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# CLIMATE VARIABILITY AND CHANGE IN CANADA

## PAST, PRESENT AND FUTURE

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# 1 Introduction

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This report presents 'state of the science' information regarding climate change and climate variability in Canada. As well as describing the changes in climate which have already been observed, it describes plausible climate futures for the country and outlines the major research challenges for the near future. In order for impacts and adaptation researchers to undertake thorough and meaningful assessments of climate change they require both observed climate information and scenarios of plausible climate futures. Until recently, many climate change assessments concentrated on determining the effects of changes in average climate, but now that the focus has shifted to determining the vulnerability of systems to climate change, rather than examining the general impacts of climate change, the emphasis is now on climate variability and, in particular, the frequency and magnitude of extreme events. The development and provision of scenarios which contain this type of information is currently the main challenge for the scenarios research community.

In this introductory chapter some background to the climate change issue is given, including its global context and why it is a cause for concern in Canada in particular.

## 1.1 The IPCC and Climate Change

Over the past 15 years, the Intergovernmental Panel on Climate Change (IPCC) has been an international driving force behind the world-wide concern over climate change and its impacts. It has published three detailed assessments of our current understanding of the issues during that time (IPCC, 1990, 1995, 2001a,b,c) and has been intimately involved with international discussions on the whole question of limits on greenhouse gas (GHG) emissions that led to the Kyoto Protocol of 1997. That Protocol included an agreement by developed nations to limit their GHG emissions relative to the levels emitted in 1990. Canada ratified the agreement in 2002, with its target being to reduce its GHG emissions to 6 percent below 1990 levels by 2012. If there are no further commitments to reducing greenhouse gas emissions, then the effect of the Protocol will be to reduce global-mean temperature by only 0.2°C, at the very most, by 2100 (Hulme *et al.*, 2002). However, the importance of the Kyoto Protocol should be viewed in other ways: although by itself it will have a minimal impact on global-mean temperature change, it should be viewed as the first step along the road of GHG emissions reductions and the fact that it has been successful in promoting international co-operation on the GHG emissions reduction issue means that it is more likely that further emissions reduction targets will be negotiated and implemented in the future (Hulme *et al.*, 2002).

The IPCC Third Assessment Report (IPCC, 2001a) reached the following conclusions:

- An increasing body of observations gives a collective picture of a warming world and other changes in the climate system.
- The global average surface air temperature has increased over the 20th century by about 0.6°C at annual scale, taking into account urban heat island effects. Although there is a great deal of variability in the instrumental record, most of the warming occurred in the 20th century, during two periods, 1910 to 1945 and 1976 to 2000. The 1990s was the warmest decade globally and 1998 the warmest year in the instrumental record since 1861.
- Temperatures have risen during the past four decades in the lowest 8km of the atmosphere.
- Snow cover and ice extent have decreased.

- Global average sea level has risen and ocean heat content has increased.
- Changes have also occurred in other important aspects of climate.

In contrast to the observed increases in surface air temperature over the last century, the emissions scenarios developed in the IPCC *Special Report on Emissions Scenarios* (SRES; Nakicenovic *et al.*, 2000) indicate that the global average surface air temperature is projected to warm between 1.4 and 5.8°C by 2100, relative to 1990. An appreciation for the concerns about such levels of climate change can be had by inspecting Figure 1.1. Some of the key concerns concerning the vulnerability and adaptive capacity of systems to climate change in North America and polar regions are outlined in Table 1.1. Canada's location in the high latitudes makes it one of the few countries likely to experience some of the largest changes in climate, in particular changes in temperature. Among the factors of most concern with respect to the projected impacts of climate change is the rate of such change. In order to determine the impacts of climate change on particular systems, the first step in the process involves the use of climate change scenarios.

## 1.2 Scenarios

The IPCC has always recognised the importance of scenarios, defining them in generic terms as "… coherent, internally consistent, and plausible description(s) of a possible future state of the world" (IPCC, 1994). Within the climate change community, the term 'scenario' is most often used to describe future socio-economic conditions, greenhouse gas emissions and climate conditions, and this general definition can be more explicitly tailored to represent any of these aspects. For example, "a climate scenario refers to a plausible future climate that has been constructed for explicit use in investigating the potential consequences of anthropogenic climate change" (IPCC, 2001a). Each scenario provides an image of how the future may unfold. There are, however, large uncertainties associated with this evolution, be it in relation to socio-economic or climate conditions (see Chapter 7 for more details of the uncertainties associated with scenarios). Such uncertainties mean that the level of confidence associated with a particular future is not yet sufficient to permit a scenario to be referred to as a prediction or a forecast.

In an effort to provide guidance on the construction and use of scenarios, the IPCC Task Group on Scenarios for Climate Impact Assessment (TGCIA)[1] was formed following a meeting in the UK in 1996. Its role was to consider the strategy for the provision of regional climate change information with particular focus on the then forthcoming IPCC Third Assessment Report (IPCC, 2001a,b,c) and on capacity building for future assessments. In addition to establishing the IPCC Data Distribution Centre (DDC), which provides access to global climate model (GCM) output and climate change scenarios derived from this information at the global scale, the TGCIA has also developed guidelines to encourage consistency in the selection and application of climate change scenarios in climate impact and adaptation assessments. These guidelines cover such scenario aspects as climatic and non-climatic baselines, climatic and non-climatic scenario development, scenario applications in impact assessment, and reporting standards (IPCC-TGCIA, 1999). The TGCIA's efforts have, as a result, been significant in highlighting the important roles that climate change scenarios play in impact assessments and in encouraging the use of a consistent set of climate change scenarios in impact studies. One only has to compare the IPCC's First (IPCC, 1990) and Third Assessment Reports (IPCC, 2001a) to appreciate this. The latter elaborated on the roles that climate change scenarios may play in the assessment of climate change impacts:

- ***Illustration of climate change:*** by providing information about the range of plausible future climates in a given region.
- ***Communication of the potential consequences of climate change:*** by examining the impact of a particular future climate, e.g., effects on species at risk of local extinction. In this way, scenarios may be used as awareness-raising devices.
- ***In strategic planning:*** by quantifying possible future sea-level and climate changes to design effective coastal or river flood defences, sewer and storm water systems, for example.

[1] The IPCC TGCLA has recently been renamed as the Task Group on Scenarios and Data Support for Impacts and Climate Analysis (TGICA) to better reflect its activities.

- ***Guiding emissions control policy:*** by specifying alternative socio-economic and technological options in order to achieve a specific atmospheric composition (e.g., concentration of greenhouse gases). In this case, scenarios may be used to challenge people to think about a range of alternative futures which may sometimes be associated with unconventional socio-economic structures. Scenarios are also vital aids for evaluating options for mitigating future greenhouse gas and aerosol emissions.
- ***For methodological purposes:*** by determining our knowledge (or ignorance) of a system through, for example, the description of altered conditions, the use of a new scenario development technique, or by evaluating the performance of impact models and determining the reasons for any differences in results.
- ***To explore the implications of decisions:*** by examining the impacts resulting from a particular scenario of future climate and the actions taken to ameliorate particular harmful impacts associated with the scenario.

## 1.3 Climate Change Scenarios for Canada

For more than two decades, Canada has played a leading role internationally in both the construction of climate change scenarios and in the evaluation of the impacts of climate change. Domestically, it has particularly applied its climate scenario work to the area of integrated regional assessments, culminating in the Canada Country Study (Maxwell *et al.*, 1997). Until recently, however, Canadian scientists had to construct their own climate change scenarios from available climate model information, and this was seen as a major hindrance to impacts research.

As a result of dialogue between the climate modelling and the vulnerability, impacts, and adaptation (VIA) communities in Canada, the Canadian Climate Impacts Scenarios (CCIS) Project was established in 1999, with support from the Climate Change Action Fund (CCAF), and is currently managed by the Meteorological Service of Canada. The main goal of this project is to provide climate scenario information and scenario construction advice to impacts researchers in Canada. This will ensure that the resulting impacts studies can be used to provide Canadians with a meaningful national assessment of the impacts of climate change and can contribute to future international assessments such as those undertaken by the IPCC.

The CCIS Project has promoted national awareness of climate change scenarios and scenario-based issues by focusing on climate change scenarios that describe changes in the mean values of many standard climatic variables and derived indicators. Its main vehicles for doing so have been its comprehensive web site (**http://www.cics.uvic.ca/scenarios**), operated by the Canadian Institute for Climate Studies at the University of Victoria, and close contact between the vulnerability, impacts, and adaptation and climate modelling research communities in Canada through a series of workshops and training sessions. Issues concerning scenarios of climate variability and extreme events have become increasingly important in the last couple of years and, as they become more tractable research problems, are now at the forefront among the major challenges that the CCIS Project is addressing. Chapter 4 illustrates some of the many scenarios which are currently available on the CCIS Project web site and also provides examples of some of the other information which can be obtained from this site.

## 1.4 Structure of the Report

It is intended that this report serve as a 'state of the science' document on climate variability and climate change in Canada. First, climate changes which have already been observed in Canada are discussed and put into context with what has been happening globally and whether or not these changes correspond with what is expected to happen in the future (Chapter 2). In Chapter 3 scenario construction methods are described and some illustrations of possible future climates are given in Chapter 4. Chapter 5 discusses Canada's coastal and offshore climates and some of the issues relevant to this sector. Chapter 6 introduces the subject of construction of scenarios of climate variability and extremes and discusses some of the research challenges associated with the development of this type of climate change scenario. In Chapter 7, we examine the uncertainties associated with climate change scenarios and finally in Chapter 8 the future challenges concerning the construction and application of climate change scenarios which will remain relevant for the vulnerability, impacts and adaptation communities in the longer-term are discussed.

**TABLE 1.1:**
Key concerns related to vulnerability and adaptive capacity in North America and Polar regions. [Source: IPCC (2001b)]

| REGION | ADAPTIVE CAPACITY, VULNERABILITY AND KEY CONCERNS |
|---|---|
| **North America** | ◆ Adaptive capacity of human systems is generally high and vulnerability low in North America, but some communities (e.g., indigenous peoples and those dependent on climate-sensitive resources) are more vulnerable; social, economic and demographic trends are changing vulnerabilities in sub-regions.<br>◆ Some crops would benefit from modest warming accompanied by increasing $CO_2$, but effects would vary among crops and regions (high confidence)*, including declines due to drought in some areas of Canada's Prairies and the US Great Plains, potential increased food production in areas of Canada north of current production areas, and increased warm-temperate mixed forest production (medium confidence). However, benefits for crops would decline at an increasing rate and possibly become a net loss with further warming (medium confidence).<br>◆ Snow-melt dominated watersheds in western North America will experience earlier spring peak flows (high confidence), reduction in summer flows (medium confidence) and reduced lake levels and outflows for the Great Lakes-St. Lawrence under most scenarios (medium confidence); adaptive responses would offset some, but not all, of the impacts on water users and on aquatic ecosystems (medium confidence).<br>◆ Unique natural ecosystems such as prairie wetlands, alpine tundra, and cold-water ecosystems will be at risk and effective adaptation is unlikely (medium confidence).<br>◆ Sea-level rise would result in enhanced coastal erosion, coastal flooding, loss of coastal wetlands and increased risk from storm surges (high confidence).<br>◆ Weather-related insured losses and public sector disaster relief payments in North America have been increasing; insurance sector planning has not yet systematically included climate change information, so there is potential for surprise (high confidence).<br>◆ Vector-borne diseases - including malaria, dengue fever and Lyme disease - may expand their ranges in North America; exacerbated air quality and heat stress morbidity and mortality would occur (medium confidence); socio-economic factors and public health measures would play a large role in determining the incidence and extent of health effects. |
| **Polar** | ◆ Natural systems in polar regions are highly vulnerable to climate change and current ecosystems have low adaptive capacity; technologically developed communities are likely to adapt readily to climate change, but some indigenous communities, in which traditional lifestyles are followed, have little capacity and few options for adaptation.<br>◆ Climate change in polar regions is expected to be among the largest and most rapid of any region on the Earth, and will cause major physical, ecological, sociological and economic impacts, especially in the Arctic, Antarctic Peninsula and Southern Ocean (high confidence).<br>◆ Changes in climate that have already taken place are manifested in the decrease in extent and thickness of Arctic sea ice, permafrost thawing, coastal erosion, changes in ice sheets and ice shelves and altered distribution and abundance of species in polar regions (high confidence).<br>◆ Some polar ecosystems may adapt through eventual replacement by migration of species and changing species composition, and possibly by eventual increases in overall productivity; ice edge systems that provide habitat for some species would be threatened (medium confidence).<br>◆ Polar regions contain important drivers of climate change. Once triggered, they may continue for centuries, long after greenhouse gas concentrations are stabilised, and cause irreversible impacts on ice sheets, global ocean circulation and sea-level rise (medium confidence). |

*The following words have been used where appropriate to indicate judgmental estimates of confidence: very high (95% or greater); high (67-95%); medium (33-67%), low (5-33%) and very low (5% or less).

# 2 Past and recent trends in Canada's climate

Contributing Authors: ***Lucie Vincent, Xuebin Zhang, Eva Mekis, Ross Brown, Walter Skinner, Tom Agnew, Dave Sauchyn***

## 2.1 The Global Context

Recent studies of climate trends indicate that the global-mean annual surface air temperature has increased by about 0.6°C since the late 19th century with about 0.4°C of this warming occurring since the 1970s (Folland *et al.*, 2001; see Figure 2.1). The warmest year in the 142 years of instrumental record was 1998, while 2001 was the third warmest. In many regions, it is the daily minimum (night-time temperature) that has increased at a greater rate than the daily maximum (day-time temperature). The warming temperature has led to longer frost-free seasons and growing seasons in many regions of the Northern Hemisphere. It is also consistent with long-term significant decreases in spring snow cover over Eurasia. Global precipitation over land has increased by only 1%; however, more intense precipitation events have been observed in many mid-to-high latitude regions. Considerable spatial and temporal variations have occurred over the past 100 years, and these tendencies of warming, increased precipitation, and lesser snow cover have not been uniform all around the world. This Chapter presents an overview of the past and recent trends in Canada's climate. The instrumental record is also compared to the proxy histories (i.e., temperature and precipitation information derived from, for example, tree rings and pollen records) to place the recent warming into a historical perspective.

## 2.2 The Instrumental Record in Canada

### *2.2.1 Temperature Trends in Canada*

Trends and variability in temperature have been examined for the 20th century. Due to limited data availability in the northern region prior to1950, the trends were computed for two periods: 1900-1998 for southern Canada (south of 60°N) and 1950-1998 for the entire country. Homogeneity problems, which may result in incorrect recordings, caused by instrument relocation, changes in observers, and changes in observing programs were addressed using a method-based regression model (Vincent, 1998).

During the 20th century, the annual mean temperature has increased by an average of 0.9°C over southern Canada (Zhang *et al.*, 2000). The warming is consistent from coast to coast (Figure 2.2) and the largest increase occurs in the west during the winter and spring. As is observed in the global record, the warming is greater in the night-time temperature as opposed to the day-time temperature, especially prior to the 1950s. The second half of the century is associated with distinct regional differences, including significant and strong warming in the west and south, and significant cooling in the north-east. This pattern is more evident in the winter and spring (Figure 2.3) where trends have been as high as +2.5°C in the Mackenzie Basin over the last 50 years, and as low as -1.0°C on Baffin Island during the same period. Summer displays slight increasing trends and autumn is generally associated with a small cooling.

Trends and variability were also examined in daily minimum and maximum temperatures with emphasis on the extremes (Bonsal *et al.*, 2001). For both periods, there are fewer days with extreme low temperature during winter, spring and summer, and there are more days with extreme high temperature during winter and spring. No consistent trends, however, are found in the higher percentiles during the summer indicating little change in the frequency of extreme hot days. The warming observed during the last century has had an important impact on Canadian activities and economy. It has led to longer frost-free seasons (Figure 2.4) with an increase of between 20 and 25 days in the Prairies, and to longer growing seasons with an increase of between 10 and 15 days in southern Quebec during the last century (Vincent and Mekis, 2004). There are, however, no increasing trends in the number of summer days (days above 25°C) or in the number of hot days (days above 30°C). It was also found that the frequency of cold waves (3 consecutive days with daily minimum temperature below the 10th percentile) has decreased across the country while the number of heat waves (3 consecutive days with daily maximum temperature above the 90th percentile) has not really changed since the beginning of the century. These results have been refined somewhat, with a recent study by Shabbar and Bonsal (2003) showing that cold spell trends since the 1950s display substantial spatial variability across the country – with decreases in the frequency, duration, and intensity of cold spells experienced in western Canada, while in the east, distinct increases in the frequency and duration have occurred. In the same way, Groisman *et al.* (2003) indicated that the annual severity of the cold season (i.e., the sum of daily negative temperatures) for the 1950-2000 period has substantially decreased everywhere in Canada except in eastern Canada. Also, winter warm spells have increased in both frequency and duration across most of Canada, with one exception in the extreme north-eastern regions where warm spells are becoming shorter and less frequent (Shabbar and Bonsal, 2003).

### *2.2.2 Precipitation Trends*

Spatial and temporal characteristics of annual and seasonal rainfall, snowfall and total precipitation were analysed for 1900-1998 for southern Canada and 1950-1998 for the entire country, as was the case for the temperature analyses. Comprehensive adjustments of daily rainfall and daily snowfall have been performed for known changes of instruments, including gauge undercatch and wetting loss, and for snow density and trace measurements (Mekis and Hogg, 1999).

Annual total precipitation has increased by an average of 12% in southern Canada over the past century (Zhang *et al.*, 2000). Increasing trends are consistent from coast to coast and for all seasons (Figure 2.5). The increase in total precipitation is associated with more rain during the spring, summer and autumn, while the ratio of snowfall to total precipitation has been decreasing in the winter and spring, mostly in the western part of the country. Over the last 50 years, annual total precipitation has increased by only 5% for the entire country. The significant increasing trends occur mostly in the Arctic. Precipitation totals also show significant increases in all seasons, although there are some areas of decrease during the winter. Whilst the ratio of snowfall to total precipitation has generally increased in the north, it has significantly decreased in the west and south during the spring (Figure 2.6). This is also consistent with the strong warming observed during the second half of the century.

Heavy precipitation events were also examined in Canada during the last century (Zhang *et al.*, 2001). In contrast with many other regions of the Northern Hemisphere, no consistent trends were identified in extreme precipitation, in neither its frequency nor its intensity. Instead, significant increases were detected in the number of days with rain and in the number of days with snow. For example, an increase of between 25 and 30 days with rain has been identified at many stations in southern Ontario (Figure 2.7) since the beginning of the 1950s (Vincent and Mekis, 2004). No important changes, however, were found in the greatest 1-day, 3-day and 5-day rain and snow totals over the same period of time.

### *2.2.3 Changes in Snow Cover*

Daily snow depth observations have been systematically collected and archived since the mid-1940s in Canada (Brown and Braaten, 1998). Trend analysis over the 1946-1995 period indicates that snow depths have significantly decreased over much of Canada during the winter and early spring, with the greatest decreases occurring in February and March. The reduction in snow depth is accompanied by significant decreases in snow cover duration over most of the western regions and in the Arctic in spring and summer (Figure 2.8). It was found that the late 20th century low-snow-cover conditions over many regions are related to a shift in atmospheric circulation in the Pacific-North America sector that occurred in the mid-1970s.

Snow cover exhibits considerable variability from one year to the next. Satellite-derived estimates of change in snow cover were also obtained for the post-1972 period. The satellite trends reveal major regional and seasonal differences. For example, snow cover has actually increased over some parts of eastern Canada during the 1972-2000 period.

### 2.2.4 Changes in Sea-Ice Cover

Annual sea ice extent over the Northern Hemisphere has decreased at approximately 3% per decade recently, but summer sea ice cover over the Hemisphere continues to decrease at more than twice that rate, or about 7% per decade (Serreze *et al.,* 2003; Comiso, 2002). This is consistent with GCM projections that suggest that summer ice will disappear towards the end of this century. Regional differences are large with most of the decrease occurring on the Eurasian side of the Arctic Ocean. This can be attributed to large-scale sea-ice dynamics caused by wind which continually pushes the ice cover up against the northern coastline of the Canadian Arctic Islands and Greenland.

As a result, there are no recent trends to less ice in the Canadian Arctic Archipelago and little or no significant trend to less ice in the Gulf of St. Lawrence, along the East Coast (e.g., Figure 2.9), in Hudson Bay, and even in the Beaufort Sea. This is despite the record low ice year in 1998 in the Beaufort Sea and Canadian Arctic Islands and the removal of very old sea ice that occurred in the Islands (Agnew *et al.,* 2001).

## 2.3 The Palaeoclimatic Record

A major shortcoming in our understanding of Canada's historic climate is the length of the instrumental record, particularly in many northern areas of the country. Fortunately, palaeoclimatic data derived from such things as tree rings and boreholes (known as proxy climate indicators) can help us to extend the instrumental record back in time. This helps scientists to develop a better idea of the magnitude and importance of climate variability, as well as putting into perspective the changes seen during the instrumental record.

### 2.3.1 Temperature and Precipitation Histories Using Palaeoclimatic Data

From the study of the Earth's past climates, it is known that the climate is always changing. Long-term departures from mean climate conditions are observable only from palaeoclimatic data, because most drivers of climate change (e.g., changes in the orbital characteristics of the Earth) have a periodicity that approaches or exceeds the length of instrumental records.[2] Global warming is a concern mostly because the forecast rate of warming is unprecedented in recent geological time. A plot of Northern Hemisphere temperature for the past millennium, reconstructed mainly from tree rings (Figure 2.10), is one of the most convincing and widely-used, including by the IPCC, illustrations of global warming.

The climate of the recent geological past best informs the evaluation of current and future global changes and their consequences for human populations. Past climates are inferred from the geological and biological archives of past environments, referred to as proxy indicators. Proxy records define what is possible in terms of natural or background climate change and variability, i.e., they "define the envelope of natural environmental variability against which anthropogenic impacts on the Earth System may be assessed" (as stated in the PAGES [Past Global Changes] mission statement, found at **http://www.pages.unibe.ch**). Palaeoclimatic change represents a shift in mean climatic conditions sufficient to have measurable ecological and human consequences. The climate sensitivity of proxy indicators is the basis for the inference of past climate conditions, so both climatic and environmental data can be derived from proxy indicators, although not from a single source. In order to be confident that the climate information derived from the proxy indicator is not as a result of circular reasoning, multiple proxies are required. The synthesis of palaeoclimatic records generally is limited to single or related proxies (e.g., Mathews *et al.*, 1999) or to multiple proxies for specific sites or time slices (e.g., Gajewski *et al.*, 2000), but is constrained in several ways (see Box 2.1).

[2] (See Soon et al. (2004) about the caution to estimate and represent the long-term trends and smoothing trends for recent instrumental temperature data.)

Although palaeoenvironmental records provide guidance on the response (adaptation) of human populations and natural systems to the impacts of climate variability and the change, is the derived most direct application of these records information about climate change at a range of time scales from centuries to millennia to millions of years.

