institute for Climate Studies. 2003*a*. *Canadian Climate Impacts and Scenarios – Emissions* [Web Page]. Accessed August 25, 2004 Available at: http://www.cics.uvic.ca/scenarios/index.cgi?

Canadian Institute for Climate Studies. 2003*b*. *Canadian Climate Impacts and Scenarios - SDSM Background* [Web Page]. Accessed August 25, 2004. Available at: http://www.cics.uvic.ca/scenarios/index.cgi?More Info-SDSM Background.

Canadian Institute for Climate Studies. 2003*c*. *Canadian Climate Impacts and Scenarios - GCM Information Table* [Web Page]. Accessed March 8, 2005. Available at: http://www.cics.uvic.ca/scenarios/index.cgi?More Info-GCM Information Table.

Canadian Institute for Climate Studies. 2003*d*. *GCM Variable Info* [Web Page]. Accessed March 8, 2005. Available at: http://www.cics.uvic.ca/scenarios/data.cgi.

Canadian Institute for Climate Studies. ND. *Canadian Climate Impacts and Scenarios: Primer - Full Presentation* [Web Page]. Accessed August 9, 2004. Available at: http://www.cics.uvic.ca/scenarios/primerfull.cgi.

Carr, A., P. Weedon, and E. Cloutis. 2004. *Climate Change Implications in Saskatchewan's Boreal Forest Fringe and Surrounding Agricultural Areas: Options and Recommendations for Suitable Forest Establishment and Maintenance.* Geospatial Consulting Incorporated, Prince Albert, Saskatchewan. 99 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.

Carter, T.R., M. Hulme, and M. Lal. 1999. *Guidelines on the Use of Scenario Data for Climate Impact and Adaptation Assessment.* Intergovernmental Panel on Climate Change, Version 1. 69 pp.

Carter, T.R., S. Fronzek, and I. Bärlund. 2004. FINSKEN: a Framework for Developing Consistent Global Change Scenarios for Finland in the 21st Century. *Boreal Environment Research*, **9**:91-107.

Caya, D. 2005. New Developments in Regional Climate Models. *In*: Environment Canada, *Climate Scenarios Workshop*, January 31 to February 1, 2005, Ottawa, Ontario.

Chiew, F.H.S., and T. McMahon. 2002. Modelling the Impacts of Climate Change on Australian Streamflow. *Hydrological Processes*, **16**:1235-1245. *Cited in*: Pittock, B. 2003. *Climate Change: An Australian Guide to the Science and Potential Impacts.* Australian Greenhouse Office, Canberra, Australia. 239 pp.

Chiew, F.H.S., T.I. Harold, L. Siriwardena, R.N. Jones and R. Srikanthan. 2003. Simulation of Climate Change Impact on Runoff Using Rainfall Scenarios that Consider Daily Patterns of Change from GCMs. *Submitted to Proceedings Modsim 2003*, International Congress on Modelling and Simulation. *Cited in*: Pittock, B. 2003. *Climate Change: An Australian Guide to the Science and Potential Impacts.* Australian Greenhouse Office, Canberra, Australia. 239 pp.

Cohen, R.D.H., C.D. Sykes, E.E. Wheaton, and J.P. Stevens. 2002. *Evaluation of the Effects of Climate Change on Forage and Livestock Production and Assessment of Adaptation Strategies on the Canadian Prairies.* University of Saskatchewan, Saskatoon, Saskatchewan. SRC Publication No. 11363-1E02. 50 pp.

Cohen, S., K. Miller, K. Duncan, E. Gregorich, P. Groffman, P. Kovacs, V. Magana, D. McKnight, E. Mills, D. Schimel, G. Chichilnisky, D. Etkin, R. Fleming, K. Hall, S. Meyn, J. Patz, R. Pulwarty, D. Scott, and G. Wall. 2001. North America. *In*: McCarthy, J.J., O.F. Canziani, N.A. Leary, D.J. Dokken, and K.S. White (Editors), *Climate Change 2001: Impacts, Adaptation, and Vulnerability*, pp. 735-800. Cambridge University Press, New York, New York . Intergovernmental Panel on Climate Change [IPCC] Working Group II.

Crommelin, D.T. 2002. Homoclinic Dynamics: A Scenario for Atmospheric Ultralow-frequency Variability. *Journal of the Atmospheric Sciences*, **59**:1533-1549. *Cited in*: Pittock, B. 2003. *Climate Change: An Australian Guide to the Science and Potential Impacts.* Australian Greenhouse Office, Canberra, Australia. 239 pp.

Diaz, H., D. Gauthier, and D. Sauchyn. 2003. *Institutional Adaptations to Climate Change - Comparative Study of Dryland River Basins in Canada and Chile.* University of Regina, Regina, Saskatchewan. Grant Application to Social Sciences and Humanities Research Council of Canada.

Döll, P. 2002. Impact of Climate Change and Variability on Irrigation Requirements: A Global Perspective. *Climatic Change*, **54**:269-293.

Droogers, P. and G. Kite. 2001. *Estimating Productivity of Water at Different Spatial Scales Using Simulation Modeling.* International Water Management Institute, Colombo, Sri Lanka. 16 pp.

Easterling, D.R., G.A. Meehl, C. Parmesan, S.A. Changnon, T.R. Karl, and L.O. Mearns. 2000. Climate Extremes: Observations, Modeling, and Impacts. *Science's Compass*, **289**:2068-2074.

Environment Canada. 2005. *Models – The Canadian Regional Climate Model (CRCM)* [Web Page]. Accessed March 11, 2005. Available at: www.cccma.bc.ec.gc.ca/models/crcm.shtml.

Environment Canada (Editor). 2004. *Threats to Water Availability in Canada*. National Water Research Institute (NWRI), Burlington, Ontario. NWRI Scientific Assessment Report Series No. 3 and ACSD Science Assessment Series No. 1. 128 pp.

Evans, J. and S. Schreider. 2002. Hydrological Impacts of Climate Change on Inflows to Perth, Australia. *Climatic Change*, **55**:361-393.

Evans, J.P. 2003. Improving the Characteristics of Streamflow Modeled by Regional Climate Models. *Journal of Hydrology*, **284**:211-227.

Evans, J.P. and A.J. Jakeman. 1998. Development of a Simple, Catchment-scale, Rainfall-Evapotranspiration-Runoff Model. *Environmental Modelling and Software*, **13**:285-393.

Feenstra, J.F., I. Burton, J.B. Smith, and R.S.J. Tol (Editors). 1998. *Handbook on Methods for Climate Change Impact Assessment and Adaptation Strategies*. United Nations Environment Programme and Institute for Environmental Studies. Version 2.0.

Flato, G.M., G.J. Boer, W.G. Lee, N.A. McFarlane, D. Ramsden, M.C. Reader, and A.J. Weaver. 2000. The Canadian Centre for Climate Modelling and Analysis Global Coupled Model and Its Climate. *Climate Dynamics*, **16**:451-467.

Gachon, P. 2005. From Modelling to Scenarios of Climate Change. *Climate Change Workshop,* February 1, 2005, Ottawa, Ontario.

Gan, T.Y. 1998. *Hydroclimatic Trends and Possible Climatic Warming in the Canadian Prairies.* University of Alberta, Edmonton, Alberta. 24 pp.

Gan, T.Y. No Date. Strategies to Study Climate Change Impact and to Reduce Vulnerability for the Water Resources of South Saskatchewan River Basin, pp. 139-143. University of Alberta, Edmonton, Alberta.