One illustration of this application is the use of borehole data from western Canada. Inversions of the temperature profiles in boreholes in this region provide evidence of high surface ground temperature warming between the mid-19th century and present (Majorowicz and Skinner, 2001). Borehole data from western Canada were used to reconstruct past ground surface temperature conditions over several centuries. These temperature histories show that the recent warming follows a lengthy cold period that had persisted over several centuries. Strong relationships are also found between the ground surface temperature histories and other higher temporal resolution proxy climate time series. For example, the ground surface temperature reconstructed from the borehole data for the Prairie Grassland is compared to the surface air temperature obtained from the tree-ring data from the Columbia Icefield in the Rocky Mountains and the instrumental surface air temperature at a few stations averaged over the Alberta Foothills (Figure 2.11). All series show strong evidence of the warming occurring from the mid-19th century onwards. This palaeoclimatic reconstruction provides the basis for stating that the annual surface air temperature warming over the past five decades in western Canada, that is twice the global average, is part of a longer trend.

A second example, for precipitation, reveals the anomalous climate of the 20th century in the northern Great Plains where periods of low precipitation (drought) were restricted in length. Figure 2.12 illustrates the reconstruction of precipitation from tree rings as the basis for identifying long periods of declining precipitation by plotting cumulative departures of the reconstructed precipitation from median values (Sauchyn *et al.*, 2003). These periods of persistent aridity immediately preceded the Euro-Canadian settlement of the northern Great Plains whereas prolonged drought was absent from the 20th century and thus from the instrumental climate records.

## 2.4 Summary

Although the instrumental record in Canada has been extant since the beginning of the last century, and even earlier at some sites, it has only provided a Canada-wide picture of climate since the 1950s when a sufficient number of weather stations were located north of 60°N to provide a more complete picture. Analysis of the instrumental record has shown that some of the changes in climate observed in Canada since the beginning of the last century are consistent with global observations (e.g., warmer night-time temperatures, longer freeze-free and growing seasons) and with projections of anticipated future conditions. However, the second half of the century is associated with contrasted regional changes, including strong warming in the west and south and significant cooling in the north-east, in winter and spring. Analyses have also shown that the main changes in Canada's temperature climatology are related to a reduction in the number of cold days particularly in winter and spring, rather than to an increase in the number of hot days in summer. Precipitation observations indicate that whilst precipitation has generally increased across the country, which is in agreement with global projections of future climate, the ratio of snowfall to total precipitation has changed, with decreases particularly in western Canada in the spring.

The instrumental record in Canada is not of a sufficient length to obtain a robust estimate of climate variability, so in order to extend the instrumental record further back in time, palaeoclimatic information is required. This type of information can be derived from, for example, tree rings, and provides valuable information about lower frequency climate cycles than can be obtained from the instrumental record, as well as providing a perspective for the changes observed during the instrumental record. For example, precipitation information reconstructed from tree rings in the northern Great Plains has shown that droughts occurring in this region prior to the instrumental record were of longer duration than those experienced in the 20th century. This type of information is invaluable for putting anticipated future changes in climate in perspective with what has already occurred in the past.

## BOX 2.1 SYNTHESISING PALAEOCLIMATIC RECORDS: THE CONSTRAINTS

The synthesis of palaeoclimatic records is constrained by the following factors:

**Variable Response -** Each proxy indicator is a signal of a particular scale and aspect of climate, from the response of terrestrial (upland) vegetation to regional temperature and precipitation over many years to the sensitivity of aquatic organisms to lake salinity, and carbonate mineralogy to lake water chemistry and temperature. The timing and strength of response to climatic forcing vary geographically according to local and antecedent conditions. Much environmental change is time-transgressive, with local and regional responses at varying times and rates. Thus indications of climatic change tend to appear at different times according to both location and type of proxy. Furthermore, the geographical distribution of proxies is such that some of the most climatically sensitive (e.g., glaciers) have a limited distribution or those with maximum climate sensitivity (the best sites) are at the margins of the distribution of a proxy.

**Resolution -** Establishing the timing of climatic changes and resolving climatic variability depend entirely on chronological control. Tree rings and varves are the source of both proxy climate and chronological control (i.e., incremental dating), but most proxies are stored in geological strata and are associated with intervals of sedimentation. Proxy records derived from bulk samples with relatively coarse dating control are presented as a sequence of characteristic climates where climate change is implied by the shift from one stable climate to the next. Stable (characteristic) palaeoclimates are identified from thresholds and limits in proxy indicators of climate (e.g., maximum and minimum positions of treelines, alpine glaciers and snowlines, lake levels, and abundance of plant species). Palaeoclimates also can be perceived as stable or homogeneous due to the climate insensitivity of some states of some proxies (e.g., some plant communities or high lake levels). In general, distant climate intervals are portrayed as homogeneous simply as a function of fewer and coarser palaeo records. Conversely the climate variability of the Little Ice Age (Middle Ages to the first part of the 20th century) is well documented, with records of the retreat and advance of glaciers as opposed to a single episode of glaciation.

**Non-climatic factors -** Other forcing factors, besides climate, and internal controls influence the behaviour of natural systems. The response to climate is indirect and non-linear. The non-linear response includes thresholds causing change which is disproportional to the magnitude of the forcing. Significant variation in proxy data can thus reflect events in the history of natural systems that correspond to internal thresholds or to forcing that is indirect or non climatic.

**Calibration -** Reconstructions of climate are only as good as our understanding of the climate forcing of natural systems and the auto-ecology of the organisms used as proxies. It also depends on the quality and proximity of instrumental data for calibration of the proxy and validation of the reconstruction. Thus the monitoring of ecological, hydrologic, meteorological and geologic processes is necessary for the calibration and interpretation of proxy climate and environmental records

# 3 Creating climate change scenarios for Canada

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As indicated in Chapter 1, scenarios of climate change have a number of roles to play in vulnerability, impacts, and adaptation studies. There are a number of different methods available for the construction of climate change scenarios and there are advantages and disadvantages associated with each. In order to ensure that climate change scenarios be of most use for impact researchers and policy makers, Smith and Hulme (1998) put forward the following four criteria to aid scenario selection:

1. ***Consistency with global projections:*** Scenarios should be consistent with a broad range of global warming projections based on increased concentrations of greenhouse gases. This range was given as 1.4°C to 5.8°C by 2100 in the IPCC Third Assessment Report (IPCC, 2001a), relative to 1990 (see Figure 3.1).
2. ***Physical plausibility:*** Scenarios should not violate the basic laws of physics, which means that not only should the changes in one region be physically consistent with those in another region and globally, but that changes in the different climate variables should also be physically consistent.
3. ***Applicability in impact assessments:*** Scenarios should describe changes in a sufficient number of climate variables on a spatial and temporal scale that allows for impact assessment. So for example, it may be necessary for scenarios to provide information about changes in temperature, precipitation, solar radiation, humidity and wind speed at spatial scales ranging from a single site to global and at temporal scales ranging from daily to annual means.
4. ***Representativeness:*** Scenarios should be representative of the potential range of future regional climate change in order for a realistic range of possible impacts to be estimated.

There are a number of ways in which climate change scenarios can be constructed, but those derived from global climate model (GCM) output generally conform better with the assumptions listed above than those constructed using synthetic and analogue techniques. Details of synthetic and analogue scenarios are given in Box 3.1.

## 3.1 Projections from Global Climate Models

GCMs are numerical models that represent mathematically the physical processes of and the known feedbacks between the atmosphere, ocean, cryosphere and land surface. The models, which are used for the simulation of past, present, and future climates, have undergone considerable evolution since their first appearance about forty years ago, not least because of the substantial advances in computing technology during this time. Most GCMs have a horizontal resolution of between 250 and 600 km, with 10 to 20 vertical layers in the atmosphere and as many as 30 layers in the ocean. This resolution is quite coarse, particularly when considered in comparison to the scales at which most impacts studies are conducted, which means that it is impossible to model directly some of the smaller-scale processes (e.g., cloud and precipitation processes) occurring in the atmosphere and ocean. Such processes have to be averaged over larger scales, or related to other variables that are explicitly modelled, in the process known as parameterisation.

The most advanced GCMs are coupled atmosphere-ocean models, in which three-dimensional models of the atmosphere are linked dynamically with three-dimensional models of the ocean. They are known as transient response models since inclusion of the ocean circulation and transfers of heat and moisture from the oceanic surface means that they are able to simulate the time dependent response of climate to changes in atmospheric composition. Thus, they can be used to simulate the climate response to changing atmospheric greenhouse gas and aerosol concentrations and provide useful information about the rate as well as the magnitude of climate change.

The more recent of these transient response GCMs begin by modelling the effects of past changes in radiative forcing, i.e., the effect of historical changes in atmospheric composition (typically from the 18th or 19th century) on the radiation balance of the atmosphere. These are known as 'warm start' experiments to distinguish them from the earlier transient experiments that did not have this capability. Simulations are then continued into the future using a scenario of future radiative forcing, which is derived from an emissions scenario.

Obviously future emissions of greenhouse gases and aerosols into the atmosphere depend very much on factors such as population and economic growth and energy use. For its Third Assessment Report (IPCC, 2001a) the IPCC commissioned a *Special Report on Emissions Scenarios* (SRES; Nakicenovic *et al.*, 2000), which developed about forty different emissions scenarios that could be classified into four families, depending on whether or not the scenarios had a global or regional development focus or were driven by environmental rather than economic considerations. Of these forty emissions scenarios, six have been chosen as illustrative, or marker, scenarios: A1FI, A1B, A1T, A2, B1 and B2[3]. The global-mean temperature changes associated with the SRES emissions scenarios are illustrated in Figure 3.1. Of these six marker scenarios most global climate modelling groups (including the Canadian Centre for Climate Modelling and Analysis) have completed climate change simulations using the A2 and B2 emissions scenarios.

Given the number of GCMs currently available, some guidelines are necessary to help determine which GCMs are suitable for climate change scenario construction. Smith and Hulme (1998) proposed four criteria for selecting GCM outputs from a large sample of experiments:

1. ***Vintage:*** Recent model simulations are likely (though by no means certain) to be more reliable than those of an earlier vintage since they are based on recent knowledge and incorporate more processes and feedbacks.
2. ***Resolution:*** In general, increased spatial resolution of models has led to better representation of climate.
3. ***Validation:*** Selection of GCMs that simulate the present-day climate most faithfully is preferred, on the premise that these GCMs are more likely (though not guaranteed) to yield a reliable representation of future climate.
4. ***Representativeness of results:*** Alternative GCMs can display large differences in the estimates of regional climate change, especially for variables such as precipitation. One option is to choose models that show a range of changes in a key variable in the study region.

More recently, Parry (2002) described the criteria that GCM experiments need to have met in order to be included as part of the IPCC DDC (**http://ipcc-ddc.cru.uea.ac.uk**), a web site established by the IPCC TGCIA to facilitate the provision of GCM output and climate change scenarios to the impacts and adaptation research community. All GCMs and experiments on the DDC must have met the following criteria:

- be full 3D coupled ocean-atmosphere GCMs,
- be documented in the peer-reviewed literature,

[3] A1FI - a future world of very rapid economic growth and intensive use of fossil fuels; A1T - a future world of very rapid economic growth, and rapid introduction of new and more efficient technology; A1B - a future world of very rapid economic growth, and a mix of technological developments and fossil fuel use; A2 - a future world of moderate economic growth, more heterogeneously distributed and with a higher population growth rate than in A1; B1 - a convergent world with rapid change in economic structures, 'dematerialisation', introduction of clean technologies, and the lowest rate of population growth; B2 - a world in which the emphasis is on local solutions to economic, social and environmental sustainability, intermediate levels of economic development and a lower population growth rate than A2.

- have performed a multi-century control run[4] (for stability reasons), and
- have participated in the Second Coupled Model Intercomparison Project (CMIP2; **http://www-pcmdi.llnl.gov/cmip/cmiphome.html**).

In addition, GCMs which have a resolution of at least 3° × 3°, which have participated in the Atmospheric Model Intercomparison Project (AMIP; **http://www-pcmdi.llnl.gov/amip/**) and which consider explicit greenhouse gases (e.g., carbon dioxide, methane, nitrous oxide etc.) are preferred. Table 3.1 indicates the GCMs and associated SRES experiments that are available from the IPCC DDC.

Despite the advances in computing technology that have enabled large increases in the resolution of GCMs over the last few years, climate model results are still not sufficiently accurate (in terms of absolute values) at regional scales to be used directly in impacts studies (Mearns *et al.*, 1997). Instead, mean differences between the model's representation of current climate (this baseline period is currently 1961-1990) and some time period in the future are calculated (the *climate change scenario;* see Figure 3.2) and then combined with some baseline observed climate data set to obtain a *climate scenario* (IPCC, 1994). Conventionally, differences (future climate minus baseline climate) are used for temperature variables and ratios (future climate/baseline climate) are used for other variables such as precipitation and wind speed. Typically, a number of fixed time horizons in the future (e.g., the 2020s, the 2050s, and the 2080s) are considered in impacts studies. Given the substantial inter-decadal climatic variability exhibited by most GCMs, it's often difficult to distinguish a climate change signal from the background noise (i.e. the internal variability of the model or the model's representation of natural variability, see chapter 4). For this reason, the IPCC (2001a) has recommended to use at least 30-year averaging periods for GCM output data (for example 2010-2039, i.e. 2020s, minus 1961-1990 baseline period).

Most climate change scenarios derived from GCM output are generally based on changes in monthly or seasonal mean climate, although the greater quantities of model output now being archived by climate modelling centres mean that daily output and information on certain types of extreme events (e.g., mid-latitude cyclone intensities) are more readily available. Even though model output is being made available at finer time resolutions, however, it does not mean that it is any more meaningful than the output at monthly or seasonal time scales.

## 3.2 Obtaining Higher Resolution Climate Change Scenarios

One of the major problems with climate change scenarios constructed from GCM output is their coarse spatial resolution, which is of the order of hundreds of kilometres compared to the site and small regional scale of many impact assessments. In the conventional application of climate change scenarios, changes in climate from the nearest GCM grid box (or changes averaged over a number of grid boxes) are applied to observed climate data from the study site/region, with the observed data providing the basis of the regional 'detail' of the future climate. An alternative method is to interpolate the coarse-scale GCM changes to a higher spatial resolution and then apply these changes to observed station data. This does not, however, add any value to the scenarios and may introduce a false geographical precision into the resulting scenarios.

Two alternative methods that are of relevance to Canadian researchers are statistical downscaling and regional climate modelling (also called dynamical downscaling).

### *3.2.1: Statistical Downscaling*

Statistical downscaling operates with the view that the regional or local climate is conditioned by the large-scale climate state and regional/local physiographic features, such as topography and land-sea distribution. Regional or

[4] A control run is carried out with all GCMs and is an experiment in which the atmospheric composition is set at or near pre-industrial conditions and there are no changes in forcing for the duration of the run. Output from such a simulation provides valuable information about the stability of the model (e.g., if there are errors in the model formulation, it may drift towards an unrealistic climate over time) and the model's representation of natural climate variability.

local climate information may then be derived by determining a statistical model which relates the large-scale climate variables to regional and local variables. Such a model is derived using observed data, with a GCM then providing the large-scale climate information to enable the derivation of future climate at the local scale, assuming that the statistical relationships developed for the present climate will remain valid under future climate conditions.

Many different statistical techniques have been developed and applied for downscaling climate variables, e.g., regression techniques and artificial neural networks, with the majority of studies concentrating on the downscaling of precipitation since the modelling of this variable is particularly problematic yet reliable information is vital for many impact studies. For a summary of the available downscaling methods, the reader is directed to Chapter 10 of the IPCC Third Assessment Report (Giorgi *et al.*, 2001) and a recent summary by Wilby and Wigley (1997). In addition, a *Guidance Document on the Use of Statistical Downscaling in Climate Scenario Production for Impact Assessment* will shortly be available from the IPCC DDC (http://ipcc-ddc.cru.uea.ac.uk/guidelines/guidelines_home.html). The CCIS Project also provides access to two widely-used downscaling tools which can be used to develop higher resolution climate change scenarios for use in impact studies in Canada (see http://www.cics.uvic.ca/scenarios/index.cgi?More_Info-Downscaling_Tools).

An example of the effect of statistical downscaling is provided in Figure 3.3. In this case maximum temperature was downscaled for Victoria, BC, using the multiple linear regression techniques in the Statistical DownScaling Model (SDSM) developed by Rob Wilby and Christian Dawson in the UK (Wilby *et al.*, 2002). A regression model was determined using large-scale climate information derived from the NCEP (National Centres for Environmental Prediction) reanalysis data (Kalnay *et al.*, 1996) and daily maximum temperature data for Victoria for the 1961-1990 period. Once the model had been verified, i.e., it had been demonstrated that the large-scale climate information selected to drive the model explained as much of the variability in the local climate data as was possible and that the model was performing satisfactorily, it was used to determine future local climate conditions by driving it with large-scale climate information for the 2050s from the first CGCM1 IS92a greenhouse gas + aerosols experiment (CGCM1 GA1). In this example, the main effects of downscaling are observed in spring and fall, when downscaled maximum temperatures are between about 1 and 2°C lower than the GCM-derived scenario values. There is little difference between the downscaled and GCM-derived scenario values in winter and summer.

One of the advantages of statistical downscaling is the fact that it is much less computationally demanding than dynamical downscaling and so provides a means of producing high resolution climate scenarios relatively quickly. Many of the downscaling techniques, however, require large amounts of observational data to establish the statistical relationships and some will also require a high degree of specialist knowledge and skill to ensure that they are applied and interpreted correctly. Also, the fundamental assumption of all downscaling techniques is that the statistical relationships developed using observed data will continue to be valid under future climate conditions, and there are already some research results available that indicate that this assumption has been violated during the observational period (e.g., Wilby, 1997).

### 3.2.2 Dynamical Downscaling: The Canadian Regional Climate Model (CRCM)

For the past 20 years, high-resolution Limited-Area Models (LAMs) nested in global or hemispheric coarser-resolution atmospheric models have been intensively used for operational weather forecasting and research purposes in many centres around the world. Giorgi and his team (Dickinson *et al.*, 1989; Giorgi, 1990) adapted this methodology for regional climate simulation by nesting a fine-mesh LAM into a GCM in order to build a tool capable of the long simulations required in climate applications. Their approach, now widely used for regional climate simulations, uses low-resolution fields (taken from a GCM or from analyses of observations) to provide time-dependent lateral boundary conditions to a Regional Climate Model (RCM). The RCM, which has a higher spatial resolution and thus a better representation of topography and some climate processes, develops fine-scale details that are superimposed upon the driving low resolution flow to generate a set of coherent high-resolution climate fields with climate features at much finer scales than the ones present in the initial and driving data used in the nesting procedure. This set of high-resolution fields constitutes the rationale for the method. Most of the enhancements in the climate simulated by RCMs are observed in the fields associated with the hydrological cycle. For example, RCMs simulate more realistic precipitating systems than those present in the driving GCM in studies over Western United States (Dickinson *et al.*, 1989; Giorgi and Bates, 1989; Giorgi, 1990) and over Europe (Marinucci and Giorgi, 1992). A RCM is therefore used to improve a GCM's poor resolution by adding fine-scale details upon the GCM's large-scale flow.

The Canadian RCM (CRCM; Caya and Laprise, 1999) began development in 1990 following this approach. The CRCM is now a mature Regional Climate Simulator and its third generation (CRCM3) is being used to generate the national regional climate projections based on the physical parameterisation package of the Second-Generation Canadian GCM (GCM2; McFarlane *et al.*, 1992). The computational points are distributed on polar-stereographic coordinates at 45-km resolution covering the domain shown in Figure 3.4. The vertical representation utilizes 29 levels from the surface to approximately 30 km. Figure 3.5 presents some preliminary results which indicate the capacity of the CRCM to simulate relatively well the precipitation rate in winter over Canada (in comparison with observed Climatic Research Unit (CRU) values; Mitchell *et al.*, 2003). Previous simulations carried out with the CRCM are presented in Laprise *et al.* (1998, 2003).

Present activities in the CRCM network are related to the development of the fourth generation of the simulator (CRCM4). The main improvement in this version is a more sophisticated land-surface scheme. The implementation of a dynamical regional ocean-ice simulator for Hudson Bay (e.g. Saucier *et al.*, 2004) and the Gulf of St-Lawrence (e.g., Saucier *et al.*, 2003) is also under way.

Whilst regional climate models may provide higher resolution climate information, the cost of running climate change experiments with these models means that there will be a much smaller suite of results available for scenario construction and, in some cases, there may be only a single experiment available from a single RCM for a particular region. This means that it may be impossible to explore the range of plausible future climates in an impacts assessment, as is recommended by the IPCC TGCIA, and so users may unintentionally place too much emphasis on the results of a single higher resolution experiment. The higher resolution climates simulated by a RCM are greatly influenced by the driving information provided by a GCM. If this larger-scale information is erroneous, these errors will likely be exacerbated in the RCM and its simulated climate of a particular region is therefore unlikely to be an improvement over that of the coarser-scale GCM. The IPCC TGCIA has recently released a guidance document on RCM use in scenario applications (*Guidelines for the Use of Climate Scenarios Developed from Regional Climate Model Experiments*) and this is available from the IPCC DDC: http://ipcc-ddc.cru.uea.ac.uk/guidelines/guidelines_rcm.html.

## 3.3 Summary

The construction and application of climate change scenarios from GCM output is a relatively simple process, but both the temporal and spatial scales of this type of scenario are generally not considered to be sufficient for many impacts studies. Hence, the development of downscaling methods is an essential requirement for impact and adaptation studies in Canada. Results from the recent CMIP and AMIP Projects (e.g. Giorgi *et al.*, 2001; Covey *et al.*, 2000; Lambert and Boer, 2001) have revealed some biases in most GCMs in the simulation of climate over the 1961-1990 period in extra-tropical regions, especially in North America including Arctic sectors and the higher elevation terrain of Canada. Biases in surface air temperature can exceed 2°C during winter although they are generally smaller in summer for all GCMs (e.g. Giorgi *et al.*, 2001; Covey *et al.*, 2000; Giorgi and Francisco, 2000). Although the method of constructing scenarios of climate change from GCM information has been designed so that it assumes that any biases in the simulation of present-day climate are the same as in the simulation of future climate, this inconsistency may pose severe constraints on the usefulness of GCM information especially in regions characterised by complex physiographic settings. Suitable regionalisation or downscaling techniques may be able to overcome some of these biases and, if this is the case, they may be used to improve GCM results over land/sea discontinuities, the seasonal sea-ice margin, and in regions of complex topography and non-homogeneous land surface types.

Despite these limitations, it is important to remember that GCM output is the starting point for the application of all regionalisation techniques. Also, the analysis of more recent GCM simulations (both in non-coupled, e.g. AMIP, and coupled mode, e.g. CMIP) for broad regions indicates that biases in the simulation of present-day averaged surface climate variables are generally reduced compared with the previous generation models (Giorgi *et al.*, 2001). These improvements imply increased confidence in the simulated climate changes. Nevertheless, the improvement in model results over key regions that have a predominant role in Canadian climate, such as the seasonal sea-ice margin and/or coastal regions (Canada's coastline is in excess of 5000 km), is a critical challenge for the development of realistic climate change scenarios.