Giorgi, F., B. Hewitson, J. Christensen, M. Hulme, H. Von Storch, P. Whetton, R. Jones, L. Mearns, C. Fu, R. Arritt, B. Bates, R. Benestad, G. Boer, A. Buishand, M. Castro, D. Chen, W. Cramer, R. Crane, J.F. Crossley, M. Dehn, K. Dethloff, J. Dippner, S. Emori, R. Francisco, J. Fyfe, F.W. Gerstengarbe, W. Gutowski, D. Gyalistras, I. Hanssen-Bauer, M. Hantel, D.C. Hassell, D. Heimann, C. Jack, J. Jacobeit, H. Kato, R. Katz, F. Kauker, T. Knutson, M. Lal, C. Landsea, R. Laprise, L.R. Leung, A.H. Lynch, W. May, J.L. McGregor, N.L. Miller, J. Murphy, J. Ribalaygua, A. Rinke, M. Rummukainen, F. Semazzi, K. Walsh, P. Werner, M. Widmann, R. Wilby, M. Wild, and Y. Xue. 2001. Regional Climate Information - Evaluation and Projections. *In*: Houghton, J.T., Y. Ding, D.J. Griggs, M. Noguer, P.J. van der Linden, X. Dai, K. Maskell, and C.A. Johnson (Editors), *Climate Change 2001: The Scientific Basis*, pp. 583-638. Cambridge University Press, New York, New York. Intergovernmental Panel on Climate Change [IPCC] Working Group I.

Gregory, J.M., J.F.B. Mitchell, and A.J. Brady. 1997. Summer Drought in Northern Midlatitudes in a Time-Dependent CO_2 Climate Experiment. *Journal of Climate*, **10**:662-686.

Hansen, J.E., A.A. Lacis, D.H. Rind, and G.L. Russell. 1984. Climate Sensitivity to Increasing Greenhouse Gases. *In*: Barth, M.C. and J.G. Titus (Editors), *Greenhouse Effect and Sea Level Rise: A Challenge for This Generation*. Van Nostrand Reinhold Company Inc.

Henderson, N., E. Hogg, E. Barrow, and B. Dolter. 2002. *Climate Change Impacts on the Island Forests of the Great Plains and the Implications for Nature Conservation Policy: The Outlook for Sweet Grass Hills (Montana), Cypress Hills (Alberta-Saskatchewan), Moose Mountain (Saskatchewan), Spruce Woods (Manitoba) and Turtle Mountain (Manitoba-North Dakota) - Summary Document.* Prairie Adaptation Research Collaborative, Regina, Saskatchewan. 12 pp.

Hengeveld, H. 2004. Uncertainties. *In*: Barrow, E., B. Maxwell, and P. Gachon (Editors), *Climate Variability and Change in Canada: Past, Present and Future,* pp. 37-41. Meteorological Service of Canada, Toronto, Ontario.

Hengeveld, H. and D. Francis. 2000. Canadian Climate Models As Windows to the Future: How Credible Are They? *The Climate Network*, **5**(1):3-7.

Hengeveld, H.G. 2000. Projections for Canada's Climate Future. *Climate Change Digest*, **CCD 00-01**(Special Edition):1-27.

Higgins, P.A.T. and M. Vellinga. 2004. Ecosystem Responses to Abrupt Climate Change: Teleconnections, Scale and the Hydrological Cycle. *Climatic Change*, **64**:127-142.

Hogg, E.H. 1994. Climate and the Southern Limit of the Western Canadian Boreal Forest. *Canadian Journal of Forest Research*, **24**(9):1835-1845.

Houghton, J.T., B.A. Callander, and S.K. Varney (Editors). 1992. *Climate Change 1992: The Supplementary Report to the IPCC Scientific Assessment.* Hadley Centre, Meteorological Office. 200 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.* Cambridge University Press, New York, New York. Intergovernmental Panel on Climate Change [IPCC] Working Group I. 881 pp.

Hughes, L. 2003. Climate Change and Australia: Trends, Projections and Impacts. *Austral Ecology*, in press. *Cited in*: Pittock, B. 2003. *Climate Change: An Australian Guide to the Science and Potential Impacts.* Australian Greenhouse Office, Canberra, Australia. 239 pp.

Hulme, M. and N. Sheard. 1999. *Climate Change Scenarios for Canada.* Climatic Research Unit, Norwich, United Kingdom. 6 pp.

Intergovernmental Panel on Climate Change [IPCC] Working Group I. 2004. *Workshop on Climate Sensitivity - Workshop Report*, Paris, France.

Irrigation Water Management Study Committee. 2002. *South Saskatchewan River Basin: Irrigation in the 21st Century. Volume 1: Summary Report*. Alberta Irrigation Projects Association, Lethbridge, Alberta. 175 pp.

Johnston, M. 2005. Personal Communication. M. Johnston is a Senior Research Scientist with the Saskatchewan Research Council, Saskatoon, Saskatchewan.

Jones, R.N. 2000. Analysing the Risk of Climate Change Using an Irrigation Demand Model. *Climate Research*, **14**:89-100. *Cited in*: Pittock, B. 2003. *Climate Change: An Australian Guide to the Science and Potential Impacts.* Australian Greenhouse Office, Canberra, Australia. 239 pp.

Kassem, A.M., D.M. Tate, and P.A. Dossett. 1994. *Water Use Analysis Model (WUAM) Demonstration* . Environmental Conservation Service, Ottawa, Ontario. Social Science Series No. 28. 88 pp.

Kerr, R.A. 2004. Three Degrees of Consensus. *Science*, **305**:932-934.

Kite, G. 2001. Hydrological Modelling of the Mekong River Basin. *In*: *Soil-Vegetation-Atmosphere Transfer Schemes and Large-Scale Hydrological Models (Proceedings of a Symposium Held During the Sixth IAHS Scientific Assembly,* Maastricht, The Netherlands, pp. 99-102.

Kite, G.W. 1998. Manual for the SLURP Hydrological Model. National Hydrological Research Institute [NHRI], Saskatoon, Saskatchewan. *As cited in*: Droogers, P. and G. Kite. 2001. *Estimating Productivity of Water at Different Spatial Scales Using Simulation Modeling.* International Water Management Institute, Colombo, Sri Lanka. 16 pp.

Kite, G.W. 1996. Use of Remotely Sensed Data in Hydrological Modelling of the Upper Columbia Watershed. *Canadian Journal of Remote Sensing*, **22**(1):14-23.

Kouwen, N., A.K. Bingeman, and A. Pietroniro. 2003. *Enhanced Nowcasting of Extreme Weather: Sub-Project B Ii) Hydrological Validation.* University of Waterloo, Waterloo, Ontario. Year 2 Progress Report . 101 pp.

Kouwen, N., A.K. Bingeman, and A. Pietroniro. 2002. *The Setup of the WATFLOOD Distributed Hydrologic Model Over the McGill Radar Coverage for Enhanced Nowcasting of Extreme Weather*. University of Waterloo, Waterloo, Ontario. Year 1 Interim Report. 51 pp.

Kulshreshtha, S.N., R. Herrington, and D. Sauchyn (Editors). 2002. *Climate Change and Water Resources in the South Saskatchewan River. Proceedings of the Workshop*, January 26 to 27, 2002, Calgary, Alberta. 184 pp.

Lacroix, M.P., L.W. Martz, G.W. Kite, and J. Garbrecht. 2002. Using Digital Terrain Analysis Modeling Techniques for the Parameterization of a Hydrologic Model. *Environmental Modelling & Software*, **17**:127-136.

Laprise, R., D. Caya, A. Frigon, and D. Paquin. 2003. Current and Perturbed Climate As Simulated by the Second-Generation Canadian Regional Climate Model (CRCM-II) Over Northwestern North America. *Climate Dynamics*, **21**:405-421.

Laprise, R., D. Caya, M. Giguère, G. Bergeron, H. Côté, J.-P. Blanchet, G.J. Boer, and N.A. McFarlane. 1998. Climate and Climate Change in Western Canada as Simulated by the Canadian Regional Climate Model. *Atmosphere-Ocean*, **36**(2):119-167.

Leggett, J., W.J. Pepper, R.J. Swart, J.A. Edmonds, L.G. Meira Filho, I. Mintzer, M.-X. Wang, and J. Wasson. 1992. Emissions Scenarios for the IPCC: an Update. *In*: Houghton, J.T., B.A. Callander, and S.K. Varney (Editors), *Climate Change 1992: The Supplementary Report to the IPCC Scientific Assessment.* Hadley Centre, Meteorological Office.