As mentioned in Chapter 10 of the IPCC Third Assessment Report (Giorgi *et al.*, 2001), the combined use of GCMs and different downscaling techniques may provide the most suitable approach for the construction of climate change scenarios for impacts and adaptation studies. The comparison of results from different approaches applied to the same problem can increase the confidence in the results and help the evaluation and the understanding of the behaviour of these different methodologies. This requires a co-ordinated effort to intercompare downscaling methods and GCMs in order to improve our capacity to build a coherent picture of regional climate change that is useful for impacts and adaptation research in Canada.

**TABLE 3.1** **Details of the SRES simulations currently available on the IPCC DDC (after Parry, 2002).**

| CLIMATE MODELLING CENTRE | COUNTRY | MODEL | SRES SIMULATIONS |
|---|---|---|---|
| Canadian Centre for Climate Modelling and Analysis | Canada | CGCM2 | A2*, B2* |
| Hadley Centre for Climate Prediction and Research | UK | HadCM3 | A1FI, A2*, B1, B2* |
| Max Planck Institute for Meteorology | Germany | ECHAM4/ OPYC3 | A2, B2 |
| Commonwealth Scientific and Industrial Research Organisation | Australia | CSIRO-Mk2 | A1, A2, B1, B2 |
| Geophysical Fluid Dynamics Laboratory | USA | GFDL-R30 | A2, B2 |
| National Centre for Atmospheric Research | USA | NCAR-PCM | A2, B2 |
| Centre for Climate Research Studies/ National Institute for Environmental Studies | Japan | CCSR/NIES AGCM + CCSR OGCM | A1FI, A1T, A1B, A2, B1, B2 |

* More than one experiment has been carried out for these emissions scenarios.

## BOX 3.1 SYNTHETIC AND ANALOGUE SCENARIOS

### Synthetic Scenarios

Synthetic scenarios (also known as 'arbitrary' or 'incremental' scenarios) are the simplest climate change scenarios to construct and apply. Their main use is in sensitivity analyses, i.e., in the determination of the response of a particular 'exposure unit' (e.g., crop yield, stream flow) to a range of climatic variations. A synthetic scenario is constructed by simply perturbing an historical record for a particular climate variable by an arbitrary amount (e.g., by increasing precipitation by 10%). Although arbitrary perturbations can be applied to different climate variables simultaneously, e.g., an increase in temperature can be coupled with a decrease in precipitation, it is more common to determine the sensitivity of the exposure unit to changes in different climate variables separately. Also, a uniform change in the particular climate variable under study may be applied throughout the year, or individual monthly or seasonal changes may be applied, if so desired.

Synthetic scenarios tend to be used to gain a better understanding of the sensitivity of the exposure unit in question to changes in particular climate variables and they are routinely used prior to more detailed climate change studies with GCM-derived scenarios. Their utility stems from the following characteristics:

- simple to apply, transparent, easily understood and interpreted by non-specialists
- allow the evaluation of the sensitivity of an exposure unit to potential changes in a single climate variable, thus identifying the climate variables which are most important for the response of the exposure unit in question.
- different components of an exposure unit can be subjected to changes in a single climate variable to determine the aggregate effect
- allow the identification of thresholds defining when the effects of climate change are no longer beneficial, or detrimental, e.g., when wind speeds exceed the threshold for structural damage occurrence.
- can also be used to determine the magnitude of climate change that a system can endure without detrimental effects occurring, i.e., the tolerance of the system to climate change, e.g., the maximum increase in temperature a particular crop can tolerate before a detrimental effect on crop growth and yield is observed.

There are, however, two main reasons why they have not been adopted for use in climate change impact assessments:

- it is virtually impossible to describe a realistic set of changes for all climate variables which are physically plausible.
- the prescribed changes tend to be arbitrary and may not conform with the uncertainty range of global changes, although this can be overcome to some extent by deriving the arbitrary changes from GCM information.

### Analogue Scenarios

In contrast to synthetic scenarios, which perturb the historical climate record for a site by an arbitrary amount to represent future conditions, analogue scenarios make use of existing climate information either at the site in question (temporal analogues), or from another location which currently experiences a climate anticipated to resemble the future climate of the site under study (spatial analogues). These methods have the advantage of representing conditions which have actually been observed and experienced, so we know that they are physically plausible and generally there are data for a number of climate variables available. Since the causes of the analogue climate are most likely due to changes in atmospheric circulation, however, rather than to greenhouse gas-induced climate change, these types of scenarios are " … not ordinarily recommended … to represent the future climate in quantitative impact assessments" (Smith and Hulme, 1998). The fundamental assumption associated with both temporal and spatial analogue scenarios is that climate will respond in the same way to a change in atmospheric composition regardless of its source and even if boundary conditions, e.g., the orbital characteristics of the Earth, land-use characteristics, sea-ice extent, etc., differ.

### Temporal Analogues

Climatic periods from the past can provide an analogue of potential future climate conditions. These analogues may be constructed from palaeoclimate information derived from, for example, the geological record, or from the historical instrumental record, the latter generally being restricted to the last 100 years or so in Canada.

### Palaeoclimate analogues

It is possible to reconstruct past climates using information from the geological record, e.g., from fossil flora and fauna remains and sedimentary deposits, as well as from information derived from tree rings, etc. These types of information are known as proxy climate indicators. It is possible to derive information about past temperature and precipitation regimes from these proxy climate indicators since the environmental conditions within which these flora and fauna species currently flourish are known. Proxy indicators from the geological record generally provide information about climates from the distant past (i.e., from between 5000 and several million years Before Present), whilst dendroclimatological information (from tree rings) can be used to infer details of climates from the past millennium. These techniques indicate that the Northern Hemisphere was between 1°C and about 4°C warmer than today during the mid-Holocene (5000 to 6000 years BP) and the Pliocene (3 to 4 million years BP), respectively.

Although palaeoclimate information may be used to construct scenarios representing future climate conditions, there are many limitations associated with this approach:

- Past changes in climate are unlikely to have been caused by increasing greenhouse gas concentrations with changes in the distant past, in particular, most probably caused by changes in the characteristics of the Earth's orbit around the Sun. These different 'boundary conditions', as they are termed, mean that we cannot be confident that the characteristics (e.g., spatial temperature and precipitation patterns) of a greenhouse gas-induced future climate which is, say, 3°C warmer than current conditions, will resemble those of a past climate which is also estimated to have been 3°C warmer than the present day.
- There may be large uncertainties related to, for example, the dating of palaeo-material, and, reconstructions of palaeo-environments or palaeo-climate tend not to be geographically comprehensive. Also, the climate information which can be derived using these techniques tends to be limited to mean temperature and precipitation, which reduces the utility of this approach in scenario studies requiring a larger suite of climate variables.
- Generally, only details of the average, and then often only seasonal (e.g., growing season), conditions prevailing in the past can be determined from the reconstructions, although some proxy indicators are more suited to providing information about extremes than others (e.g., the stratigraphic record for geological sequences is best used for extreme events since these are typically best preserved).
- The more reliable palaeoclimate reconstructions tend to indicate climate changes which lie at the 'low end' of the range of anticipated future climate warming, so temporal analogue scenarios derived from this type of information may not represent the range of possible future climate conditions. Also, the older the palaeoclimate information, the less confidence there is in its reliability and the less data there are available. For example, although conditions during the Pliocene period are estimated to have been between 3 and

4°C warmer than today, thus representing more mid-range estimates of future warming, less data are available from this period and accurate dating of those data which do exist is problematic. Some climate reconstructions derived from tree rings, however, may indicate more severe and long-lasting climate events (e.g. droughts) than exist in the instrumental record and so are able to provide valuable information about the range of natural climate variability.

### Instrumental analogues

Instrumental analogues have greater utility for the construction of scenarios of future climate than their palaeoclimate counterparts. In this case, the instrumental record is used to identify past periods of observed hemispheric- or global-scale warmth in order to provide an analogue for greenhouse gas-induced future climate. These types of 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 cool period. Although it is possible to select warmer periods from an individual station record and to use data from these periods as possible future climate scenarios, the selection of these warmer periods should be related to conditions at the hemispheric- or global-scale, rather than made from the station record without reference to the larger-scale conditions. This will ensure that the station information used represents a likely local climate response to the larger-scale projections of future climate.

Despite the fact that instrumental analogues tend to conform better with the criteria outlined earlier (Smith and Hulme, 1998), they exhibit the following problems:

- the magnitude of the warming which can be obtained from the observational record generally lies at the low end of the anticipated future warming;
- it is unlikely that the past periods of global warmth identified in the instrumental record are a result of changes in the concentration of atmospheric greenhouse gases, rather they are more likely to be due to changes in atmospheric circulation;
- they do not represent the full range of possible future climates.

Their strength, however, lies in the fact that:

- the climate conditions this type of scenario represents have actually been observed and are therefore physically plausible;
- information for a larger number of climate variables is generally available from the instrumental record and at the temporal scales generally required in vulnerability, impacts and adaptation assessments.

### Spatial Analogues

In the spatial analogue approach to scenario construction the climate record from another location, which currently experiences the climate anticipated for the study site in the future, is used to represent the climate scenario for the study site. As is the case with instrumental analogues, spatial analogue scenarios are physically plausible since they are derived from observed climate data. Further, observed instrumental records, comprising several climate variables, are available for many locations and the scenarios may be drawn from other geographic regions that have climates similar to that anticipated for Canadian locations in the future.

On the other hand, the main problem with using spatial analogues as scenarios of future climate relates to the lack of correspondence between such features as day-length, vegetation cover, soil type, proximity to water bodies or other geographic features, i.e., the boundary conditions are generally different from one location to another. This means that it is unlikely that the analogue scenario would represent physically-plausible conditions for the site in question in the future.

# 4 Future changes in Canada's climate

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This Chapter describes the possible future changes in Canada's average annual and seasonal[5] climate for the 2020s, 2050s and 2080s, with the emphasis on the 2050s. These scenarios of possible climate futures have been constructed from GCMs' results according to the methodology outlined in Chapter 3 and so represent 'state of the science' scenarios of average climate change. In order to reduce the amount of information being presented, the focus is on scenarios constructed from a number of climate change experiments conducted with the CGCM2 model from the Canadian Centre for Climate Modelling and Analysis (CCCma). However, results from other GCMs are also presented in order to illustrate the range of uncertainty that exists in projections of future climate and to emphasise that a number of different climate change scenarios should be used in any assessment of climate change impacts. This will ensure that the possible range of future climate is captured in these assessments and that decisions are not based solely on single climate change scenarios. Chapter 7 outlines the main sources of uncertainty associated with scenarios of climate change and again emphasises the use of multiple scenarios in any assessment of climate change impacts.

Six climate change experiments driven by the SRES emissions scenarios (see section 3.1 in Chapter 3) have been undertaken with the CGCM2 model, the second generation of the CCCma's coupled global climate model: three experiments using A2 emissions forcing, and three using B2 emissions forcing. Figure 3.1 indicates the response of global-mean temperature to these different emissions scenarios: A2, with an economic and regional focus, indicates an increase in global-mean temperature of about 3.8°C by 2100, whilst the corresponding value for B2, which has an environmental and regional focus, is 2.7°C. In order to summarise the results of these climate change experiments, ensemble-mean results are sometimes presented. The ensemble-mean is simply the average of the output from a number of climate change experiments and in this case averaging the results of the three A2 experiments and the three B2 experiments results in two ensemble-means. The averaging process reduces the noise due to the model's natural climate variability and concentrates its climate response (i.e., the climate change signal) to the imposed emissions forcing.

All of the information presented in this Chapter plus additional details, as well as a number of different tools for visualising and downloading the scenarios, are available on the CCIS Project web site (**http://www.cics.uvic.ca/scenarios**).

## 4.1: Uncertainty in Canada's Future Climate

Before concentrating on climate change scenarios constructed using output from the A2 and B2 climate change experiments conducted with the CGCM2 model, these scenarios are put into context by also considering the projected changes in future mean temperature and precipitation from a number of other GCMs which are considered to meet the criteria of the IPCC TGCIA (outlined in Chapter 3). Although only scenarios from

[5] The seasonal presentations correspond to the standard climatological definitions: winter refers to December through February; spring to March through May; summer to June through August; and fall to September through November.

the experiments undertaken with CGCM2 are reported in any detail, it is again emphasised that any climate change impacts study should use multiple climate change scenarios derived from a number of GCMs.

Scatter plots are a simple way of comparing the projected changes in mean temperature and precipitation for a number of climate change scenarios. Figure 4.1 illustrates the annual changes in mean temperature and precipitation averaged over the Canadian land area for the 2020s, 2050s and 2080s and shows the results of all SRES experiments undertaken with the CGCM2, HadCM3, CCSR-NIES, CSIROMk2b, ECHAM4, NCAR-PCM and GFDL-R30 GCMs (see Table 3.1 for more details of these GCMs).

There are two additional types of information included in these scatter plots. First, blue lines representing the median changes in mean temperature and precipitation have also been added to help the reader identify scenarios which represent warmer, cooler, wetter or drier conditions in the future (compared to the 1961-1990 baseline) from the whole suite of scenarios illustrated on the plot. It is apparent that in the 2020s there is little difference between the scenarios on an annual basis, whilst over time these differences become more pronounced so that the scatter amongst the scenarios is relatively large by the 2080s - some of this scatter is due to the increase in uncertainty over time in, for example, the projections of future emissions and in model behaviour. For the 2050s, the CGCM2 A2 (black circles) and B2 (black squares) scenarios indicate slightly drier but median warming conditions compared to the other scenarios.

Second, an indication of CGCM2's representation of natural climate variability is indicated by the grey squares centred on the origin of the plot. As well as undertaking climate change experiments with an individual GCM, a control experiment, in which there are no imposed changes in atmospheric composition, is also carried out. This control experiment is typically left to run for many years and gives the climate modellers valuable information about the behaviour of the GCM. It is most commonly used in scenarios work to give an indication of the model's representation of natural climate variability. In this case, the 1000-year control run from CGCM2 was used to construct scenarios of natural climate variability on multi-decadal (30-year) time scales, i.e., for each 30-year period of the control run the changes in mean temperature and precipitation were calculated with respect to the 1000-year mean value. If the climate change scenario values on the scatter plot lie within the range of the simulated natural variability values, this indicates that the projected changes in future climate are not significant. Since in this case results are being averaged over a huge area, the scenario changes tend to be significantly larger than those due to natural climate variability. In contrast, scenario changes are more likely to be insignificant, particularly for precipitation in the 2020s and 2050s, over smaller regions (not shown).

Figure 4.2 illustrates seasonal scatter plots for the 2050s. For Canada as a whole the largest projected increases in mean temperature occur in winter as a result of decreases in snow cover and sea ice, and a concomitant reduction in the reflectivity (albedo) of the land surface. Precipitation is also likely to increase, although not in all scenarios in the summer. The projected changes in summer precipitation for the A2 and B2 scenarios constructed from the ECHAM4 and GFDL-R30 models lie within the range of natural precipitation variability and therefore do not indicate significant changes in average precipitation for the 2050s. As suggested in annual changes, the CGCM2 A2 and B2 scenarios tend to indicate slightly drier but generally median-warming conditions in all seasons compared with the other scenarios.

These scatter plots represent changes in climate averaged over Canada as a whole. At more regional scales the patterns of climate change may be quite different. Figures 4.3 to 4.6 illustrate the regional patterns of climate change for the eleven SRES A2 experiments available from 7 GCMs. Figures 4.3 and 4.4 show winter and summer mean temperature change for the 2050s, respectively. In winter all GCMs indicate that the largest warming, anywhere between 5°C and in excess of 9°C, occurs in northern and eastern areas where there are reductions in snow cover and sea ice. Elsewhere increases in mean temperature are typically between about 2°C and 5°C. In summer the projected increases in mean temperature are typically between 1°C and 3°C. Winter and summer changes in precipitation are illustrated in

Figures 4.5 and 4.6, respectively. In winter, all GCMs, with the exception of the CGCM2scenarios, indicate increases in precipitation across Canada. The three CGCM2-derived A2 scenarios indicate lower increases in precipitation and some areas of precipitation decrease. In summer, most GCMs indicate increases in precipitation in northern Canada, with some areas of precipitation decrease in the south. The changes in precipitation are noticeably less homogeneous than the changes in mean temperature and this stems, to a large extent, from the difficulty of modelling the precipitation process and the sensitivity of this process to the algorithms used to describe cloud and precipitation formation within the GCM. In all GCMs, the process of precipitation formation is parameterised, i.e., it is related to other atmospheric processes which can be modelled directly, since the precipitation process itself occurs at sub-grid scale, that is at scales smaller than a GCM can resolve.

## 4.2: Canada's Future Climate

Having given an indication of the range of possible future climates for Canada from a number of GCMs, the A2 and B2 scenarios from the CGCM2 GCM are now considered in more detail. It is again emphasised that multiple climate change scenarios should be used in any climate change impacts assessment in order to capture the range of possible future climates, rather than concentrating on a single scenario of climate change. Here only the ensemble-mean scenarios are described in order to save space. For the mean temperature and precipitation scenarios the changes are shown within an estimate of the CGCM2-simulated natural climate variability, i.e., one standard deviation of model-simulated multi-decadal (30-year) average climates. Areas where the scenario changes are within this natural variability value are shaded grey, whilst areas which exceed this value are shaded the appropriate colour. The grey-shaded areas thus indicate where the projected changes in climate are not significantly different from natural climate variability values.

### *4.2.1: Future Changes in Mean Temperature*

Climate change scenarios based on the A2 and B2 emissions scenarios indicate that virtually all of Canada will be increasingly warmer than 1961-1990 baseline conditions over the next 80 years (Figures 4.7 and 4.8, respectively). The only exception is the Atlantic offshore area where minimal warming or even slight cooling is indicated. These projected changes are significantly larger than natural variability values except in the north-west Atlantic and southern Greenland regions. The annual patterns generally show a warming gradient from the south and west to the north and east. Deviating from this general picture are regional features such as a tongue of enhanced warming extending into the south central Prairies from the United States and a moderating maritime effect on warming in southern Atlantic Canada. By the 2080s the A2 ensemble-mean scenario indicates annual warming of between 4 and 5°C in the south and west ranging to between 8 and 9°C over the High Arctic. Annual warming in the south central Prairies is between 6 and 7°C, but only 2 and 3°C in the land areas of the southern Atlantic region. The B2 ensemble-mean scenario illustrates similar patterns of climate change, but magnitudes of change are generally about 2°C lower except in the southern Atlantic region where there is little difference between the A2 and B2 ensemble-mean scenarios. These annual patterns and magnitudes of climate change are strongly related to winter and spring conditions in particular, such as for the present day climate trends (see section 2.2.1 in chapter 2).

In winter, the A2 ensemble-mean scenario indicates that by the 2080s southern and western Canada is likely to be between 6 and 8°C warmer than at present whilst the Hudson Bay and High Arctic areas are generally about 8°C warmer, but in some areas the warming is in excess of 9°C. In contrast, southwestern British Columbia and the southern Atlantic region show the least warming - between 3 and 4°C. The winter diurnal temperature range (not shown) decreases across virtually the entire country with the greatest decreases (of between 2 and 3°C) occurring across the southern half of the country. This is consistent with warmer winters and suggests that winter nights will warm more than winter days.

In spring, the largest warming is seen in the south central Prairies (between 8 and 9°C), Hudson Bay, Baffin Bay and the High Arctic by the 2080s. Warming over most of the rest of the country is between 4 and 6°C. Changes in the diurnal temperature range in spring (as with summer and fall) are small.

In summer the pattern of warming is somewhat different from that of the other seasons. Warming is limited to between 4 and 5°C over most of the land areas by the 2080s, except in the north-east adjacent to Hudson Bay where warming is between 5 and 8°C. In marine areas, including the east and west coasts, Hudson Bay, and the inter-island waters of the High Arctic, warming is between about 1 and 4°C.

Fall shows the largest latitudinal warming gradient of any season. This is essentially due to the delay in the formation of seasonal sea ice in Arctic basin, with a decrease in the thickness and extent of multi-annual sea ice compared to the present day climate. South of about 65°N, warming is between 3 and 5°C by the 2080s whilst in the north it is between 8 and 9°C over the extreme High Arctic. The B2 ensemble-mean scenario shows similar patterns of climate change in all seasons, although the magnitude of the warming is generally less.

### *4.2.2: Future Changes in Mean Precipitation*

Figures 4.9 and 4.10 illustrate the changes in precipitation for the CGCM2 A2 and B2 ensemble-mean scenarios, respectively. It is readily apparent that there is much more variation in the patterns of precipitation change compared with those for mean temperature. It is also apparent that these changes in precipitation are not always significant, i.e., they do not exceed the natural variability estimates calculated from the control run of CGCM2.

Under both the A2 and B2 emissions scenario, there is a clear trend for increased annual precipitation over Canada as a whole by the 2080s. The largest increases in precipitation (generally 20 to 25% wetter) are projected to occur in northern and eastern areas under the A2 ensemble-mean scenario, whilst in more southern regions precipitation increases are likely to be between 0 and 10% above 1961-1990 baseline conditions. The B2 ensemble-mean scenario indicates similar patterns, but reduced magnitude, of precipitation change.

On a seasonal basis, the patterns of precipitation change are generally quite different from the annual picture. In winter increases in precipitation are generally projected for southern Canada, whilst decreases of up to 20% are indicated for northern regions by the 2080s. In spring significant increases in precipitation are projected for southern Canada in all three future time periods, although there is an area of significant precipitation decrease in south-west British Columbia in the 2050s and 2080s. In summer significant decreases (10 to 20%) in precipitation are projected for the southern Prairie provinces and British Columbia, whilst large increases in precipitation (10-25%) are projected in northern and eastern regions by the 2080s. Precipitation changes over the Canadian Great Lakes region are not projected to be significant under this scenario. In fall, increases in precipitation are projected over most of the Canadian land area by the 2080s, although there is an area of slight precipitation decrease (up to 5%) in eastern Ontario and western Quebec. For the B2 ensemble-mean scenario the projected changes in precipitation follow similar seasonal patterns, are less significant and generally of a lower magnitude compared with those of the A2 ensemble-mean scenario.

### *4.2.3: Future Changes in Mean Sea Level Pressure and Wind Speed*

Figure 4.11 illustrates the seasonal and annual changes in mean sea level pressure (MSLP) for the 2050s for both the A2 and B2 ensemble-mean scenarios. It is readily apparent that both scenarios exhibit very similar patterns of change, although the magnitudes are generally slightly reduced in the B2 ensemble-mean scenario.

On an annual basis, there is generally a decrease in MSLP across Canada, with the exception being the east and west coasts and south-eastern regions where there are modest increases in MSLP. These MSLP changes result in a higher pressure gradient across the country and result in increased annual-average wind speeds, generally of the order of between 5 and 10% (see Figure 4.12).