Levy, P.E., M.G.R. Cannell, and A.D. Friend. 2004. Modelling the Impact of Future Changes in Climate, CO_2 Concentration and Land Use on Natural Ecosystems and the Terrestrial Carbon Sink. *Global Environmental Change*, **14**:21-30.

Li, T., R.F. Grant, and L.B. Flanagan. 2004. Climate Impact on Net Ecosystem Productivity of a Semi-Arid Natural Grassland: Modeling and Measurement. *Agricultural and Forest Meteorology*, **126**:99-116.

McAvaney, B.J., C. Covey, S. Joussaume, V. Kattsov, A. Kitoch, W. Ogana, A.J. Pitman, A.J. Weaver, R.A. Wood, Z.-C. Zhao, K. AchutaRao, A. Arking, A. Barnston, R. Betts, C. Bitz, G. Boer, P. Braconnot, A. Broccoli, F.Bryan, M. Claussen, R. Colman, P. Delecluse, A. Del Genio, K. Dixon, P. Duffy. L. Dumenil, M. England, T. Fichefet, G. Flato, J.C. Fyfe, N. Gedney, P. Gent, C. Genthon, J. Gregory, E. Guilyardi, S. Harrison, N. Hasegawa, G. Holland, M. Holland, Y. Jia, P.D. Jones, M. Kageyama, D. Keight, K. Kodera, J. Kutzbach, S. Lambert, S. Legutke, G. Madec, S. Maeda, M.E. Mann, G. Meehl, I. Mokov, T. Motoi, T. Phillips, J. Polcher, G.L. Potter, V. Pope, C. Prentice, G. Roff, F. Semazzi, P. Sellers, D.J. Stensrud, T. Stockdale, R. Stouffer, K.E. Taylor, K. Trenberth, R. Tol, J. Walsh, M. Wild, D. Williamson, S.-P. Xie, X.-H. Zhang, F. Zwiers, Y. Qian, and J. Stone. 2001. Model Evaluation. *In*: Houghton, J.T., Y. Ding, D.J. Griggs, M. Noguer, P.J. van der Linden, X. Dai, K. Maskell, and C.A. Johnson (Editors), *Climate Change 2001: The Scientific Basis*, pp. 473-523. Cambridge University Press, New York, New York. Intergovernmental Panel on Climate Change [IPCC] Working Group I.

McCarthy, J.J., O.F. Canziani, N.A. Leary, D.J. Dokken, and K.S. White (Editors). 2001. *Climate Change 2001: Impacts, Adaptation, and Vulnerability*. Cambridge University Press, New York, New York. Intergovernmental Panel on Climate Change [IPCC] Working Group II. 1032 pp.

Mearns, L.O. 2004. Use of Regional Climate Models in Impacts Assessments and Adaptations Studies. *COP 10: In Session Workshop on Impacts and Adaptation to Climate Change*, December 8, 2004, Buenos Aires, Argentina.

Mearns, L.O., F. Giorgi, P. Whetton, D. Pabon, M. Hulme, and M. Lal. 2003. *Guidelines for Use of Climate Scenarios Developed From Regional Climate Model Experiments*. 38 pp.

Meehl, G.A., F. Zwiers, J. Evans, T. Knutson, L. Mearns, and P. Whetton. 2000*a*. Trends in Extreme Weather and Climate Events: Issues Related to Modeling Extremes in Projections of Future Climate Change. *Bulletin of the American Meteorological Society*, **8**(3):427-436.

Meehl, G.A., T. Karl, D.R. Easterling, S. Changnon, R. Pielke, D. Changnon, J. Evans, P.Y. Groisman, T.R. Knutson, K.E. Kunkel, L.O. Mearns, C. Parmesan, R. Pulwarty, T. Root, R.T. Sylves, P. Whetton, and F. Zwiers. 2000*b*. An Introduction to Trends in Extreme Weather and Climate Events: Observations, Socioeconomic Impacts, Terrestrial Ecological Impacts, and Model Projections. *Bulletin of the American Meteorological Society*, **81**(3):413-416.