In all seasons there is a general decrease in MSLP in the high Arctic and this is strongest in the fall, reflecting the effect of large areas of open water. In winter there are strong decreases in pressure off the west coast of Canada, in contrast to the increases in pressure off the east coast. This leads to increased wind speeds over Canada as a whole. In spring most of the country experiences slight increases in MSLP, with the exception of the far north and this again leads to general increases in wind speed across most of the Canadian land area. In summer there are large areas of MSLP increase off the east and west coasts, although most of the country experiences decreases in MSLP. Large decreases in wind speed occur in all coastal areas in this season, whilst most of the land area experiences increases in wind speed, particularly in northern regions. In fall, decreases in MSLP are projected for most of the country, although there are areas of MSLP increase in east and west coastal regions. Wind speeds in this season generally increase, with the largest increases again seen in the far north.

### *4.2.4: Future Changes in Soil Moisture Content*

The seasonal and annual patterns and magnitudes of soil moisture change are very similar in both the A2 and B2 ensemble-mean scenarios for the 2050s (see Figure 4.13). Noticeable declines in soil moisture are apparent over the south-central Prairies and the southern Mackenzie Valley in all seasons, but on an annual basis there is little change in soil moisture content across the rest of the country. In winter and spring more northern regions exhibit a slight increase in soil moisture content, but in summer and fall slight decreases in soil moisture are indicated for most of the country. In these two seasons the area of noticeable decline in soil moisture in the prairies expands both westwards and eastwards to include southern British Columbia and southern Ontario. These patterns are generally consistent with higher winter and spring evaporation caused by higher temperatures and reduced snow cover, and lower precipitation amounts during the summer.

However, as mentioned in IPCC (chapter 8, 2001a), water storage and runoff in regions of frozen soil moisture remain outstanding problems in GCMs, especially in models using poor land surface parameterizations as the standard bucket hydrology scheme used in this version of CGCM2. (The next version of this model, CGCM3, uses a more sophisticated land surface parameterization, namely the Canadian Land Surface Scheme, which will potentially be able to improve the simulation of liquid and frozen soil moisture. Results from CGCM3 are not yet widely available). Hence, the changes in soil moisture must be taken with caution, as the confidence in the simulation of this land surface quantity is limited.

### *4.2.5: Future Changes in Incident Solar Radiation*

Both the A2 and B2 ensemble-mean scenarios indicate reduced incident solar radiation amounts (due to increased cloudiness) over almost the entire country by the 2050s (see Figure 4.14). The largest declines in incident solar radiation occur in spring (in excess of 6 $Wm^{-2}$) and, in particular, in the summer (between 8 and 10 $Wm^{-2}$) , whilst fall and winter exhibit much smaller reductions in incident solar radiation.

## 4.3: Interpreting Future Climate Change in Canada

Descriptions of possible future changes in average climate, as given above, are not necessarily very meaningful unless they are expressed in more useful terms, such as, for example, changes in growing season length, or changes in demand for air conditioning in summer or space heating in winter. In the next two sub-sections two interpretative methods are described which express these average climate changes in a more meaningful manner.

### *4.3.1: Future Changes in the Climate Severity Index*

The Climate Severity Index (CSI) is an annual measure of the impact of climate on human comfort and well-being and of the risk of certain climatic hazards to human health and life, with a scale ranging from 0 to 100 (Phillips and Crowe, 1984; Murdock *et al.*, 2002). It is weighted equally between winter and summer discomfort factors and psychological, hazard, and outdoor mobility factors. For Canada, it varies strongly from south to north and from coastal areas to inland. Canada's least severe climates (i.e. low values of CSI) are found on southeastern Vancouver Island, the Okanagan Valley of British Columbia, southern Alberta, and southern Ontario and the most severe (i.e. high values of CSI) are found in the Arctic Archipelago. Of Canada's major cities, Victoria has the lowest CSI value (i.e., least severe), while St. John's, Newfoundland has the highest (i.e., most severe) value.

Using model results from an earlier version of the Canadian coupled global climate model (CGCM1) and the IS92a emissions scenario (a business-as-usual emissions scenario, which was in widespread use by the climate modelling and impacts communities until the advent of the SRES emissions scenarios, and which exhibits a similar increase in global-mean temperature as the SRES B2 emissions scenario by 2100, as shown in Figure 3.1), indicate that by the 2050s the CSI is reduced in magnitude (less severe) for the whole country. (This strictly applies to only the regions south of about 70°N, as future index values were not calculated for more northerly areas.) The greatest reduction in severity occurs in the regions adjacent to Hudson Bay. Most of the reduction is related to decreases in the winter discomfort factor across the country. The only aspect of the index that indicates a significantly increased severity is the summer discomfort factor, which is projected to be higher across most of southern Canada, especially in the southern Prairies (see Figures 4.15 and 4.16).

### *4.3.2: Future Changes in the Bioclimate Profiles*

Bioclimate profiles (BCPs), described by MacIver and Isaac (1989) as 'climate at a glance', provide a graphical representation of climate and related indices on a site-by-site basis. A typical bioclimate profile consists of a number of elements that describe the temperature and moisture conditions at the site in question. These elements generally include:

- minimum, mean and maximum temperature and also extreme minimum and extreme maximum temperature,
- degree-day accumulations with threshold temperatures relevant for energy use and agricultural applications,
- probability of frost and freeze-free season information,
- monthly total precipitation, actual and potential evapotranspiration,
- frequency of precipitation (number of days with rain and days with snow), and
- water surplus and deficit.

A bioclimate profile is calculated using daily observations for maximum and minimum temperature, total precipitation, total rain, total snow (expressed as water equivalent) and snow depth, where available, and are typically calculated for 30-year climate normal periods. The baseline bioclimate profiles illustrated here were calculated using daily data for the 1961-1990 period. Scenarios of climate change (here designated as A21 and B21, and calculated from the first [of three] climate change experiments undertaken with the CGCM2 model using the SRES emissions scenarios A2 and B2) were applied to the 1961-1990 daily data in the standard manner (see Chapter 3) in order to construct corresponding profiles for the 2050s. Because of space restrictions results for only a single station from each province and territory are illustrated. To view results for additional sites, and also for other climate change scenarios, the reader is invited to visit the CCIS Project web site (http://www.cics.uvic.ca/scenarios).

Results are summarised in Table 4.1 and in Figures 4.17 to 4.28. The Figures illustrate the number of days above or below particular temperature thresholds, as well as the number of growing degree days[6] above specific threshold temperatures relevant to agricultural applications (e.g., 5°C is often used as the threshold temperature for general crop growth, whilst 10°C is used for more heat-loving species, such as corn). In addition, the water balance profiles are also provided. These indicate total monthly precipitation, actual and potential evapotranspiration and the average annual water surplus or deficit.

At all sites the number of days with maximum temperatures above the temperature thresholds increases. For Kamloops, Regina and Winnipeg the number of days with maximum temperatures above 30°C and above 35°C double under the CGCM2 A21 scenario. Days with maximum temperatures above 30°C are projected to occur at Norman Wells, Whitehorse, Sept-Iles, Nappan and St. John's under one (usually the more extreme CGCM2 A21) or both climate change scenarios by the 2050s, in contrast to during the 1961-1990 baseline period when there were no days recorded with such high maximum temperatures. For Ottawa and Fredericton days with maximum temperatures above the extreme value of 35°C are projected to occur during the 2050s. In contrast the number of days with maximum temperatures below cold extremes (-10°C and -20°C) are projected to decrease. This is reflected in the annual heating (cooling) degree day values which generally decrease (increase)

[6] Degree days are calculated, normally over seasons or a year, by totalling the number of degrees above or below a particular threshold temperature. So, for example, to calculate the number of degree days above a threshold temperature of 5°C, for each day of the year when the observed mean temperature was greater than 5°C the difference between the observed mean temperature and the threshold value is calculated and totalled, resulting in an annual degree day value. Degree days are often used in agricultural (growing degree days) and energy demand (heating or cooling degree days with 18°C as a threshold for defining space heating/cooling) applications.

under both scenarios by the 2050s and reflect the reduced space heating requirements in winter and increased space cooling requirements in summer, respectively, as a result of the warming climate.

The growing degree day profiles also tell a similar story. Degree day values increase for all threshold temperatures (0, 5 and 10°C) and this is reflected in the lengthening of the growing season, in some cases by over 40 days. So, by the 2050s, earlier planting and later harvest may be possible, and it may be possible to grow different crop species in order to take advantage of the warmer conditions.

The final component of the profile illustrated in Figures 4.17 to 4.28 is the water balance. This indicates, on a monthly basis, when water surplus (indicated by the blue bars on the Figures) and deficit (when potential evapotranspiration exceeds actual evapotranspiration) occur. In general, the magnitude of the annual-average water deficit increases at all sites, with the deficit most prominent in summer months. The timing of peak water surplus conditions changes at some sites and there may be increases or decreases in the magnitude of this peak value. In general, the magnitude of the changes under the CGCM2 B21 scenario are not as great as those of the CGCM2 A21 scenario.

Changes in the number of rain and snow days are also given in Table 4.1. These changes reflect the simplistic nature of scenario application and arise as a result of snow events changing to rain events as the mean temperature exceeds 0°C, rather than from changes in climate variability which would result in changes in the sequence of precipitation events and in the number of days with precipitation. In general, there is a decrease in the number of snow days and a concomitant increase in the number of rain days. Chapter 6 introduces the concept of constructing scenarios of climate variability change (and of extreme events), the research for which is still in its infancy.

## 4.4: Summary

This Chapter had described some of the possible changes to Canada's climate in the future. Whilst the focus has been on scenarios of climate change constructed from a single GCM (CGCM2) and two emissions scenarios (A2 and B2), results from other GCMs have also been illustrated in order to emphasise that there is uncertainty in these results and that researchers should ensure that they use a range of scenarios, rather than relying on a single representation of the future climate, in any climate change impacts assessments that they undertake.

The main conclusions can be summarised as follows:

### *Temperature*

- average annual warming by the 2080s of between 1 and 9°C depending on the region
- greater warming in winter and spring than in summer and fall (as suggested in recent climatic trends)
- greatest warming in the north, particularly in the High Arctic
- least warming in the southern Atlantic region

### *Precipitation*

- Wetter conditions for Canada as a whole by the 2080s
- Strongest geographic contrast occurs in summer with up to 25% wetter conditions north of 60°N and up to 25 % drier in the south-central Prairies by the 2080s
- Up to 25% increase in wetness in spring for the southern Prairies by the 2080s
- Fall and winter are the seasons of greatest increase in dryness for southern Ontario and Quebec by the 2080s
- A change in precipitation type from snow to rain with warming temperatures

### *Wind Speed*

- Higher wind speeds for most of Canada by the 2080s
- Increases average about 10%, but greatest increases reach 25% over north-eastern regions of the country
- Increases are mainly a winter and spring characteristic as for temperature changes

### *Climate Severity Index*

- Reduced annually throughout Canada by the 2080s, with the major contributor to this reduction being less severe winter conditions

For all climate variables the CGCM2-derived B2 scenarios indicate similar patterns of climate change, but slight reductions in the magnitude of the changes, when compared with the A2 scenarios.

## TABLE 4.1 Bioclimate profile values for 1961-1990 and for the 2050s under the CGCM2-derived A21 and B21 climate change scenarios.

| LOCATION | | MEAN TEMPERATURE (°C) | | | | ANNUAL DEGREE DAY TOTALS | | | GROWING SEASON LENGTH (DAYS) | ANNUAL DAYS WITH | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | WINTER | SPRING | SUMMER | FALL | HEATING | COOLING | GROWING (ABOVE 5°C) | | RAIN | SNOW |
| **KAMLOOPS, BC** | 1961-1990 | -3.0 | 9.3 | 19.8 | 8.4 | 3664 | 249 | 2253 | 206 | 117 | 12 |
| | A21 | -0.7 | 12.1 | 22.0 | 10.2 | 3014 | 444 | 2835 | 237 | 130 | 8 |
| | B21 | -1.2 | 11.4 | 21.6 | 9.9 | 3142 | 407 | 2714 | 233 | 130 | 8 |
| **WHITEHORSE, YT** | 1961-1990 | -16.0 | -0.20 | 12.50 | -0.80 | 6979 | 4 | 850 | 115 | 102 | 21 |
| | A21 | -14.4 | 0.5 | 15.3 | 1.5 | 6314 | 36 | 1229 | 148 | 115 | 18 |
| | B21 | -14.6 | 0.4 | 14.4 | 1.1 | 6443 | 20 | 1114 | 140 | 116 | 18 |
| **NORMAN WELLS, NWT** | 1961-1990 | -26.2 | -6.6 | 14.9 | -6.1 | 8780 | 44 | 1067 | 125 | 82 | 28 |
| | A21 | -22.3 | -3.4 | 17.5 | -3.3 | 7699 | 127 | 1433 | 151 | 85 | 20 |
| | B21 | -24.0 | -4.4 | 16.9 | -3.8 | 8022 | 101 | 1349 | 145 | 84 | 23 |
| **RESOLUTE, NU** | 1961-1990 | -31.5 | -22.0 | 1.7 | -15.0 | 12641 | 0 | 28 | N/A | 54 | 23 |
| | A21 | -25.0 | -17.5 | 6.7 | -8.8 | 10599 | 0 | 227 | N/A | 63 | 12 |
| | B21 | -26.7 | -18.6 | 5.9 | -9.4 | 10982 | 0 | 180 | N/A | 61 | 14 |
| **CALGARY, AB** | 1961-1990 | -8.1 | 3.7 | 15.3 | 4.4 | 5197 | 43 | 1430 | 160 | 98 | 20 |
| | A21 | -4.5 | 8.8 | 18.1 | 6.4 | 4083 | 153 | 2092 | 202 | 120 | 13 |
| | B21 | -5.2 | 7.8 | 17.6 | 6.1 | 4277 | 126 | 1955 | 197 | 118 | 14 |
| **REGINA, SK** | 1961-1990 | -14.4 | 3.1 | 17.8 | 3.8 | 5756 | 154 | 1718 | 154 | 113 | 20 |
| | A21 | -10.3 | 9.3 | 21.5 | 6.3 | 4534 | 430 | 2507 | 193 | 115 | 15 |
| | B21 | -11.0 | 8.2 | 20.6 | 5.8 | 4745 | 345 | 2317 | 186 | 113 | 15 |
| **WINNIPEG, MB** | 1961-1990 | -16.6 | 2.3 | 17.8 | 3.9 | 6022 | 158 | 1707 | 151 | 121 | 20 |
| | A21 | -12.2 | 8.1 | 21.5 | 6.5 | 4791 | 440 | 2458 | 186 | 120 | 14 |
| | B21 | -12.9 | 6.6 | 20.4 | 5.8 | 5063 | 337 | 2224 | 178 | 118 | 15 |
| **OTTAWA, ON** | 1961-1990 | -9.1 | 5.4 | 19.4 | 8.1 | 4608 | 240 | 2087 | 188 | 115 | 31 |
| | A21 | -5.3 | 8.5 | 22.1 | 10.6 | 3742 | 473 | 2651 | 219 | 139 | 24 |
| | B21 | -6.3 | 8.0 | 21.6 | 9.9 | 3942 | 422 | 2528 | 212 | 128 | 27 |
| **SEPT ILES, PQ** | 1961-1990 | -12.9 | -0.4 | 13.5 | 3.2 | 6250 | 9 | 984 | 139 | 130 | 52 |
| | A21 | -8.9 | 2.6 | 16.5 | 5.6 | 5166 | 61 | 1439 | 175 | 142 | 36 |
| | B21 | -10.0 | 1.8 | 15.8 | 5.0 | 5439 | 42 | 1321 | 165 | 138 | 39 |
| **NAPPAN, NS** | 1961-1990 | -6.3 | 3.5 | 16.7 | 8.1 | 4611 | 73 | 1663 | 170 | 116 | 32 |
| | A21 | -2.5 | 6.5 | 19.4 | 10.6 | 3664 | 221 | 2225 | 211 | 131 | 19 |
| | B21 | -3.5 | 6.0 | 18.9 | 9.8 | 3876 | 184 | 2097 | 201 | 128 | 22 |
| **FREDERICTON, NB** | 1961-1990 | -7.8 | 4.2 | 17.9 | 7.7 | 4678 | 130 | 1773 | 172 | 115 | 29 |
| | A21 | -4.0 | 7.3 | 20.5 | 10.1 | 3759 | 308 | 2331 | 213 | 132 | 21 |
| | B21 | -5.1 | 6.8 | 20.0 | 9.4 | 3968 | 265 | 2207 | 204 | 126 | 23 |
| **ST. JOHN'S, NFLD** | 1961-1990 | -3.8 | 1.5 | 13.7 | 7.1 | 4900 | 29 | 1184 | 176 | 210 | 47 |
| | A21 | 0.0 | 4.5 | 16.3 | 9.6 | 3878 | 100 | 1687 | 222 | 227 | 23 |
| | B21 | -1.1 | 4.0 | 15.8 | 8.9 | 4108 | 79 | 1566 | 211 | 216 | 27 |

# 5 Canada's coastal and offshore climate

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With its extensive length of coastal territory (in excess of 5000 km) bordering on three oceans, issues pertaining to the immediate offshore regions are key concerns for Canada's coastal areas. As a result, sea level, storm surges, waves, and sea ice have long been topics attracting significant Canadian research efforts. In this Chapter we consider these aspects of Canada's coastal climate and how they may change in the future.

## 5.1: Sea Level

"Mean sea level" at the coast is defined as the height of the sea with respect to a local land benchmark, averaged over a period of time, such as a month or a year, but long enough that fluctuations caused by waves and tides are largely removed. Changes in mean sea level come about either by movement of the land on which the measurement gauge is situated or by changes in the height of the adjacent sea surface. The latter component is of most direct concern in connection with climate change, although obviously the former component must also be taken into account in determining the local impacts of mean sea level change. Depending on the direction of the local land movement, the effects of mean sea level change may be exacerbated or reduced.

In the last report, the IPCC (2001a) has estimated that global average sea level rise over the last one hundred years is within the range of 0.10 to 0.20 m (i.e., between 1 and 2 mm/yr). For the full set of SRES scenarios (see section 3.1 in Chapter 3), a sea level rise of between 0.09m and 0.88m is projected for the 21st century (or about 1 to 9 mm/yr), primarily from thermal expansion (sea water increases in volume as it warms) and with a secondary contribution from loss of mass from glaciers and ice caps as warmer conditions occur. The central value is 0.48m, which corresponds to an average rate of increase about two to four times that which occurred during the 20th century (see Figure 5.1).

For specific regions, the IPCC global estimates must be combined with local terrain effects and tectonic motions, such as rebound or subsidence of the land surface still occurring as a result of the retreat of the last ice sheets (i.e. from "isostatic" adjustment). For British Columbia in the 21st century, the results of applying data from Thompson and Crawford (1997) suggest that there will be differences in sea-level change between the northern (0 to 12 mm/yr) and southern (-1 to 8 mm/yr) coasts. The Yukon coast is experiencing subsidence (2 to 4 mm/yr) so that anticipated sea level rises there will be significant (3 to15 mm/yr).

Aside from the Yukon coast (and the immediately adjacent North West Territories coast), most of the Arctic is experiencing considerable rebound so that coastal areas there (particularly in the Hudson Bay area) will have little sensitivity directly to global sea-level rise. The possible exceptions are the glacial tidewater shores of such eastern islands such as Baffin, Devon, and Ellesmere, where the rebound is marginal (Maxwell, 1997).

In Atlantic Canada, postglacial adjustments are such that rising relative sea levels have prevailed in most areas south of the Gulf of St. Lawrence and Strait of Belle Isle for the past few thousand years (Forbes *et al.*, 1997). Thus the global sea level rise during the 21st century will be accentuated there, though perhaps not quite as much as along the Yukon coast. As an example, in the Charlottetown, P.E.I. area, the projected rise is 7 mm/year based on the IPCC's projected central value for the 21st century of 0.5 m and a local crustal subsidence value of 0.2m. If the maximum IPCC projection is used, the rise in mean sea level at Charlottetown is as much as 11mm/year (McCulloch *et al.,* 2002) during the 21st century. The Labrador coast continues to experience crustal rebound so that the impact of global sea level rise will be tempered there.

## 5.2: Storm Surge

Storm surges result from meteorological effects on sea level (generally as a result of the combined effects of atmospheric pressure, wind speed and wind direction) and can be defined at the coast as the difference between the observed water level and the predicted astronomical tide. Storm surges can be positive or negative and may therefore raise or lower sea level from its predicted value. They occur everywhere along Canada's coastlines, and can occur anywhere in the tidal cycle or may last over several tidal cycles. Large positive storm surges at times of (high) high tide are events that lead to coastal inundation.

Along Canada's west coast, a number of areas are currently at risk due to storm-surge-induced flooding. These include parts of Greater Vancouver, Victoria and Vancouver Island in general, the Queen Charlotte Islands, and parts of the adjacent mainland coast (Neil, 2001). Even with some of these areas experiencing modest crustal rebound, climate-induced sea-level rise in the future will tend to dominate particularly in the more northerly areas, leading to an increased frequency of the sort of severe storm surge events that currently occur.

In east coast, at Charlottetown, storm surges above 0.6 m are frequent events, occurring about 8 times a year on average (compared to twice a year along the Atlantic coast near Halifax). Generally a storm surge of about 0.7 m is needed, in combination with the highest high tide (about 2.9m), to cause flooding of the Charlottetown waterfront – in other words a storm-surge-induced positive sea-level anomaly of about 3.6 m. Such an event occurred only 6 times in the period 1911 to 1998. By 2100, the same type of event is likely to occur once every year with an event in excess of 4.0m once every 10 years or so (McCulloch *et al.,* 2002).

In the Beaufort Sea region, sea-ice cover is a complicating factor. The highest storm water levels tend to be related to high wind speeds and low sea-ice extent. Currently, a storm with a 30-year return period (such as those which actually occurred in 1944 and 1970) brings peak water levels of 2.4m and wind speeds of 97 km/hr. With expected increases in sea level (the current 3.5mm/year in the Beaufort area and the projected general sea-level rise of 0.48m by 2100) and lengthened open water seasons (May to November by 2050 and April to December by 2100), such peak water levels (2.4m) may occur every 5 years by 2050 and annually by 2100 (Manson, 2003).

## 5.3: Wave Height

The oceans are an important component of the climate system and ocean-borne commerce is sensitive to the state of the ocean surface. Amongst other surface characteristics, ocean wave height could be affected by anthropogenic forcing of the climate system. Information on ocean wave climate and its variability and trends are required for a wide range of applications, including the determination of engineering design parameters for offshore oil and gas exploration, production and transportation; coastal development; and the detailed planning of shipping routes. Since the design of marine and coastal infrastructure is constrained by the largest wave height event anticipated during a fixed design period, increases in the extremes of wave height could have an impact on the life-span of these installations that will be in excess of impacts anticipated from the rising sea level alone.