Nakicenovic, N., O. Davidson, G. Davis, A. Grubler, T. Kram, E. Lebre La Rovere, B. Metz, T. Morita, W. Pepper, H. Pitcher, A. Sankovski, P. Shukla, R. Swart, R. Watson and Z. Dadi. 2000. *Summary for Policymakers: Emissions Scenarios*. Intergovernmental Panel on Climate Change [IPCC], Geneva Switzerland. 20 pp.

Neilson, R.P. and S.W. Running. 1996. Global Dynamic Vegetation Modelling: Coupling Biogeochemistry and Biogeography Models. *In*: Walker, B. and W. Steffen (Editors), *Global Change and Terrestrial Ecosystems*, pp. 451-465. Cambridge University Press, Cambridge, United Kingdom.

Nielsen, D.L. 2003. *Consideration of Climate Change in Electricity Demand and Supply Planning in Saskatchewan*. Royal Roads University, Victoria, British Columbia. 153 pp. + Appendices.

Oegema, B.W. 2000. Application of the SLURP Model to the Upper Assiniboine River Basin Study. *In*: *Promoting Effective Water Management: Science Meets Policy. 53rd Annual Canadian Water Resources Association Conference*, June 21 to 23, 2000, Saskatoon, Saskatchewan. Canadian Water Resources Association, Saskatoon, Saskatchewan.

Palmer, T.N. 1999. A Nonlinear Dynamical Perspective on Climate Prediction. *Journal of Climate*, **12**:575-591. *Cited in*: Pittock, B. 2003. *Climate Change: An Australian Guide to the Science and Potential Impacts.* Australian Greenhouse Office, Canberra, Australia. 239 pp.

Palutikof, J. No Date. Extremes in Climate Models. *Workshop on Development of Scenarios of Climate Variability and Extremes,* Victoria, British Columbia.

Parry, M.L., C. Rosenzweig, A. Iglesias, M. Livermore, and G. Fischer. 2004. Effects of Climate Change on Global Food Production Under SRES Emissions and Socio-Economic Scenarios. *Global Environmental Change*, **14**:53-67.

Pietroniro, A., R. Halliday, N. Kouwen, D.H. Burn, C. Lin, and S. Figliuzzi. 2004. Floods. *In*: Environment Canada (Editor), *Threats to Water Availability in Canada*, pp. 27-33. National Water Research Institute (NWRI), Burlington, Ontario. NWRI Scientific Assessment Report Series No. 3 and ACSD Science Assessment Series No. 1.

Pietroniro, A., T.Y. Gan, J. Byrne, M. Demuth, and G. van der Kamp. 2003. *Water Availability in the South Saskatchewan River Basin Under Climate Change.* National Water Research Institute, Saskatoon, Saskatchewan. 8 pp.

Pittock, B. 2003. *Climate Change: An Australian Guide to the Science and Potential Impacts.* Australian Greenhouse Office, Canberra, Australia. 239 pp.

Qian, B., S. Gameda, H. Hayhoe, R. De Jong, and A. Bootsma. 2004. Comparison of LARS-WG and AAFC-WG Stochastic Weather Generators for Diverse Canadian Climates. *Climate Research*, **26**:175-191.

Ramaswamy, V., O. Boucher, J. Haigh, D. Hauglustaine, J. Haywood, G. Myhre, T. Nakajima, G.Y. Shi, S. Solomon, R. Betts, R. Charlson, C. Chuang, J.S. Daniel, A. Del Genio, R. van Dorland, J. Feichter, J. Fuglestvedt, P.M. de F. Forster, S.J. Ghan, A. Jones, J.T. Kiehl, D. Koch, C. Land, J. Lean, U. Lohmann, K. Minschwaner, J.E. Penner, D.L. Roberts, H. Rodhe, G.J. Roelofs, L.D. Rotstayn, T.L. Schneider, U. Schumann, S.E. Schwartz, M.D. Schwarzkopf, K.P. Shine, S. Smith, D.S. Stevenson, F. Stordal, I. Tegen, Y. Zhang, F. Joos, J. Srinivasan. 2001. Radiative Forcing of Climate Change. *In*: Houghton, J.T., Y. Ding, D.J. Griggs, M. Noguer, P.J. van der Linden, X. Dai, K. Maskell, and C.A. Johnson (Editors), *Climate Change 2001: The Scientific Basis*, pp. 350-416. Cambridge University Press, New York, New York. Intergovernmental Panel on Climate Change [IPCC] Working Group I.