Analysis of the observed variability and trends in ocean wave height, and projections of possible future changes, are therefore useful for the design and operation of coastal and offshore industries. In-depth analyses of the trends and variability in wave height extremes, and their relationships to atmospheric circulation regimes, have been carried out by Wang and Swail (2001, 2002). In these analyses, two wave hindcasts (i.e., the reconstruction of actual conditions using model data) were used as observed waves for 1958-1997: a global wave hindcast based on the NCEP/NCAR reanalysis (NRA) 10 m winds (Cox and Swail, 2001), and a detailed North Atlantic wave hindcast produced with painstakingly reanalysed surface winds over the North Atlantic basin. Further, Wang *et al.* (2003b) used the observed relationships between sea level pressure (SLP) and significant wave height (SWH) to construct climate change scenarios of SWH. Complex statistical procedures were used in this process: scenarios of seasonal mean SWH were constructed using redundancy analysis (RA), while projections of seasonal extreme SWH were made using non-stationary generalised extreme value (GEV) models. These models were tuned using the observed SLP and SWH data for 1958-1997. The SWH scenarios were constructed using seasonal mean SLP and SLP gradient data from CGCM2 under three different forcing scenarios (i.e., IS92a, SRES A2 and B2; see Chapter 3 for more details of these emissions scenarios). The projected trends and changes in SWH were then assessed by conducting a trend analysis, in which linear trends were evaluated against quadratic trends.

Recently, Wang and Swail (2003) reviewed and extended previous studies on changes in SWH, focusing on both observed and possible future changes in the North Atlantic and in the North Pacific. They concluded that changes in mean and extreme SWH observed during 1958-1997 in both the North Atlantic and the North Pacific are statistically significant and basically linear. The changes in winter SWH in the North Atlantic (Figure 5.2a) are characterised by increases in the north-east North Atlantic matched by decreases in the mid-latitudes, which were found to be closely associated with changes in the North Atlantic Oscillation (NAO)[7]. Significant increases in the area off the Canadian east coast are the dominant feature of changes in fall SWH in the North Atlantic (Figure 5.2b). The changes in both mean and extreme SWH in the North Pacific are characterised by a centre of significant increase in the west-central North Pacific (Figures 5.2c and 5.2d), which was found to be connected with a deeper and eastward extended Aleutian low or, equivalently, with a southward dip and eastward extension of the storm track. Also, both oceans are projected to have significant changes in the 21st century under all three forcing scenarios (Figures 5.3 and 5.4 for the SRES A2 forcing scenario). For example, in the subtropical eastern North Pacific, the average waiting time between extreme SWH events of a fixed size was projected to decrease by approximately half in the 90-yr period from 1990 to 2080 (i.e., an extreme event of the same size is projected to occur twice as often in the 2080's climate than in the 1990's climate), especially in the nearshore region of the American west coast in fall; and a similar change was also projected for the Norwegian Sea. Wang and Swail (2003) also found that the trends in SWH in the projected warmer climate are not just a simple continuation of the trends observed in the last fifty years. Neither is the rate and sign of the projected future SWH change constant throughout the 21st century, and in some regions, these appear to be quite dependent on the forcing conditions. Often, the projected SWH changes are characterised either by faster increases in the later decades than in the earlier decades, or by decreases in the earlier decades.

## 5.4: Sea Ice

Sea ice is a defining characteristic of the marine environment annually in northern Canada and seasonally for much of the country's eastern seaboard. Its presence affects the development, characteristics, and movement of weather systems that can affect the entire country at one time or another. Marine transportation and offshore exploration and development are but two areas that are immediately constrained by its presence. For those reasons alone, existing and possible future sea ice conditions have long been considered a high priority environmental research issue for Canada.

Projections of future sea-ice conditions suffer from the natural amplification of both the climate warming signal and climate model error due to positive feedbacks such as that involving ice (and its overlying snow) albedo. As a consequence, the error in model simulations of contemporary climate and the range of response to increasing greenhouse gas concentrations is largest in areas affected by sea ice (Flato, 2003). Limitations in the

[7] The North Atlantic Oscillation (NAO) is a large-scale mode of natural climate variability in winter which is usually described in terms of the difference in sea level pressure between two stations near the Icelandic low pressure and the Azores high pressure systems. In its positive phase the high and low pressure centres are stronger than normal and the increased pressure difference between them results in more winter storms crossing the Atlantic Ocean on a more northerly track. In its negative phase both pressure centres are weaker than normal resulting in a reduced pressure gradient and fewer and weaker storms crossing the Atlantic Ocean on a more west-east track.

observational database make direct evaluation of the model temperature response difficult at high latitudes, and even indirect measures, such as the amplitude of the seasonal cycle (e.g. Covey *et al.*, 2000) are not feasible. Comparisons with observed changes in sea-ice extent suffer from the fact that natural variability is large, although there is some hint of correspondence between modelled and observed trends in late 20th century hemispheric ice extent (Flato and Boer, 2001). Near the ice edge, model simulations of inter-annual variability in surface air temperature do not exhibit the large variance seen in the observations (Lambert and Boer, 2001). This is linked to discrepancies in representing the variability in seasonal sea-ice cover that plays a crucial role in the intensity and the position of low-level air temperature gradients (Gachon *et al.*, 2003). In the Canadian Arctic, model errors and uncertainties are compounded by the inability of global climate models to resolve the complex geography of the Canadian Arctic Archipelago – indeed most models represent the Archipelago as a solid land mass connecting northern Canada and Greenland.

Despite these limitations, when viewed at the large scale, GCM simulations in polar regions simulate an amplification of global warming that seems to be consistent with recent observations of increasing temperature and reduced sea ice extent (e.g., SEARCH SSC, 2001). By the end of the 21st century, many GCMs project a substantial reduction in Arctic sea ice coverage with nearly complete disappearance of multi-year sea ice. For example, CGCM1 (Boer *et al.*, 2000) and CGCM2 (Flato and Boer, 2001) indicate essentially only seasonal ice at the end of the century whilst ECHAM4 indicates a reduction of 80% (e.g., Johannessen *et al.*, 2002). [It should be noted, however, that if the large-scale sea ice dynamics continue to push the pack ice of the Arctic Ocean up against the Arctic Islands, then the Islands will be one of the last regions of the hemisphere to lose its sea ice cover (T. Agnew, pers. comm.). This does not bode well for the opening up of a Northwest passage, with a navigable Northeast passage more likely to occur first.]

During winter, the projected reduction of sea-ice extent and thickness seen over the Beaufort Sea, Baffin and Hudson Bays, and the Labrador Sea (Figure 5.5) is accompanied by a warming of about 8 to 10°C (as shown in the 2nd right panel of Figure 4.7), compared to the 1961-1990 baseline period.

In discussing future trends in sea-ice conditions, one must also bear in mind that local or regional conditions do not necessarily reflect the broader hemispheric average. For example, since the 1960s, the Northern Hemisphere has experienced a pronounced warming which has been associated with a reduction in total Arctic sea ice extent (Parkinson and Cavalieri, 1989; Parkinson *et al.*, 1999; Rothrock *et al.*, 1999; Vinnikov *et al.*, 1999). At the same time, the Davis Strait-Labrador Sea region has experienced a cooling of about 0.5°C (over the 1961-1990 period; Chapman and Walsh, 1993; as confirmed in Zhang *et al.*, 2000 and Walsh *et al.*, 2002 for the last five decades) whilst ice extent has typically been greater than in the 1960s (Parkinson *et al.*, 1999; Brown, 1993). These local anomalies may reflect natural internal variability in the climate system, or localised responses to large-scale changes (i.e., as a result of the influence of the NAO or Arctic Oscillation [AO]) and/or to regional-scale feedbacks in atmosphere-ocean-sea ice exchanges. In any case, as with other climate quantities, uncertainty increases substantially as the domain of interest gets smaller and the complexity of geographical characteristics increases.

In order to provide more confident scenarios of sea ice change for impacts and adaptation studies (e.g., transportation, fisheries, oil offshore development, coastal erosion), improvements in GCM performance in the high-latitudes and in their representation of sea-ice processes are of particular importance. As noted by Walsh and Chapman (2001), while the observed Northern Hemisphere sea-ice extent has decreased substantially during the 20th century, with a stronger retreat in summer than in winter, most climate models simulate the largest reduction in winter and autumn and a weaker reduction in summer. (This is likely due to the fact that the models do not simulate well the different processes that are involved in sea-ice formation in winter versus those of sea-ice retreat in summer).

In eastern Canada, GCM results are particularly affected by inadequate representation of coastal oceanic currents (e.g. Lambert and Boer, 2001), poor spatial resolution, and possibly by shortcomings in the parameterisation of processes important in the marginal ice zone. The lower surface elevations of the Greenland ice mass in GCMs compared to reality is in part responsible for the systematic biases around Baffin Bay-Labrador Sea (see Figure 5 in Walsh *et al.*, 2002) and may also be a source of systematic errors in the sea-ice coverage simulated in these areas. In fact, Greenland constitutes an important sink of heat for the regional atmosphere throughout the year, controlling in part regional sea-ice formation via cold air advection from this inland ice. Also, the lack of tidal effects in such models may also be important, especially in inland seas such as Hudson Bay and the Gulf of St. Lawrence, where sea-ice formation and tidally-driven mixing are crucial (e.g., Wang *et al.*, 2003a). In these regions, the development of regional climate models, both oceanic (Saucier *et al.*, 2003, 2004) and atmospheric (Laprise *et al.*, 1998), is of particular importance to improve seasonal sea-ice scenarios at the regional scale. High resolution coupled climate models could add some important small-scale processes, but they retain the biases from the GCM simulations used as boundary conditions. Hence, the development of regional numerical tools and the improvement of global climate models must be viewed as complementary solutions toward the development of climate change scenarios, especially those related to sea ice which is a key issue for a northern climate such as Canada's.

## 5.5: Summary

The anticipated climate warming in the 21st century will have significant ramifications for Canada's coastal areas due to the associated changes in sea level, sea-ice cover, and wind speed. The results include increased storm surge frequencies on both east and west coasts and in the Beaufort Sea, and increased significant wave heights in autumn off the east coast. These effects along with general decreases in sea-ice cover, age and thickness are likely to make the Canadian offshore areas distinctly different places in which to operate by 2100, when compared to the present.

# 6 Scenarios of climate variability and extremes

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As mentioned in Chapter 3, the emphasis for climate change scenario construction was, until recently, on the development of scenarios of average climate change and many impacts and adaptation studies had focused on the assessment of impacts arising as a result of these changes in mean climate. However, the focus of many climate change impacts studies has switched to identifying the vulnerability of different systems to climate change and to developing strategies which will reduce this vulnerability as far as is possible. As a result of this switch in impacts thinking, it has become apparent that the vulnerability of many systems is to climate variability and, in particular, to the frequency and magnitude of extreme events, rather than to changes in average climate. Many of the important aspects of climate variability and extreme events occur at a range of spatial and temporal scales - for example some events arise as a result of large-scale climate oscillations (such as the El Niño phenomenon) whilst others occur as a result of much smaller-scale systems, such as severe thunderstorms. Constructing climate change scenarios which are at the spatial and temporal scales required by the impacts and adaptation community and which contain useful information about climate variability and extreme events is the focus of current scenarios research and is a major challenge for this research community.

Enough is known about the characteristics of some larger-scale climate systems that we are able to make reasonable forecasts about near-future conditions if a particular system is in a certain phase. For instance, in south-western Canada, winter and spring are usually milder and drier following the onset of El Niño conditions in the tropical Pacific. Conversely, a colder and wetter winter and spring are expected after the onset of La Niña conditions in the tropical Pacific. As a result, the risk of extreme wet /dry and cold/warm conditions also changes (Figure 6.1). In addition to these year-to-year variations, climate also varies on longer time scales. Phase changes in the oceanic and atmospheric circulation at decadal and multi-decadal time scales alter the state of the climate, and hence the sequence of daily weather.

Whilst determining local changes in climate variability and extreme events presents a major challenge for the scenarios research community, analysis of observed data and GCM projections has permitted an assessment of the confidence placed in observed changes in extreme weather and climate during the latter half of the 20th century and in the projected changes during the 21st century (see Table 6.1). This assessment is based on expert judgement (IPCC, 2001a). Since the science behind constructing scenarios of climate variability and extremes is still in its infancy, this Chapter provides a general description of the different aspects of climate variability and extremes and outlines some of the possible ways in which GCM data can be used to construct such scenarios. However, detailed scenarios for the future at the spatial and temporal scales required by the impacts community are not yet available.

## 6.1: Climate Variability in the Future

In order to provide a comprehensive scenario of climate change, the scenario should contain information about changes in climate variability and extremes as well as about changes in average climate. The standard method of scenario construction and application described in Chapter 3, i.e., determining changes between some future time period and baseline conditions and then applying these changes to observed climate data for the baseline period, means that the variability in the future climate is inherited from the observed climate data rather than from the GCM climate change experiment. Changes in variability, however, may be very important since they can have a larger effect on the frequency of extremes than changes in mean climate conditions (Katz and Brown, 1992). This is illustrated in Figure 6.2, using temperature as an example and assuming it is normally distributed (which is a rough approximation). An increase in the mean value simply shifts the distribution to the right and results in more extreme hot weather and a reduction in cold weather. Changing the variance alone (in this case increasing the temperature variability) results in increases in both hot and cold weather, whilst combining increases in the mean with increases in the variance results in much more hot weather and record hot weather than was the case with either a change in the mean alone, or only a change in variability.

In recent years, there have been improvements in the GCM simulation of climatic variability on daily to inter-annual time scales (Mearns *et al.*, 2001), with many GCMs simulating temperature variability decreases in winter and increases in summer in northern mid-latitude land areas. Räisänen (2002) compared inter-annual temperature and precipitation variability simulated by 19 AOGCMs (atmosphere-ocean GCMs, i.e., coupled GCMs) participating in the CMIP2 Project. The magnitude of inter-annual variability in the model control runs (see footnote 4 in Chapter 3) appears generally reasonable, though it varies a great deal among different models. Gradual doubling of $CO_2$ leads, in most models, to a decrease in temperature variability in the winter half-year in the extra-tropical Northern Hemisphere, probably due to the reduced snow and ice cover. Over land in northern mid-latitudes in summer, there is a slight tendency toward increased temperature variability. The inter-annual variability of monthly precipitation totals increases where the mean precipitation increases and even in some places where the mean precipitation decreases. The increase in precipitation variability may be related to a decrease in the frequency of precipitation days.

It is important to note that the consensus on changes in variability is not as strong as that on changes in the mean state. This is reflected by the fact that changes in variability differ substantially among the 19 CMIP2 experiments. A majority of the inter-experiment differences in variability change appear to be due to noise in the simulations, rather than as a result of model differences. This implies that we are less certain of how the variability at inter-annual time scales will change in the future than of how the mean will change. Due in part to the relatively coarse resolution and the outstanding difficulty to simulate the convective activity over tropical oceans, there is still great uncertainty in GCM-simulated ENSO (El Niño Southern Oscillation)-related variability – a very important mode of variability that exerts a wide-spread influence on global climate and weather, and which is usually associated with higher probabilities of extremes such as floods and droughts. In addition, it is still too expensive to perform enough simulations to provide an adequate amount of samples to assess low-frequency variability in the future. Thus, the uncertainties in projected future changes in variability are large.

As a result of this lower confidence in the simulation of climate variability, changes in variability have not generally been incorporated into climate change scenarios and, in addition, the techniques for incorporating changing variability are more complex than those for incorporating changes in mean values. There are, however, some relatively simple techniques for incorporating changes in inter-annual variability into scenarios, and these are adequate in cases where impacts models use monthly climate data for input. The simplest of these techniques applies year-by-year anomalies (calculated with respect to the modelled baseline period) to the long-term mean observed baseline climate. This method produces climate time series having an inter-annual variability equivalent to that modelled for the future, but superimposed on the observed baseline climate. The main technique for constructing scenarios with changes in inter-annual and daily variability involves the manipulation of the parameters of a stochastic weather generator, with the changes imposed on the statistical parameters being derived in general from GCM information.

## 6.2 Scenarios of Extremes

One way of producing scenarios of extremes for the future is to use GCM simulations. This can be done at different temporal scales. For example, scenarios of mean changes in climate are generally provided at the monthly or seasonal scale. Analysis of GCM output at this level can give an indication of changes in extremes at the spatial scale of the GCM. For example, Figure 6.3 illustrates the change in threshold temperature defining a 'hot' summer (using the 90th percentile to define a hot summer) for the 2020s, 2050s and 2080s, relative to the 1961-1990 baseline conditions, using the pooled data from the three A2 climate change experiments undertaken with CGCM2. There are a variety of ways in which this type of information can be presented to the VIA community - here simply the change in the threshold value is illustrated (indicating that by the 2080s a 'hot' summer is generally between about 3 and 8°C warmer than one occurring in the current climate). Other options include the use of return periods or the probability of the baseline threshold values being exceeded in the future time periods. The percentile method can also be used to look at extreme precipitation (e.g., dry summers, or wet winters).

Most extreme events, however, are generally considered to occur at the daily time step and GCM output can also be used to investigate changes at this time step. Canadian model results show an increase in extreme high daily temperature (Figure 6.4). They also project an increase in extreme daily precipitation over Canada (Zwiers and Kharin, 1998; Kharin and Zwiers, 2000). By the middle of 21st century, the 20-year return values of annual maximum 24-hr precipitation over Canada are likely to increase by an average of approximately 14% as compared to present values. As a result, an extreme precipitation event that occurs once in 20 years on average in the current climate would occur once in less than 10 years, in 50 years time (Figure 6.5). These simulations suggest that the extremes, which exert the strongest impact on society, will change in the future. Many aspects need to be taken into careful consideration if the GCM-simulated extremes are to be used directly as scenarios for the future. The existing GCMs, by design, have only limited capability in simulating some of the real world extremes. For example, the surface topography which has a strong influence on precipitation and surface wind is much smoother in the model than in reality. As mean climate conditions simulated by a GCM exhibit biases, so do GCM simulations of extreme events, and a GCM which performs well at simulating current climate conditions will not necessarily perform as well at simulating extreme conditions.

The spatial scale, in particular, of many extreme events is much finer than can be resolved by a GCM and so other techniques must be used or developed to construct scenarios for extremes. Both statistical and dynamical downscaling (see Chapter 3) are likely to have utility for developing such scenarios (see for example the European projects PRUDENCE, http://prudence.dmi.dk/ and STARDEX, http://www.cru.uea.ac.uk/projects/stardex/). Dynamical downscaling, i.e., regional climate modelling, is likely to be able to produce more robust information on extremes at finer spatial and temporal scales since RCMs are physically-based models. However, the spatial scale of RCMs (approximately 45km) may still be too coarse to resolve some of the processes leading to extreme events. Statistical downscaling, in which the characteristics of small-scale local extremes are related to larger-scale atmospheric circulation, is another possibility for developing extremes scenarios.

There are two potential problems associated with downscaling. Firstly, a good relationship between the large-scale fields and regional extremes should exist, i.e., the large-scale atmospheric circulation should be a major control on extreme event occurrence. If it is possible to develop robust statistical downscaling relationships, it must also be assumed that these relationships will remain valid in the future and this may not be the case. Secondly, uncertainties in the large-scale fields will be inherited and may even be amplified in the scenarios. Downscaling has been successful for the construction of scenarios for monthly and daily values, but its use in constructing scenarios for extremes is still an area of active research and will be pursued by the CCIS Project and other research groups in the next couple of years. An example of statistical downscaling for the construction of extreme high wave scenarios over the Atlantic, using projected changes in the seasonal mean sea level pressures, has been provided in Chapter 5.

Our confidence in future extremes also varies with both the time scale and the climate variable being considered. GCMs project an increase in temperature over all of Canada and so the extreme high monthly temperature will be higher and extreme low monthly temperature will become less severe. This is because the change in the variability is relatively small when compared with changes in the mean. This is also because the projected small increase in variability over mid-latitude land areas during summer would reinforce the increase in the mean, yielding even hotter temperatures (see Figure 6.2); and the projected small decrease in winter temperature variability would similarly result in less cold winter temperatures. Our confidence in this projection is high. On the other hand, the same cannot be said about extremes of monthly precipitation. The sign of the projected change in precipitation varies with location due to changes in atmospheric circulation. In addition, different models project different spatial patterns of precipitation change. For changes in temperature and precipitation extremes on daily time scales, variability changes are potentially more important than is the case for the extreme monthly values. Nevertheless, there is no indication so far that suggests a reduction in daily temperature variability that can potentially offset the effect of the increase in mean temperature on the extremes. Therefore, it is highly plausible that extreme high daily temperatures in Canada would be even higher. Similarly, it is also highly plausible that heat waves will become more frequent while the number of cold waves and frost days will be reduced. Given that the hydrological cycle in the warmer world would be more vigorous and that model simulations show a tendency for extreme precipitation to increase everywhere, even though mean conditions may increase or decrease, it is also plausible that future extreme precipitation, either its frequency or intensity, or both, would likely increase.

## 6.3: Summary

The construction of scenarios of climate variability and extremes is one of the major challenges facing the scenarios research community. Climate change scenarios which are currently available are at spatial and temporal scales which are too coarse to provide meaningful information about future extreme events to the VIA community, although GCM output can be used to obtain more qualitative information about these changes.

Many of the extremes which are of importance to the VIA community, such as extreme precipitation overwhelming municipal stormwater capacity, require much higher resolution climate information than is currently available from the scenarios community. Statistical and dynamical downscaling are potential sources of scenarios at the scales required by this community, but research is still in its early stages and it is likely to be some time before comprehensive scenarios containing changes in means, variability and extremes are available for use in vulnerability, impacts and adaptation studies.

## TABLE 6.1 Estimates of confidence in observed and projected changes in extreme weather and climate events. [Source: IPCC, 2001a]

| CONFIDENCE IN OBSERVED CHANGES (LATTER HALF OF THE 20TH CENTURY) | CHANGES IN PHENOMENON | CONFIDENCE IN PROJECTED CHANGES (DURING 21ST CENTURY) |
|---|---|---|
| Likely* | Higher maximum temperatures and more hot days over nearly all land areas | Very likely |
| Very likely | Higher minimum temperatures, fewer cold days and frost days over nearly all land areas | Very likely |
| Very likely | Reduced diurnal temperature range over most land areas | Very likely |
| Likely, over many areas | Increase in heat index over land areas | Very likely, over most areas |
| Likely, over many Northern Hemisphere mid- to high-latitude land areas | More intense precipitation events | Very likely, over many areas |
| Likely, in a few areas | Increased summer continental drying and associated risk of drought | Likely, over most mid-latitude continental interiors (lack of consistent projections in other areas) |
| Not observed in the few analyses available | Increase in tropical cyclone peak wind intensities | Likely, over some areas |
| Insufficient data for assessment | Increase in tropical cyclone mean and peak precipitation intensities | Likely, over some areas |

*The following words have been used where appropriate to indicate judgmental estimates of confidence: virtually certain (greater than 99% chance that a result is true); very likely (90-99% chance); likely (66-90% chance); medium likelihood (33-66% chance); unlikely (10-33% chance); very unlikely (1-10% chance); exceptionally unlikely (less than 1% chance).

# 7 Uncertainties

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In many respects, climate change scenarios are 'what if' examples of how climate and its variability for a particular region or locale may evolve over time as a result of continued human interference with the climate system. That is, they are not predictions of what will happen, but simply useful illustrations of what may happen. Ideally, they can provide users with both a perspective of what is probable, but also some indications of the range of what is plausible.

Our knowledge, however, of both future human behaviour (the primary driver for the scenarios) and the response of the climate system itself (the sensitivity of climate to the driver), as presented in GCM-derived scenarios, have inherent uncertainties that need to be kept in mind when using climate change scenarios. These uncertainties are complex, and arise from changes in a number of variables within the human-climate system that are poorly understood and difficult to predict with accuracy.

This Chapter considers these variables and how they contribute to climate scenario uncertainty. It also addresses how these uncertainties might be put into proper context when undertaking climate change impacts and adaptation research.

## 7.1: Human Forcing of the Climate System

◆ ***Greenhouse gas emissions and concentrations:*** There are five primary demographic factors that contribute to the rate of human emissions of greenhouse gases: population growth, economic growth, energy efficiency, type of energy used, and land-use change. While these factors are not entirely independent of each other, their evolution over time will vary geographically, and be subject to surprises and revolutionary changes. They are therefore difficult to predict with confidence. As mentioned in Chapter 3, from forty SRES plausible emission scenarios based on the plausible range of change in these five variables over time (Nakicenovic *et al.*, 2000), six of those were then selected as representative of future uncertainties and made available to researchers for use in climate change scenario development. Understandably, uncertainties with respect to these emissions increase with time. While, for the next few decades, these demographic uncertainties are secondary to the scientific uncertainties inherent in climate model simulations of climate response, they become the dominant uncertainty in climate change scenarios by the mid-21st century (Zwiers, 2002; Wigley and Raper, 2001). By 2050, for example, the range of projected $CO_2$ emissions in the SRES scenarios varies by a factor of 2, from a low of 11.2 GtC/yr for scenario B2 to a high of 23.1 GtC/yr for scenario A1FI. This range increases to a factor of almost 6 by 2100, from 5.2 GtC/yr for scenario B1 to 30.3 for A1FI. Most climate change scenarios derived from models are based on emissions scenarios A2 (second highest SRES scenario, at 28.9 GtC/yr emissions by 2100) or B2 (which is similar to IS92a, an older IPCC emissions scenario, commonly referred to as a business-as-usual emissions scenario). The atmospheric lifetime of emitted greenhouse gases is largely determined by the rate of destruction by natural processes within the atmosphere or removal into the terrestrial and ocean systems. This varies significantly from one gas to another. For some gases, such as nitrous oxide, perfluorocarbons and many halocarbons, atmospheric removal processes are very slow and hence there is little uncertainty involved in estimating how future emissions will affect atmospheric concentrations. The removal processes for $CO_2$ (the key greenhouse gas), however, involve the global carbon cycle. The latter is, in turn, very sensitive to changes in temperature, precipitation, ocean circulation, atmospheric $CO_2$ concentrations, nitrogen deposition and other factors. Currently, physical and biological processes within the global carbon cycle remove approximately 60% of the estimated 8 billion tonnes of excess carbon added into the atmosphere by humans each year. Global carbon cycle models are used to estimate how these factors will affect the amount of future emissions remaining in the atmosphere to enhance $CO_2$ concentrations. There are significant uncertainties regarding the extent of saturation of terrestrial carbon sinks, and how ocean processes will alter oceanic sequestering of carbon in the deep oceans. These uncertainties are, however, secondary to the large uncertainties relating to future human emissions and in modelling the climate system (Prentice *et al.*, 2001).

- ***Aerosol emissions:*** The climatic effects of increased aerosol concentrations in the atmosphere due to human emissions are not well understood, for a variety of reasons. These include the very uneven distribution of these aerosols, the different kinds of aerosols involved, and the unique effects of each type of aerosol on local radiation budgets (which, in turn, depend on other local environmental variables and conditions). However, projections for human emissions of these aerosols have significantly smaller uncertainty ranges than those for greenhouse gases, partly because of constraints posed by other environmental concerns associated with their release (smog, acid precipitation, etc.). For example, for the dominant aerosol, sulphur dioxide, projected emissions for 2050 under the various SRES scenarios vary from 61 to 100 MtS/yr. This range decreases to 20 to 60 MtS/yr by 2100 (Nakicenovic *et al.*, 2000).
- ***Albedo effects of land-use change:*** While the impact of land use and land-use change on greenhouse gas emissions are already included in the SRES greenhouse gas emission scenarios, such land activities can also change the regional surface albedo and hydrological cycle, thus affecting regional and potentially global climates. In the future, these effects are likely to be small compared to those for greenhouse gas emissions when considered at the global scale. While local effects could be very significant in tropical regions undergoing large-scale land-use change, they are not likely to be large in developed countries such as Canada (since most land-use change has already taken place). Most climate models have not included these effects, and hence related uncertainties are not included in climate change scenarios (Betts, 2000; Chase *et al.*, 2001).

## 7.2: Natural Forcing of Climate

The two primary processes by which natural factors external to the climate system can cause climate change on century time scales are volcanic eruptions (which alter planetary albedo by releasing reflecting aerosols into the stratosphere) and changes in solar irradiance. These factors can contribute to inter-annual and inter-decadal changes in climate, and have been implicated in such changes during the past century. For example, increasing solar irradiance and a decreasing frequency in large volcanic eruptions both appear to have contributed to a warming of climate during the first half of the 20th century. In contrast, during the latter half of the century, solar irradiance showed little trend while volcanic eruptions became more frequent again. The latter thus caused a cooling influence (in contrast to observed warming). It is uncertain how these natural factors will evolve during the next century, but there is no reason to suggest they will exceed their role within the past 1000 years. Hence, while most climate change scenarios do not include these forcing factors, this should not add significantly to the uncertainty in decadal scale projections (Ramaswamy *et al.*, 2001). Figure 7.1 (from IPCC, 2001a) illustrates the current level of scientific understanding concerning global, annual-mean radiative forcings due to a number of agents for the period from pre-industrial (1750) to the present.

## 7.3: Internal Climate Variability

The primary sources of uncertainty due to internal climate variability are the decadal- and longer-scale changes in ocean circulation. A number of Pacific and Atlantic Ocean multi-decadal oscillations have been identified within the last decade. These oscillations can, in turn, have significant influence on global atmospheric circulation and hence on regional climates around the hemisphere. While climate models capture some of the main features of such low frequency variability reasonably well, climate change scenarios may not fully capture changes in this variability. This adds to the uncertainty in the variability component of climate change scenarios.

## 7.4: Climate Model Limitations

While very complex, coupled atmosphere-ocean climate models still remain crude simulators of the real climate system. There are two fundamental reasons for this. First, many of the processes important to the climate system and its variations are very complex and/or highly variable in time and space, and are as yet poorly understood. Second, computing power remains a major limitation to how much detail can be included in describing these processes within the models and simulating them with adequate resolution. Various modelling groups have used different techniques and schemes for parameterising these processes at scales that current computing systems can handle. They also often use different assumptions with respect to how these processes actually work. These differences between models are both a major source for disagreements between various climate scenarios and a basis for enhancing understanding through model simulation inter-comparisons and analysis. (Figures 7.2a and b, taken from IPCC (2001a), illustrate GCM inter-model consistency in regional warming and regional precipitation change around the world.) Following are several of the key sources of model differences, and hence uncertainty in climate change scenarios:

- ***The hydrological system:*** While all advanced models now use sophisticated schemes to simulate **water vapour and cloud** processes within the atmosphere, these processes and related feedbacks remain a major source of uncertainty in climate change scenarios. Many aspects of these processes take place at the microphysical level, but must be parameterised to allow simulation at model resolutions of 100km or lower. Furthermore, these processes can change dramatically on scales of metres and minutes, and differ significantly with altitude and geographical location. Observational databases to help improve understanding and test models are also inadequate, particularly in the upper atmosphere and in high latitudes. Yet, these processes have a large impact on atmospheric energy fluxes and on terrestrial albedo, and hence on global and regional response to climate forcings. In addition, related uncertainties in the projection of regional **rainfall** can have significant impact on estimates of local surface latent and sensible heat fluxes, and hence surface temperatures and convective precipitation processes.
- ***Ocean System:*** A second major source of uncertainty in climate simulations is behaviour and response of **oceans and sea ice** to climate forcings. These uncertainties relate to the thermohaline circulation system and its sensitivity to climate change, to response of oscillations, such as the ENSO, the NAO/AO and the Pacific Decadal Oscillation (PDO), that influence global weather and climate from year to year and decade to decade, to the heat flux between atmosphere and ocean, and to the response of sea ice in the polar and sub-polar regions of oceans.
- ***Biological system:*** A third significant source of uncertainty is the response of the terrestrial biological system to changing environmental conditions, including climate change and coincident $CO_2$ and nitrogen fertilisation effects. These feedbacks can affect local hydrological cycles, heat fluxes and surface albedo. More importantly, they can influence the carbon cycle, thus modifying the rate of change of atmospheric $CO_2$ concentrations. Most climate change scenarios do not include the possible implications of these feedbacks.
- ***Upper atmospheric chemistry:*** The chemistry of the upper atmosphere, particularly with respect to ozone, is sensitive to climate variability and change (se for example the recent work of Rex *et al.*, 2004). Related changes in the upper atmosphere can, in turn, affect stratospheric circulation and, ultimately, the behaviour of the troposphere. Many models used to develop the current generation of climate change scenarios do not adequately incorporate these processes. Most, however, will include a higher and more detailed stratosphere in future generations.
- ***Resolution:*** Most global coupled climate models, due to computing limitations, use spatial resolutions of 250 km or lower. Hence, their ability to simulate regional and local scale climatological and meteorological features is

very limited. These features include lake, regional inland seas and orographic effects, convective storms and even larger scale features such as hurricanes. Yet these features are often those that have the largest impact on ecosystems and society. Regional climate models, high-resolution tropical-ocean sub-components, and other downscaling techniques can be useful in addressing this limitation, but also have shortcomings. Hence, uncertainties in regional and local-scale weather response to global climate change remains very high.

## 7.5: Addressing Scenario Uncertainty in Regional Climate Impact Studies

The large uncertainty inherent in climate change scenarios, particularly at the regional scale and for hydrological variables, can result in significant misuse if these uncertainties are not properly considered and addressed. There are a number of methods that can help avoid such misuse. These include:

- ***Ensemble scenarios:*** Various studies have demonstrated that ensemble scenarios, where the output of a number of model simulations conducted under similar forcing scenarios are averaged, generally appear to simulate observed climate behaviour better that any single model simulation. This suggests that, while individual models may have serious limitations, averaging can reduce the errors these cause. This suggests that, for any specific forcing scenario, ensemble climate scenarios may also be more accurate than single scenarios (Lambert and Boer, 2001). However, the averaging process reduces the internal consistency between climate variables, i.e., the projected changes in temperature and precipitation may no longer be consistently related, and so for impacts modelling purposes single climate change scenarios should be used.
- ***Scatter plots:*** While there may be indications that some models may provide more realistic simulations of climate response to radiative forcing than others, there is sufficient uncertainty in the art of modelling to suggest all scenarios developed with advanced coupled climate models forced by plausible trends in future radiative forcing should be considered. Scatter plots for changes in temperature and precipitation for a given location as projected by these various models can help provide a quick visual appreciation of the range of possible outcomes that may need to be considered. Figure 7.3 is an example of such a plot that shows both the scatter of projections and ensemble-mean values for the 2050s summer season.
- ***Sensitivity analyses:*** While scatter plots, as described above, show a significant range of projections for future changes in local temperature, they all agree than temperatures over land areas, averaged over decadal time scales, will become warmer. However, for most regions, this does not hold for changes in precipitation. In Figure 7.3, for example, some scenarios project an **increase** in average precipitation over the Ottawa region of as much as 30% by 2050. At the other extreme, other scenarios suggest a modest **reduction** in precipitation. Hence, even the sign of projected changes may differ between scenarios. This suggests that related impacts studies should focus more on assessing ecological and socio-economic sensitivity to a range of possible change and undertake related risk assessments as to how vulnerability to such changes can be reduced (Hulme and Brown, 1998).
- ***Extreme event risk assessments:*** With the exception of certain parameters such as extreme temperatures, most climate change scenarios are as yet unable to estimate with confidence how the frequency, severity and duration of extreme weather events may change as the climate warms. However, there is increased evidence that, at least in the past, climate has become less stable during periods of rapid transition. Furthermore, past ENSO events remind us that a change in atmospheric circulation can create havoc with weather world-wide, sending everyone weather for which they are ill prepared. Again, sensitivity analyses and risk assessment of vulnerabilities to extreme events can be one approach to examining adaptive options in the face of uncertainty.
- ***Adjusting timing of threshold events:*** As previously noted, demographic uncertainties become very important in climate change scenarios in the more distant future (beyond 2050). This enhanced uncertainty, however, relates more to the rate of global-scale temperature change than to the details of changes in local climates. Hence, to a first approximation, these

uncertainties can be best considered by acknowledging that the timing of various climate change thresholds as presented in climate change scenarios may be delayed or accelerated by a few decades, depending on the forcing scenario considered.

- ***Downscaling and intercomparison of methods:*** As put forward by IPCC (in Chapter 10, 2001a), in order to address with a more coherent picture the regional climate change and the associated uncertainties, more coordinated efforts are necessary to improve the integrated hierarchy of models, evaluate different methodologies and apply these methods in a comprehensive strategy. In that way for example, statistical downscaling techniques have been recognized as a viable complement to process-based dynamical downscaling, and so provide the means of producing rapidly different climate change scenarios as recommended in any assessment of climate change impacts. Hence RCMs can be used as a complementary tool with the necessary length of simulation as possible in order also to help to identify the most suitable and robust downscaling methods and to apply them to provide reliable and plausible scenarios, especially those related to extremes. As noted in Chapters 3 and 4, in order to improve signal to noise ratio, 30-year samples of run may be required to confidently assess the mesoscale response of a RCM to produce mean climate and obviously realistic extremes. In general, most RCM simulations to date are not long enough (typically 5 or 10 years for nested climate change simulations; e.g. Mearns *et al.*, 2001) to evaluate extremes well with robust statistics. The recent PRUDENCE project in Europe addresses this problem with series of RCMs simulation of 30-year samples, conducted both for the current period (1961-1990) and for the future (2020s, 2050s, and 2080s periods), as recommended by IPCC.

## 7.6: Summary

There are large uncertainties with respect to regional changes in climate as projected by different climate change scenarios. While uncertainties in forcing factors associated with demographic behaviour can significantly alter the timing of critical climate change thresholds, they are less likely to affect the characteristics of related impacts and the related need for adaptation. In contrast, uncertainties in the response of regional characteristics of weather caused by climate change are largely linked to climate model limitations, and are much more problematic for impact studies and adaptation research. Here, the use of ensemble simulations, scatter plots and other tools that provide both the mean and range of projected changes can be helpful in undertaking related sensitivity and risk assessments.

# 8 Scenarios - the long term challenges and looking forward

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In this Chapter, the major issues facing the scenarios community in the future, as viewed by the VIA community are discussed. A number of different impacts studies are considered in brief to highlight some of the scenario limitations identified by this community and scenario issues which are still considered to be unresolved are considered on a sector by sector basis. Finally, the short- and longer-term issues facing the scenarios community are outlined.

## 8.1: Background

Scenarios of climate change have been used by the VIA community for many years in a number of roles, e.g., to provide an illustration of climate change, to communicate the potential consequences of climate change, to aid strategic planning, to guide emissions control policy, to help determine our degree of knowledge, or ignorance, about systems, and to explore the implications of decisions (see Chapter 3 for more detail). Whilst the construction techniques used to create these scenarios have kept pace with developments in the global climate modelling community, and attempt to account for the bias in GCM simulations of current climate by making a number of straightforward assumptions, the scenarios are still relatively simple and reflect to a large extent the features of the observed climate information which is combined with the climate change scenario to produce a future climate scenario (i.e., 'actual' climate information for the future time period, rather than simply projected changes for particular climate variables for the future). For example, the variability of a future temperature time series created in the standard scenarios manner (sometimes referred to as the 'delta' method, and as outlined in Chapter 3) is the same as the variability of the observed time series used to create the climate scenario. Whilst this approach has been considered suitable for many impacts studies, now that the emphasis is on reducing the vulnerability of systems to climate variability and climate change, it is not likely to be sufficient to meet the needs of the VIA community in the future. In fact, Mearns *et al.* (2001) argue that climate scenarios should represent future conditions that account for human-induced climate change and natural climate variability, and that climate change scenarios, therefore, are only an interim step towards this goal.

Although there are a number of methods of climate change scenario construction (see Box 3.1 in Chapter 3), most impacts studies have used scenarios which are based on GCM output, mainly because they are able to supply information for a suite of climate variables and this information is physically plausible and internally consistent (again see Chapter 3). However, the information provided by GCMs is of coarse resolution, and whilst considered to be sufficient for examining system response to mean changes in climate, it is not likely to be completely suitable for studies which focus on the impacts of changes in climate variability and extreme events. To provide scenarios which contain useful information for these types of studies, higher resolution information will be necessary. Although there are a number of methods for constructing higher resolution scenarios from GCM output, i.e., simple interpolation, and statistical and dynamic downscaling, only statistical and dynamical downscaling are likely to be useful approaches for providing robust information about regional and local climate changes at the spatial and temporal scales required by the VIA community.

It is a particularly challenging problem to be able to provide higher resolution climate information across Canada since it is virtually impossible to include all of the features which have an effect on Canada's climate in a global climate model, or even in a regional climate model. Complex physiographic features strongly modify the large-scale atmospheric circulation, from the Rocky mountains in the west to the regional inland seas and a variety of coastline areas in the east (e.g., the Appalachian mountains, St. Lawrence valley, and the strong spatial discontinuities in coastal oceanic conditions arising from Gulf Stream warm water and cold water with a seasonal sea ice margin in the Gulf of St. Lawrence, Labrador Sea and Baffin Bay). In addition, there are many feedbacks relating to snow cover, coastal ocean and sea-ice cover, land-surface processes and radiative-cloud-albedo processes which make it particularly difficult to accurately simulate Canada's nordic climate. The AMIP and CMIP projects (see, for example, Walsh *et al.,* 2002; Covey *et al.,* 2000; Lambert and Boer, 2001) demonstrated that the stronger biases in many GCM simulations appear in the north (both in uncoupled and coupled models), especially in the Arctic and sub-polar basins, such as Hudson Bay, as well as over high-latitude land masses. This is indicated in Figure 8.1, which illustrates the large differences between surface air temperature as simulated by coupled GCMs and observations in high latitude regions.

Statistical and dynamical downscaling techniques are therefore key issues for the provision of climate change scenarios to the VIA community and a necessity for many assessments related to climate change research in Canada. This in itself is a major challenge for the scenarios research community, since the diversity in Canada's climate and in the factors governing regional climate mean that it is unlikely that a single statistical downscaling method will be able to provide higher resolution scenarios for the whole country, whilst the complexity to include all the relevant sub-component surface scheme (over land surface and in coupling with ocean-ice and Great Lakes models, see Chapter 3) in the CRCM and the expensive cost to run this model covering the entire American continent (as shown in Figure 3.4) will limit the number of scenarios which will eventually be available from this source and thus constrain the exploration of uncertainty in the future climate.

To date, many climate change studies by the VIA community have focused on examining only the impacts of the changes in climate itself and have generally neglected other important aspects, i.e., the non-climatic component of these studies. The main non-climatic components relate to socio-economic, land-use, land-cover and environmental conditions. In order to obtain a comprehensive view of the future, both baseline and scenario information is required for these non-climatic components. The IPCC TGCIA (1999) underscored the need for baseline information for these non-climatic scenarios which is comparable to baseline climate information.

Climate change scenarios are based on global climate modelling experiments which have used different emissions scenarios, expressed in terms of atmospheric composition. Ideally, for a comprehensive view of the future, the non-climatic scenarios should, at the regional and local level, reflect these more globally-based emissions scenarios. This means that the socio-economic (e.g., population, human development, economic conditions, energy use, governance, social values, etc.), land-use and land-cover (e.g., arable and permanent cropland, permanent pasture, forest, woodland, etc.) and environmental (e.g., air and water quality, marine pollution, etc.) scenarios should be 'downscaled' to the more local level. Most impacts studies have inherently assumed no change in these non-climatic components in the future. Providing non-climatic scenarios comparable to the climate change scenarios is yet another major challenge for the scenarios community in general.

## 8.2: Uses of Scenarios and Limitations in their Application

A number of climate change impacts studies have been undertaken in Canada which have highlighted some of the shortcomings of the available climate change scenarios, but which have also illustrated how some of these shortcomings have been overcome as climate modelling and scenario construction techniques have progressed.

The Great Lakes-St. Lawrence Basin Project on adapting to the impacts of climate change and climate variability initially used scenarios based on equilibrium GCM experiments which provided future climate information at the time of $CO_2$ doubling. Historical analogues representing extreme conditions were also used to illustrate to stakeholders the region's current vulnerability to climate. Whilst these scenarios worked reasonably well in providing first approximations for changes in future water supply and water levels, the fact that no timing could be applied to these scenarios (one of the major drawbacks of scenarios based on equilibrium GCM experiments) was problematic for stakeholders. This was overcome once scenarios based on transient GCM output became available and thus some context could be supplied for planning purposes for 2020, 2050 and 2100. However, one of the main criticisms of this scenarios work related to the fact that none of the available GCMs contained a physical characterisation of the Great Lakes and so their important influence as a moisture source and their effect on storm tracks was missing from the model simulations. The inclusion of these effects in a GCM could have important implications for the projected changes in precipitation and temperature, and therefore ultimately water supply changes, in this region.

In another water management climate change study, this time in the Okanagan Basin in British Columbia, a Swedish hydrological model was used to determine the sensitivity of watersheds in this region to climate change. In the first phase of the study, climate change scenarios from three GCMs (CGCM1, HadCM2 and ECHAM4) using IS92a emissions forcing were used. In the second phase of the project, the UBC Watershed Model was chosen for modelling the precipitation-runoff processes and the climate change scenarios were updated with, in total, six scenarios based on the SRES A2 and B2 emissions scenarios (see Chapter 3) from the CGCM2, HadCM3 and CSIROMk2 GCMs being used (Taylor *et al.*, 2003). In both phases of the project, one of the major concerns was the inadequate representation in the GCMs of the very rugged topography in this region of Canada. In an attempt to overcome this problem, the utility of statistical downscaling using multiple linear regression techniques was explored. Whilst some success was achieved for temperature, little value was added to the GCM-derived precipitation scenarios. In this region the local topographic control of precipitation occurrence is far greater than the effects of the large-scale atmospheric conditions and therefore it was difficult to obtain a robust statistical model with the data available. Instead, the standard procedure of applying the climate change scenarios to local station data was adopted (see Chapter 3). However, when monthly scenario changes are applied to daily observed data, large discontinuities at the monthly boundaries can occur, usually as a result of the differences in the scenario values from one month to the next. To overcome this problem a smoothing algorithm (Morrison, 2002) was applied and this redistributed the discontinuity throughout the entire month and produced smooth transitions from one month to the next whilst, at the same time, preserving the GCM-derived changes in the monthly mean values (Figure 8.2).