Roach, R., V. Huynh, and S. Dobson. 2004. *Drop by Drop: Urban Water Conservation Practices in Western Canada.* CanadaWest Foundation, Calgary, Alberta. Western Cities Project Report #29. 37 pp.

Rochefort, L., and F.I. Woodward. 1992. Effect of Climate Change and A Doubling of CO_2 on Vegetation Diversity. *Journal of Experimental Botany*, **43**:1169-1180. *Cited in*: Pittock, B. 2003. *Climate Change: An Australian Guide to the Science and Potential Impacts.* Australian Greenhouse Office, Canberra, Australia. 239 pp.

Romero, D., C.A. Madramootoo, and P. Enright. 2002. Modelling the Hydrology of an Agricultural Watershed in Quebec Using SLURP. *Canadian Biosystems Engineering,* **44**:1.11-1.20.

Ruosteenoja, K., T.R. Carter, K. Jylhä, and H. Tuomenvirta. 2003. *Future Climate in World Regions: An Intercomparison of Model-Based Projections for the New IPCC Emissions Scenarios.* Finnish Environment Institute. The Finnish Environment 644. 83 pp.

Sauchyn, D., M. Johnston, E. Wheaton, D. Schindler, D. Johnson, and J. Byrne. 2005. *Sensitivity of Terrestrial and Aquatic Ecosystems to Climate Change and Variability in the Saskatchewan and Athabasca Watersheds*.

Scheffer, M., S. Carpenter, J.A. Foley, C. Folke, and B. Walker. 2001. Catastrophic Shifts in Ecosystem. *Nature*, **413**:591-596. *Cited in*: Pittock, B. 2003. *Climate Change: An Australian Guide to the Science and Potential Impacts.* Australian Greenhouse Office, Canberra, Australia. 239 pp.

Smith, J.B., M. Hulme, J. Jaagus, S. Keevallik, A. Mekonnen, and K. Hailemariam 1998. Climate Change Scenarios. *In*: Feenstra, J.F., I. Burton, J.B. Smith, and R.S.J. Tol (Editors), *Handbook on Methods for Climate Change Impact Assessment and Adaptation Strategies,* pp. 3-1-3-40. United Nations Environment Programme and Institute for Environmental Studies. Version 2.0.

Sobool, D. and S. Kulshreshtha. 2003. *Socio-Economic Database: South Saskatchewan River Basin (Saskatchewan and Alberta).* University of Saskatchewan, Saskatoon, Saskatchewan. 56 pp.

Soulis, E.D., K.R. Snelgrove, N. Kouwen, F. Seglenieks, and D.L. Verseghy. 2000. Towards Closing the Vertical Water Balance in Canadian Atmospheric Models: Coupling of the Land Surface Scheme CLASS With the Distributed Hydrological Model WATFLOOD. *Atmosphere-Ocean*, **38**(1):251-269.

Stewart, I. 2003. Regime Change in Meteorology. *Nature*, **422**:571-573. *Cited in*: Pittock, B. 2003. *Climate Change: An Australian Guide to the Science and Potential Impacts.* Australian Greenhouse Office, Canberra, Australia. 239 pp.

Thorpe, J., B. Houston, and S. Wolfe. 2004. *Impacts of Climate Change on Grazing Capacity of Native Grasslands in the Canadian Prairies.* Saskatchewan Research Council, Saskatoon, Saskatchewan. SRC Publication No. 11561-1E04. 55 pp.

University of Alberta, Faculty of Engineering. No Date. *Hydrology* [Web Page]. Accessed May 25, 2005. Available at: http://www.uofaweb.ualberta.ca/CMS.

Varis, O., T. Kajander, and R. Lemmelä. 2004. Climate and Water: From Climate Models to Water Resources Management and Vice Versa. *Climatic Change*, **66**:321-344.