## 8.3: Scenarios and Uncertainty

Uncertainty in climate change scenarios (see Chapter 7) is another aspect which has generally not been adequately explored by the majority of climate change impacts assessments. One way of attempting to incorporate uncertainty in such assessments is by the use of multiple scenarios, derived from different GCMs which have used a number of alternative emissions futures in their climate change experiments. This approach attempts to deal with the major sources of uncertainty identified by Mearns *et al.* (2001), i.e., specifying alternative emission futures, uncertainties in converting emissions to concentrations, uncertainties in converting concentrations to radiative forcing, uncertainties in modelling the climate response to a given forcing and uncertainties in converting model response into inputs for impacts studies. Uncertainty should be a characteristic feature of all climate change impact assessments and will in part be due to the choices researchers make regarding the selection and application of climate change scenarios, but it should be remembered that there is also an uncertainty component related to impacts modelling. A cascade of uncertainties is illustrated in Figure 8.3.

Mills *et al.* (2001) attempted to incorporate uncertainty in their study of climate change impacts in Toronto. They concluded that the selection of emission scenario, climate model, base climate period, base climate station(s), and use of downscaling procedures significantly influenced the estimated impacts of climate change on the occurrence of Heat Stress Days (HSDs) in this city. All scenarios selected for use indicated that heat stress conditions will become more frequent as a result of climate change. Using a limited set of scenarios for the 2080s resulted in mean annual HSDs ranging from 10.5 to 45.0 days, relative to a baseline of 4.5 days, and this could lead to a similarly wide range of human health outcomes. It is likely that the same observation may be made about more complex indicators and for other places. This range of outcomes is simply from incorporating (some of the) climate change scenario uncertainty, and yet there exists other, likely greater, sources of uncertainty related to the long-term interactions between heat stress and an ever-changing, mobile and acclimatising human population. In order to obtain a more complete picture of the city's response to heat stress, the socio-economic and policy aspects of uncertainty should be explored in more detail, and more quantitative risk estimates developed by using other scenario techniques.

## 8.4: Specific Problems of Scenarios for Impacts Assessment - Views of the Research Community

In this section, scenario limitations and challenges for specific impacts sectors are discussed.

### *8.4.1: Water*

Development of climate change scenarios is relevant to assessment of water quantity and water quality impacts in surface water and groundwater. Climate impact assessment research has focused on water quantity impact assessment in particular determining changes in water supply to lakes, rivers and ground water and resulting changes to lake levels, streamflow and groundwater recharge and levels. Most climate change impact assessments have used GCM-based scenarios where change fields have been applied to observed climate station data at hourly, daily, monthly or seasonal time periods (as described in Chapter 3). Key inputs to many hydrologic models include precipitation, temperature, cloud, solar radiation, and wind speed. Instead of direct use of GCM climate data in models, this method tries to overcome the poor spatial resolution of the GCM, the bias in the GCM's simulation of current climate, as well as lower confidence in GCM output at the daily, and finer resolution, time-steps. Initial, valuable assessments have been provided from a water balance perspective with potential sensitivities due to more or less water identified most notably at monthly and seasonal time scales.

However, this scenario construction methodology does not address event-driven water quantity problems such as flooding from extreme precipitation events or water quality problems due to erosion from intense precipitation events. For these assessments, the changes in the number of rain days, the sequence of wet and dry days and most importantly changes in precipitation amount and duration – how much rain falls in an event and over what period of time – are critical. Another important component for this sector is the estimation of changes in evapotranspiration, which is critical for determining water loss in a watershed. This component of the hydrologic cycle is problematic because of the ongoing challenge of modelling current evaporation and plant transpiration combined with obtaining reasonable estimates of factors influencing this evapotranspiration, such as wind speed, from GCMs. New issues, such as the role of rain on snow events for winter runoff and flooding, and the influence of the frequency and duration of thawing and freezing on winter groundwater infiltration and winter runoff, are also emerging.

Improvements in the spatial resolution of GCMs would allow more detailed assessments of climate change impacts in this sector, since the spatial variability of climate is critical to realistic hydrological modelling. Many studies would benefit from climate scenario information at a spatial resolution of between 0.5 and 1.0° latitude/longitude. Information at this resolution is likely best obtained from regional climate models, which are process-based. Statistical downscaling may have limited use for constructing higher resolution scenarios for this sector since there is, currently, a lack of spatial coherence between downscaled outputs at adjacent stations within a watershed, making scaling up to the watershed level problematic. There are also concerns about the validity of statistical relationships developed using observed data being valid for the future climate. However, it may be useful for local (i.e., single point) applications.

### *8.4.2: Drought*

Drought is another important aspect of Canada's climate, particularly for the prairie region. In order to determine how drought frequency and severity will be affected by climate change, an improvement in the quality of GCM outputs for a number of climate variables is desired. The Palmer Drought Severity Index is one of the most widely-used drought indices in North America and requires reliable soil moisture, wind, evapotranspiration and precipitation information in order to provide robust estimates of drought severity. Improved model resolution and a better representation of the land surface and land surface processes may result in improvements in the simulation of some of these variables.

The majority of GCMs indicate major continental dryness in the future for North America and it is important to note that prolonged droughts occur when large-scale anomalies in atmospheric circulation patterns persist for months or seasons (or longer). Drought in Canada (and other areas of the world) has been linked to phenomena such as the ENSO, with a major portion of the atmospheric variability associated with this phenomenon being related to variations in tropical sea surface temperatures. Improved representation of this type of phenomena in GCMs would increase confidence in their use for scenario construction, and the scenarios of changes in sea surface temperature, and even of changes in the frequency and severity of ENSO events would have utility for determining changes in future drought frequency and severity.

### *8.4.3: Extreme events*

Information about changes in the frequency and magnitude of extreme events is vital for determining system and sector vulnerability to climate change. In some instances, it will be sufficient to supply information about changes in return periods (of 50 to 100 year events) of various extreme events related to precipitation amounts, wind speed and temperature. However, for regions such as the Maritimes and the Prairie Provinces, information about the frequency of extra-tropical storms and hurricanes, and high wind and precipitation events associated with severe thunderstorms and tornadoes, respectively, would be of use to planners and engineers to feed into design criteria and risk analyses. However, global climate models are unable to provide this type of information since these phenomena occur at sub-grid scales and cannot be resolved by the GCM. Regional climate models, depending on their resolution, may be able to provide more meaningful information about such extreme phenomena. Historically, the greatest impacts of extreme events in Canada have been associated with droughts, floods and ice storms. In the future, however, heat waves are highly likely to become more important and, as seen in the tragedy in southern Europe in the summer of 2003, can result in a large numbers of deaths.

### *8.4.4: Agriculture*

Although the principal drivers for agricultural production are biophysical effects, socio-economic factors are also very important for this sector. Parry *et al.* (2004) identified the following factors as important for crop production: rising and falling temperatures, changes in precipitation regimes, increased atmospheric $CO_2$ concentrations, the magnitude and rate of climate change, and socio-economic factors influencing responses to changes in crop productivity. Of these, precipitation is still not considered to be adequately simulated, both spatially and temporally, in most GCMs. Higher resolution precipitation scenarios, constructed using either dynamical or statistical downscaling techniques, would be of use to this sector, assuming that an indication of the uncertainty associated with these scenarios could be provided. Improved soil moisture information is also required, particularly for crop simulation modelling. In addition, more information about the soil classification and characteristics (e.g., porosity, hydraulic conductivity, etc.) used in the GCMs is required, as well as information on seasonal runoff and infiltration.

### *8.4.5: Health*

Climate change will affect human health directly (e.g., due to heat stress, and injury or death caused by weather disasters) and indirectly (e.g., through changes in the ranges of disease vectors, waterborne pathogens, air quality, and water and food quality). However, the actual health effects will be influenced by local environmental conditions as well as a wide range of social, technological, and behavioural measures taken to reduce the adverse impacts (World Health Organisation, 2003). Three examples of scenario challenges in the health sector follow.

Under climate change, summer mortality and morbidity rates are expected to rise significantly as a result of increased frequency, duration and intensity of heat waves. Heat waves which occur earlier in the summer are usually more deadly than late season ones, simply because the population is not yet acclimatised to the higher temperatures. Future scenarios, providing information about the onset and frequency of heat waves of, or in excess of, 30°C, which last for at least 3 consecutive days, would be of use to this sector, particularly if they are expressed in relation to current climate conditions. Heat stress can also be aggravated by high humidity and/or high night-time temperatures. Hence, scenarios of thermal stress indices which take into account the combined effect of two or more meteorological variables are also required.

Waterborne pathogens are spread through, for example, contaminated drinking water or food contaminated with infected water. Existing wells, and water and sewage treatment systems have been designed, on the basis of current climatic conditions (the so-called 30-year climate normals), to operate within expected levels of precipitation, ambient temperature, snow cover, snow melt, water levels, and coastal conditions. All of these parameters could change significantly with climate change. As a result, pathogen entry into and behaviour in municipal water systems will also be subject to change. Future scenarios for drought and flood frequency and severity, sea-level rise, extreme rainfall events, changes in snow cover, timing of snowmelt, ground temperature, and soil moisture at a spatial resolution of about 50km are required. Public health officials and water managers need to know as much as possible about the potential changes in all these parameters in order to take the necessary steps to protect public health in future.

The interaction between climate, human behaviour and vector-borne diseases is too complex to allow accurate predictions to be made. However, factors such as temperature fluctuations and extremes, atmospheric humidity, soil moisture and drought conditions, heavy rainfall events, and prevailing wind patterns at various levels in the lower atmosphere influence disease vectors, the pathogenic micro-organisms, and the migratory pattern of intermediary hosts (such as wild animals and birds which often serve as a reservoir for the pathogen until susceptible human populations are exposed). Dynamic disease transmission models would benefit from climate change scenarios for the variables listed above on a temporal scale of 24 hours or shorter, and on a spatial scale of 50 km or less.

### *8.4.6: Energy*

Climate change impacts on the energy sector typically involve questions of supply and demand, although more recent applications in the Toronto-Niagara Region have considered power transmission and distribution, the performance of specific technologies and buildings, as well as air quality. Although impacts have been examined at a variety of spatial scales, from a single building site up to the provincial level, issues of supply and demand may also involve consideration of national- or global-scale conditions. Scenario data requirements range from single variables such as temperature to a range of variables including wet-bulb temperature, humidity, wind speed and precipitation. Whilst most studies have used projections of changes in mean climate, information about changes in extremes is also vital for the energy industry. For climate change applications, this has focused primarily on high values of variables that influence demand, such as temperature and humidity, and on low values for variables that influence supply or operations, such as precipitation.

For climate change studies at the scale of single building site, simulation models can be used to assess the performance of new technologies, designs or practices that lower the consumption of energy. In general these models require large amounts of data at spatial and temporal scales that cannot yet be supplied by climate change scenarios. For these studies, it is necessary to utilise statistical tools to create the necessary data inputs from the projected changes in the mean, maximum or minimum values, and in some cases, the variance of the required climate inputs. Energy models that forecast future demand and supply are not designed to accommodate climate inputs, but instead use demand curves to relate future temperatures to changes in demand, and similar procedure is used for the supply of hydropower. These models operate on long time intervals, which fit well with existing scenarios, but make it more difficult to do meaningful work with extreme events. There are two future directions that are required to facilitate climate change impacts studies in the energy sector. On the scenario side, information about averages and extreme values is required for a broader range of variables, in particular for humidity. Higher spatial and temporal resolution scenario information is also required, including, in some cases, data at sub-daily time steps. On the energy modelling side, this research community should be redesigning regional models for demand and supply to utilise climate data as a direct input.

### 8.4.7: Infrastructure and municipalities

The most important scenario issues in this sector relate to the utility and validity of the GCM output used to construct scenarios of climate change for the main climate variables, and also for derived indices which are of use in this sector. Related to this are concerns that climate change scenarios cannot adequately provide information about antecedent conditions leading to a complex hazard/impact chain. There is also a question of language, with many of the definitions used by climatologists being interpreted in a different manner by engineers. For example, a climatologist defines a frost day when the surface air temperature is below 0°C, whilst for an engineer it relates to the sub-surface temperature when soil conditions are conducive to the development of frost lenses. Spatial and temporal scale issues are also important since many systems, such as small urban stormwater catchments, respond to environmental variables in minutes or hours. Most of the available scenario data and historic trend analyses, which are used to evaluate whether conditions are becoming more extreme over time, are available only at daily, monthly or seasonal time steps. Without developing climate change scenarios at higher spatial and temporal resolutions and providing a measure of uncertainty with the scenarios, engineers will be unlikely to consider answering questions concerning, for example, the likelihood of a municipal storm sewer failing in a 5-hectare catchment in Toronto as useful when the precipitation scenarios have been derived from climate model output at a coarse temporal scale (usually monthly) and for a grid box representing at least 40,000 km$^2$.

It is not necessary to prove to the engineering/planning community that an ounce of prevention is worth a pound of cure once a particular problem has been made compelling enough. "Engineers in general and municipal engineers in particular are often viewed as being more conservative than the average citizen. Whether or not this is true, the fact remains that most engineers will not revise long-standing design inputs unless the revised input can be defined with an acceptable level of uncertainty. Simply put, a reliable authority must state, for example, that storm rainfall in a specified region of Canada is expected to increase by a certain amount, with a defined margin of error, by a particular point in the future" (Watt *et al.*, 2003). Hence, until climate change scenarios are provided at the spatial and temporal scales which are of use to this community and an estimate of the uncertainty is associated with the scenarios, they are unlikely to be considered seriously by this community.

The timing of the future climate changes is probably one of the most important elements of a climate change scenario for this community. The lifecycle of infrastructure and related systems consists of a number of phases including planning and design, approval, construction, maintenance, redesign, approval, retrofitting, maintenance, redesign, and so on. This introduces a tremendous inertia into the system such that generally less than 5% of stock (buildings, pipes, roads, bridges, etc.) is turned over in any given year. When conducting cost-benefit analyses or broader service planning exercises, infrastructure planners/developers/managers need to know about the climate futures expected at specific times with similar levels of certainty as is required for demand factors (population growth, expenditure, travel, etc.) or material factors (performance/fatigue/failure rates). Until probabilistic and other techniques are sufficiently refined to treat and communicate these uncertainties, it will be difficult to convince people that action is a necessary precaution (until significant changes in infrastructure failure that can be readily attributed to climate change are observed).

### 8.4.8: Parks and Tourism

During a climate change impacts assessment undertaken for Canada's national parks, Scott and Suffling (2000) assumed that the anticipated climate change impacts would be relatively similar. Using climate change scenarios constructed from GCM output, they encountered the common problems related to coarse spatial and temporal resolution, which meant that micro-scale climatological influences were not incorporated and coastal areas and complex terrain were inadequately represented. In order to adequately reflect the magnitude of uncertainty associated with the GCM outputs, a range of scenarios was considered in this research, in line with the recommendations from the IPCC TGCIA on scenario application (see Chapter 3). The scenarios available did not include possible changes in climate variability.

Tourism is a multi-faceted industry with many climate-related dependencies. Scenario issues relate to the estimation of future conditions of ecosystems, water resources, sea-level rise/storm surge, snowfall and other environmental features that are necessary to support various tourism and recreation activities or that compromise the safety of visitors and the viability of infrastructure. Given the variety, high level of substitution and competition within the industry, as noted by Wall (1998), the main scenario challenge is not related to determining if conditions supporting activities will be adversely affected, but rather when business and management thresholds may be reached (e.g., in the downhill skiing industry; Scott *et al.* (2003); protection of natural areas/ecosystems in national parks, Scott and Suffling (2000)). Unfortunately, understanding of current climate sensitivities and vulnerabilities in this industry is very limited. Until this is resolved, even the most accurate and precise climate change scenario information will be of limited value (Wall 1998).

### *8.4.9: Insurance*

Extreme events and climate change are of concern to the insurance industry, but climate scenarios are unlikely to ever be used by them in an operational way, except perhaps as optics to help justify increases in premiums. Insurance rates can be modified on a year-to-year basis based upon the historical record, and are therefore very responsive in the short term. Also, rates tend to be very much determined by competition within the industry and recent events. So although climate change may well affect the industry in significant ways in the long term, the mismatch between their needs and climate scenarios is so large that it is unlikely to ever be bridged.

## 8.5: Scenarios for the Future: Looking Forward

### *8.5.1: The long term vision*

The original vision for climate change scenarios was provided by the International Geosphere-Biosphere Programme — Biospheric Aspects of the Hydrological Cycle (IGBP-BAHC; BAHC, 1993). Much of this vision has been realised with facilities such as the Canadian Climate Impact Scenarios (CCIS) Project which provides scenarios of climate change, advice and access to, and training in, downscaling tools, including weather generators. The original BAHC vision identified a list of variables, spatial and temporal scales and the minimal and desired uncertainties that were required for impact assessment. The most difficult part of this exercise is quantifying the uncertainty due to the number of components that must be considered (as exemplified in Chapter 7). This is still an active area of research and needs to move beyond a comparison of GCM simulations to include contributions from the different downscaling methodologies and other impact assessment models that might be used in research.

Expanding the current scenarios to include more variables and uncertainties is still not a vision for the long term. The user community is more sophisticated and has a different set of needs that go beyond the provision of climate variables. These needs include both the product as well as the process of delivery. On the climate side, we can expect more calls for scenarios with extremes in temperature and precipitation, followed by the demand for extremes in other variables. However, climate impact assessment is moving beyond impacts to look at risks and adaptations. Applying only a changed climate assumes that a lot of other environmental and socio-economic factors remain constant. The actual future risks may involve a combination of climate, demographic and technical changes and the pathways open for adaptation.

For example, changes in water supply may only be a risk under certain demographic scenarios. In many parts of the developed world, population is only increasing due to immigration, but by the 2050s the developed world will have already witnessed two decades of population decline. The risks of the 2020s may be significantly altered by the 2050s and the 2080s. Technological change may lead to clean and abundant energy sources and changes in manufacturing that will remove many of the agricultural and air quality impacts associated with climate change. The way in which society uses these technologies may increase or decrease its vulnerability to climate.

As climate begins to change, the users of the scenarios will change. We can expect the demand for information to come from decision-makers as well as researchers. This demand will have to be met, not just through the provision of climate data, but through the provision of information that is required for a decision. For example, decision-makers will not want temperature, radiation and precipitation data, but information on leaf wetness and the risk of different pests, the demand for air conditioning or the likelihood of a new disease vector under different scenarios. In addition, as climate does begin to change, scenarios should start to be compared to indicators of climate change to obtain a better quantification of the uncertainty.

When all of this information is available, it will have to be presented in a format that is easily accessible and easily interpreted. The type of information required will also change, with most users unlikely to want long time series, as the demand switches from research to decisions, but rather specific statistics and a quantification of the risk, based on the climate and the socio-economic scenarios as well as the uncertainty.

As demonstrated by the establishment of UK Climate Impacts LINK Project (http://www.cru.uea.ac.uk/link) and the CCIS Project, it is possible for these visions to become achievable goals. The constraint is not the technology nor is it the research, but a commitment of the requisite resources. It is difficult to speculate on the resource needs that will required for the future, but perhaps user-pay models will have to be considered to maintain and expand these services.

### *8.5.2: Short term deliverables*

In the next couple of years, climate and climate change scenarios (see Chapter 3) at the regional scale will be more systematically developed, in comparison to the coarser-scale climate change scenario information available in the last ten years. In the near future, the development of scenarios of climate variability and extremes, suggested both at the international and national scales, will necessitate the development of downscaling techniques which will be able to provide information at the daily scale, at least, as suggested in Chapters 3 and 6. With the development of integrated research at the national scale and with collaboration with international programs such as AMIP and CMIP for GCM research, and STARDEX (Statistical and Regional Dynamical downscaling of Extremes for European regions), MICE (Modelling the impact of climate extremes, **http://www.cru.uea.ac.uk/cru/projects/mice/**) and PRUDENCE (Prediction of regional scenarios and uncertainties for defining European climate change risks and effects) in Europe for downscaling and VIA research, the necessary scenarios will be developed and disseminated to the Canadian VIA community. In addition, this type of collaboration will ensure that research excellence in scenarios development is maintained.

Climate scenarios with a higher temporal resolution than the monthly, seasonal or annual anomalies of the currently available climate change scenarios is vital for the development of scenarios of extremes and climate variability, which require daily or sub-daily information. In order to fulfill the demand for products such as climate scenarios containing information about changes in means, variability and extremes, it will be necessary for stronger links to be built between the climate modelling, data, scenario and VIA communities. This effort will allow the CCIS Project, in close partnership with regional groups, such as the OURANOS consortium, to deliver in the near future more comprehensive information related to the strength and limitations of statistical downscaling techniques, in particular concerning their utility for the development of scenarios of climate variability and extremes. In addition, current capacity for the development of higher resolution climate scenario information will be expanded when output from the CRCM (see Chapter 3) simulations over Canada becomes available.

## 8.6: Summary and concluding remarks

As recommended in the last national workshop on the Development of Scenarios of Climate Variability and

Extremes held in Victoria (BC) on 16-17 October 2003, the CCIS facility, and similar projects, such as IPCC DDC, at international scales, must continue to be supported in the future. The further identification of current vulnerability to historical climate extremes and a refining of stakeholder knowledge related to these vulnerabilities were also identified as a necessary requirement for the future development of scenarios. In addition, scenarios must also provide information which allows the assessment of changes in the risk of future impacts, especially those related to future changes in extremes and climate variability, rather than to changes in mean climate only. The lack of information related to extremes and variability is an important gap that must be filled in order to deal with problems related to modification of temperature regimes and the hydrological cycle. Changes in water yields and in precipitation and flow extremes will have important impacts on stormflow management, hydropower generation, agricultural activities and aquatic ecosystem integrity, to name but a few areas of concern. All this work must be developed in an integrated manner, with constant dialogue between climate scientists, scenario developers, and users and stakeholders from the VIA community. Climate modeling work, at both global and regional scales, and the development of other downscaling methods must occur within a coherent strategy, since all are complementary. This more integrated approach will result in the development of useful and plausible scenarios at regional scales.

These are significant, but not insurmountable, challenges for Canada, given the huge variety in our climate and the complexity of representing all key climate factors within a climate model. Since it is anticipated that there will be large changes in climate, particularly in the north, and because of the differences in regional climate variability, the need for coherent, integrated scenarios is pressing. However, the opportunity for progress exists, particularly if the requisite resources are committed. The development of coherent, integrated scenarios is vital to help the next generation adapt to a changing climate, and to better understand the fundamental behaviour of the climate system.