Walker, B. and W. Steffen (Editors). 1996. *Global Change and Terrestrial Ecosystems*, pp. 451-465. Cambridge University Press, Cambridge, United Kingdom.

Water Survey of Canada. 2005. *Hydrometric Program* [Web Page]. Accessed March 30, 2005. Available at: www.wsc.ec.gc.ca/hydrometric/main_e.cfm?

Watson, R.T., D.L. Albritton, T. Barker, I.A. Bashmakov, O. Canziani, R. Christ, U. Cubasch, O. Davidson, H. Gitay, D. Griggs, J. Houghton, J. House, Z. Kundzewicz, M. Lal, N. Leary, C. Magadza, J.J. McCarthy, J.F.B. Mitchell, J.R. Moreira, M. Munasinghe, I. Noble, R. Pachauri, B. Pittock, M. Prather, R.G. Richels, J.B. Robinson, J. Sathaye, S. Schneider , R. Scholes, T. Stocker, N. Sundararaman, R. Swart, T. Taniguchi, and D. Zhou. 2001*a*. *Summary for Policymakers - Climate Change 2001: Synthesis Report.* Intergovernmental Panel on Climate Change [IPCC], Geneva, Switzerland.

Watson, R.T., D.L. Albritton, T. Barker, I.A. Bashmakov, O. Canziani, R. Christ, U. Cubasch, O. Davidson, H. Gitay, D. Griggs, K. Halsnaes, J. Houghton, J. House, Z. Kundzewicz, M. Lal, N. Leary, C. Magadza, J.J. McCarthy, J.F.B. Mitchell, J.R. Moreira, M. Munasinghe, I. Noble, R. Pachauri, B. Pittock, M. Prather, R.G. Richels, J.B. Robinson, J. Sathaye, S. Schneider, R. Scholes, T. Stocker, N. Sundararaman, R. Swart, T. Taniguchi, and D. Zhou. 2001*b*. *Climate Change 2001: Synthesis Report.* IPCC, Geneva, Switzerland. Intergovernmental Panel on Climate Change [IPCC] Working Groups. 397 pp.

Whitfield, P.H., P.J. Pilon, D.H. Burn, V. Arora, H.F. Lins, T. Ouarda, C.D. Sellars, and C. Spence. 2004. Climate Variability and Change - Rivers and Streams. *In*: Environment Canada, *Threats to Water Availability in Canada*, pp. 85-90. National Water Research Institute (NWRI), Burlington, Ontario. NWRI Scientific Assessment Report Series No. 3 and ACSD Science Assessment Series No. 1.

Wiebe, R. 2004. Personal Communication. R. Wiebe is a Manager with the Saskatchewan Watershed Authority, Swift Current, Saskatchewan.

Wittrock, V. 2004. *An Assessment of the Vulnerability of Key Water Use Sectors in the South Saskatchewan River Basin (Alberta and Saskatchewan) to Changes in Water Supply Resulting From Climate Change: An Assessment of Recent Past and Current Projects Relevant to the Study*. Prepared for the University of Saskatchewan. Saskatchewan Research Council (SRC), Saskatoon, Saskatchewan. SRC Publication No. 11759-2E04. 47 pp.

Yonetani, T. and H.B. Gordon. 2001. Simulated Changes in the Frequency of Extremes and Regional Features of Seasonal/Annual Temperature and Precipitation when Atmospheric CO_2 is Doubled. *Journal of Climate*, **14**:1765-1779. *Cited in*: Pittock, B. 2003. *Climate Change: An Australian Guide to the Science and Potential Impacts.* Australian Greenhouse Office, Canberra, Australia. 239 pp.

Zhang, X. and E. Barrow. 2004. Scenarios of Climate Variability and Extremes. *In*: Barrow, E., B. Maxwell, and P. Gachon (Editors), *Climate Variability and Change in Canada: Past, Present and Future*, pp. 32-36. Meteorological Service of Canada, Toronto, Ontario.

Zwiers, F. 2005. New Developments in Global Climate Models. *In*: Environment Canada, *Climate Scenarios Workshop*, January 31 to February 1, 2005, Ottawa, Ontario.