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# Figures

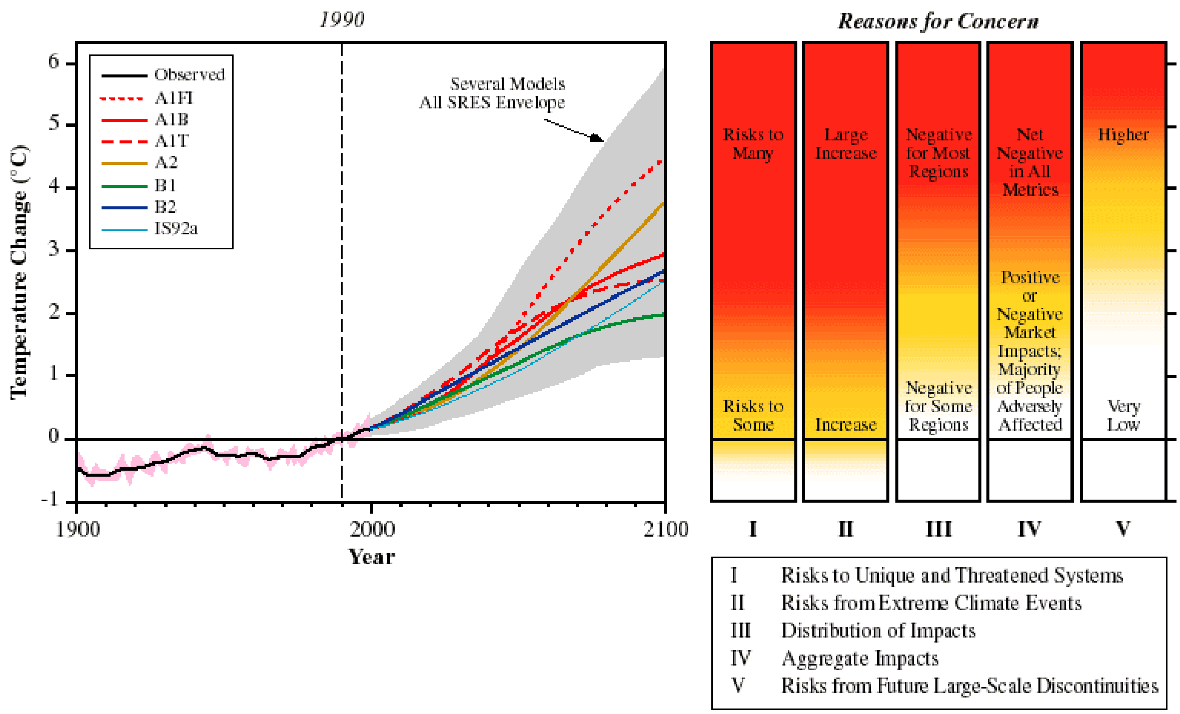



**Figure 1.1**

Reasons for concern about projected climate change impacts. The risks of adverse impacts from climate change increase with the magnitude of climate change. The left part of the figure displays the observed temperature increase relative to 1990 and the range of projected temperature increase after 1990 as estimated by Working Group I of the IPCC for scenarios from the Special Report on Emissions Scenarios. The right panel displays conceptualisations of five reasons for concern regarding climate change risks evolving through 2100. White indicates neutral or small negative or positive impacts or risks, yellow indicates negative impacts for some systems or low risks, and red means negative impacts or risks that are more widespread and/or greater in magnitude. The assessment of impacts or risks takes into account only the magnitude of change and not the rate of change. Global mean annual temperature change is used in the figure as a proxy for the magnitude of climate change, but projected impacts will be a function of, among, other factors, the magnitude and rate of global and regional changes in mean climate, climate variability and extreme climate phenomena, social and economic conditions and adaptation.

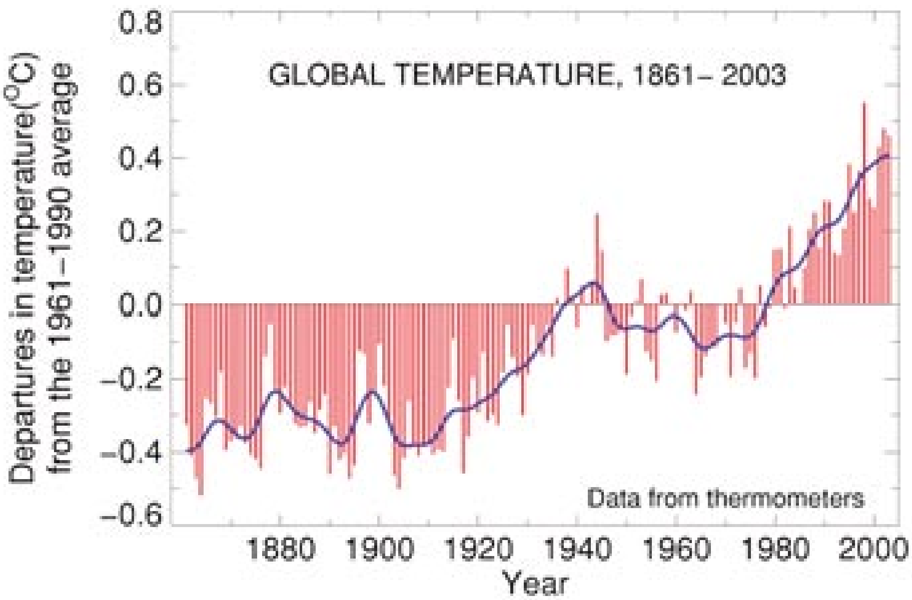



**Figure 2.1**

Global annual anomalies of combined land-surface air and sea surface temperatures (°C), 1861-2003 (red bars). The smooth blue curve represents near-decadal averages. [Source: UK Hadley Centre for Climate Prediction and Research]

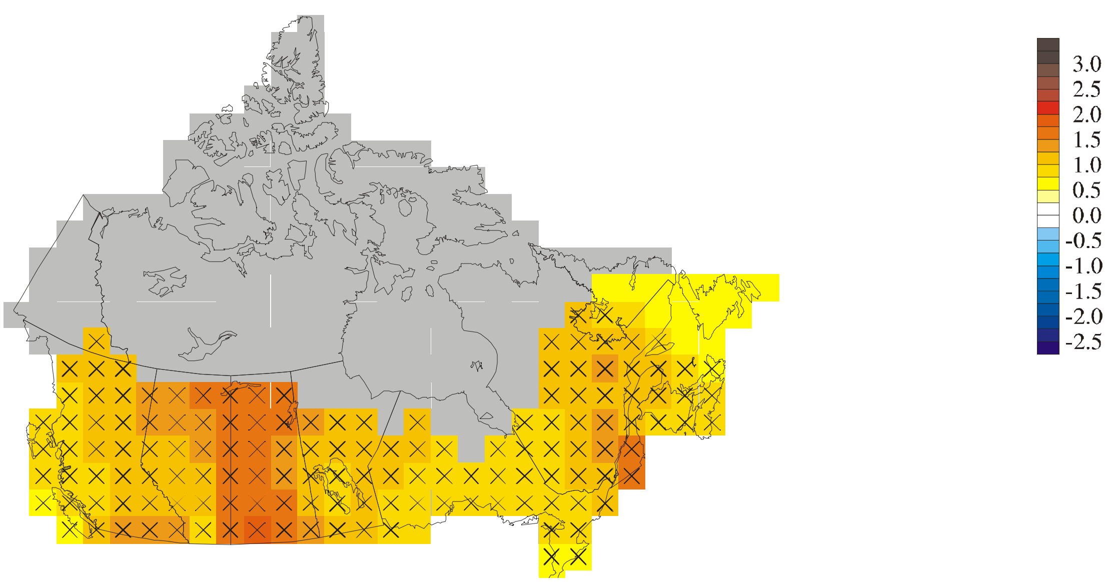
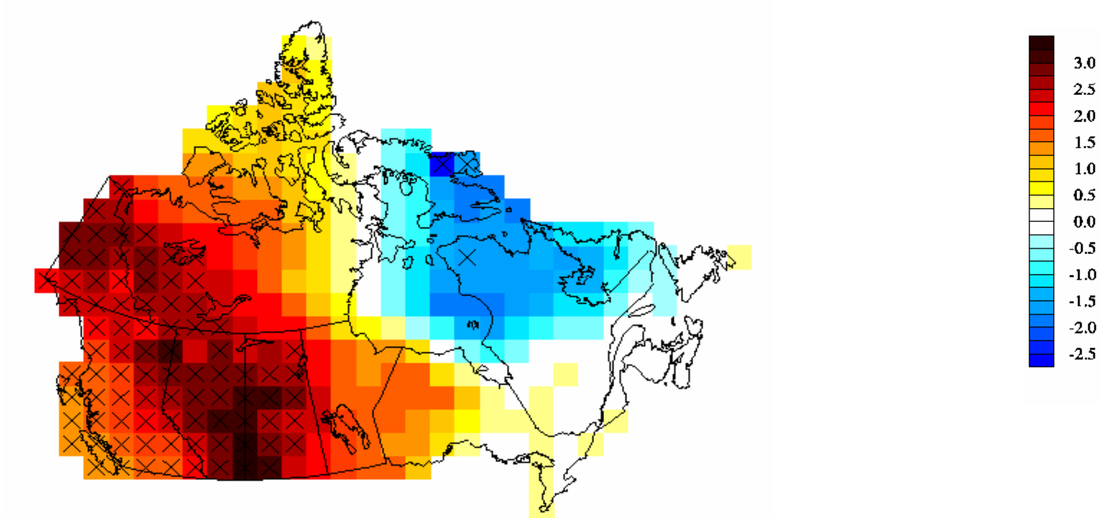


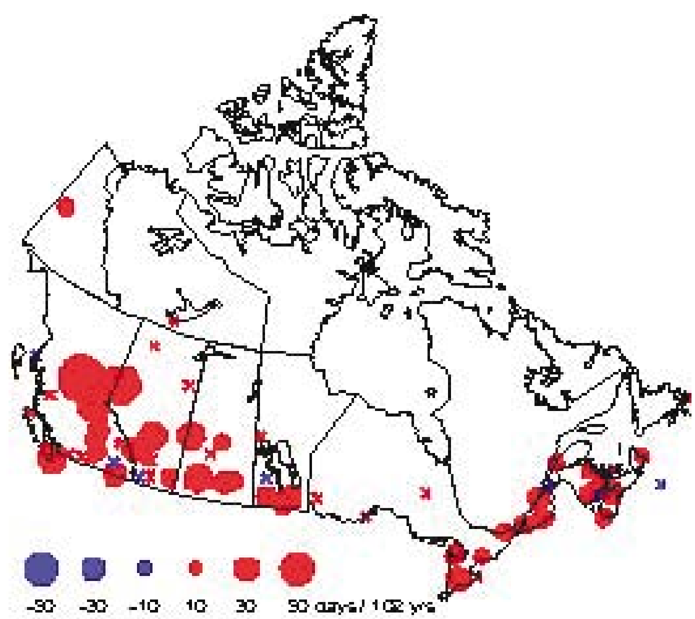

**Figure 2.2**

Trends in annual mean temperature over 1900-1998 (°C per 99 years). Grid squares marked by crosses indicate trends which are statistically significant at the 5% level. Grey areas indicate insufficient data. [Source: Zhang et al., 2000]



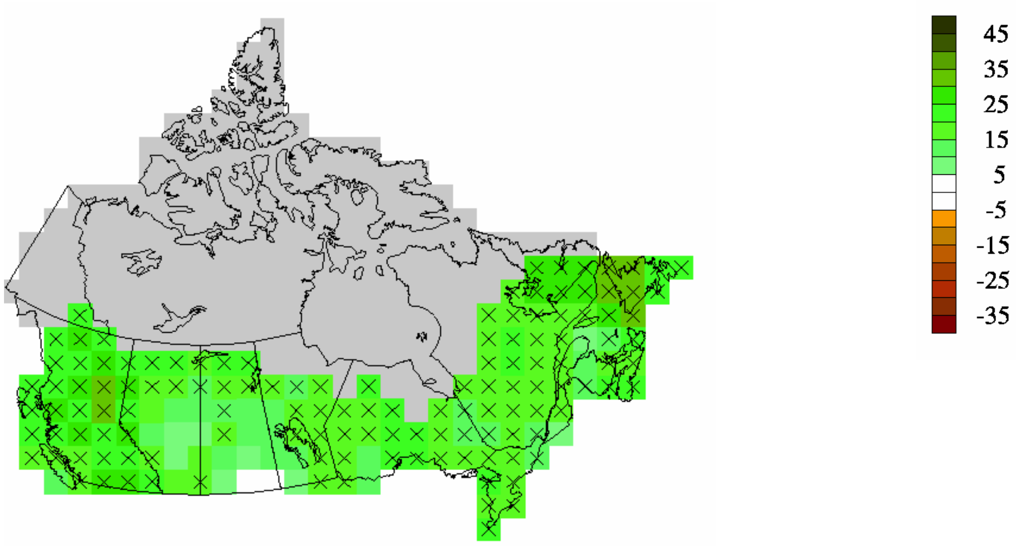

## Figure 2.3

Trends in spring mean temperature over 1950-1998 (°C per 49 years). Grid squares marked by crosses indicate trends which are statistically significant at the 5% level. [Source: Zhang et al., 2000]



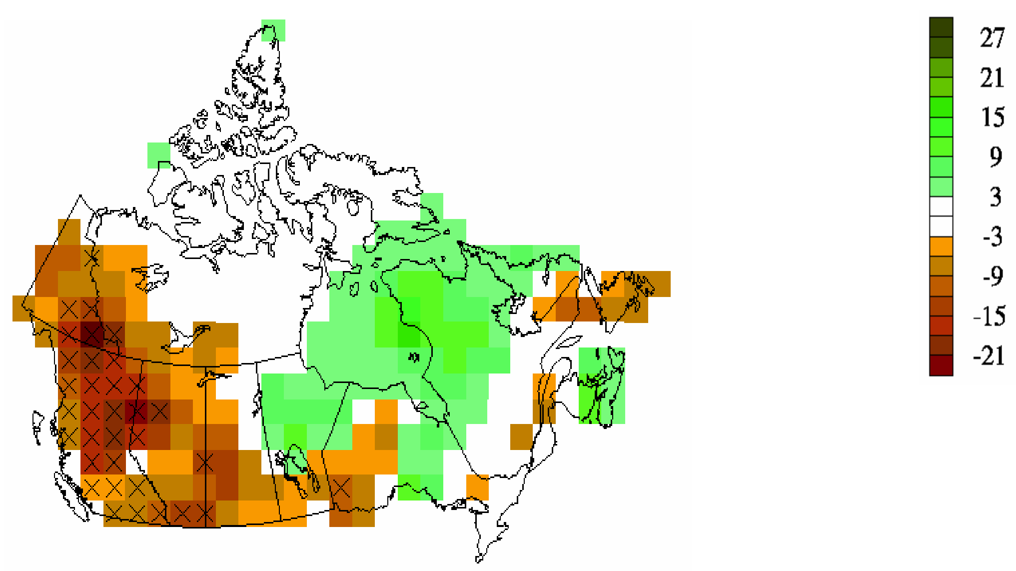

## Figure 2.4

Trends in the length of the frost-free season over 1900-2001. Crosses indicate trends that are not statistically significant. Circles indicate trends which are statistically significant at the 5% level. [Source: Vincent and Mekis, 2004]



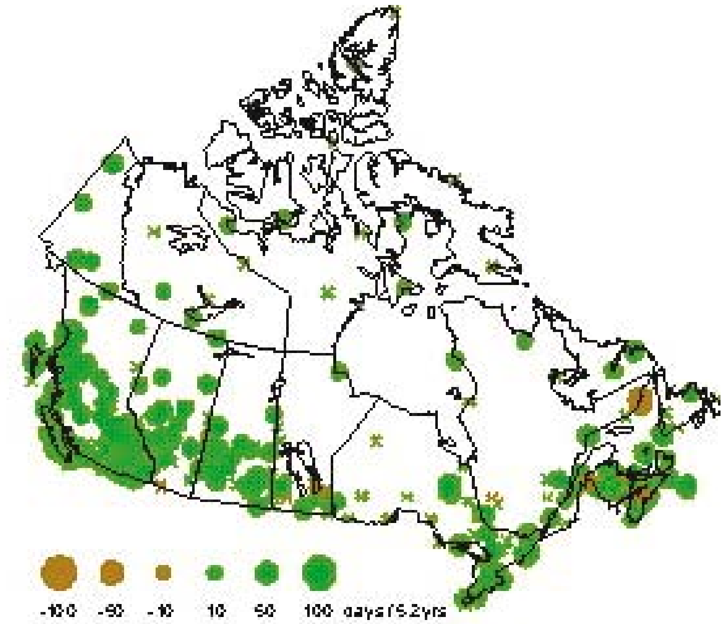

## Figure 2.5

Trends in annual total precipitation over 1900-1998 (% per 99 years). Grid squares marked by crosses indicate trends which are statistically significant at the 5% level. Grey areas indicate insufficient data. [Source: Zhang et al., 2000]



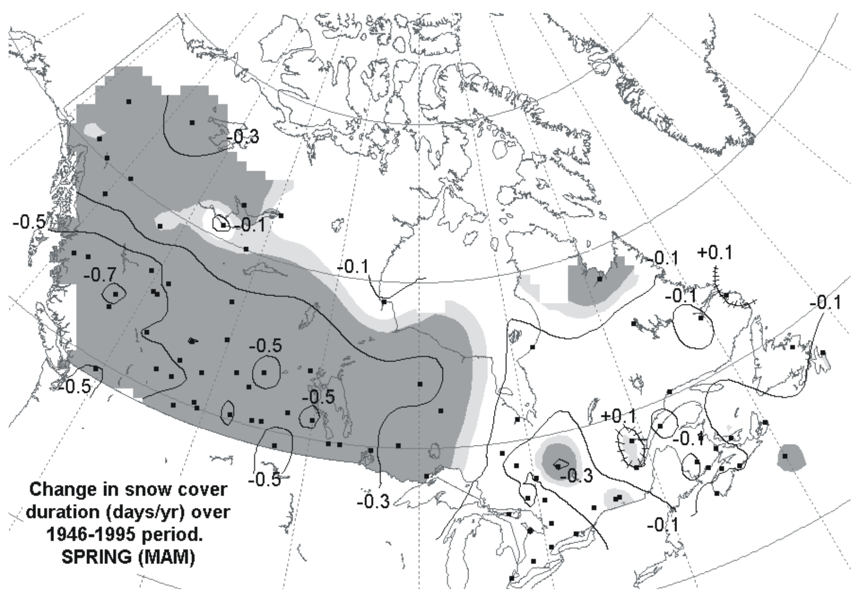

## Figure 2.6

Trends in spring snow to precipitation ratio over 1950-1999 (% per 49 years). Grid squares marked by crosses indicate trends which are statistically significant at the 5% level. [Source: Zhang et al., 2000]



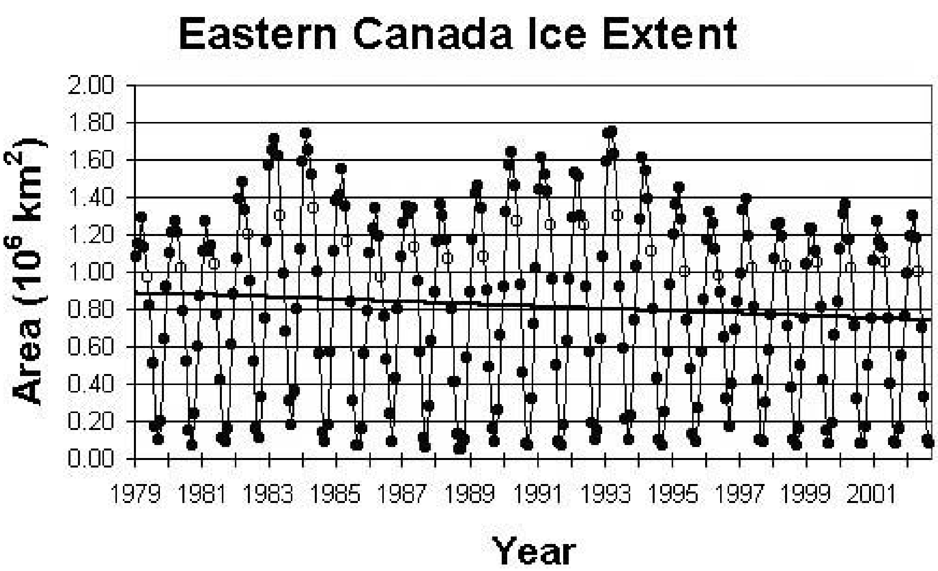

## Figure 2.7

Trends in days with measurable rain over 1950-2001. Crosses indicate trends that are not statistically significant. Circles indicate trends which are statistically significant at the 5% level. [Source: Vincent and Mekis, 2004]



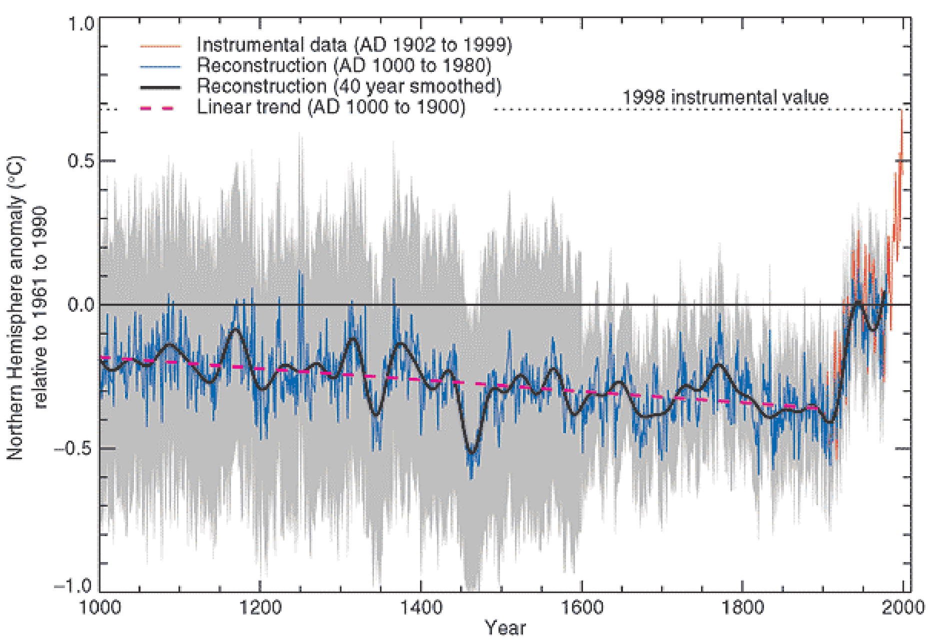

## Figure 2.8

Trends in spring snow cover duration over 1946-1995 (days per year). Dark shading is used to highlight areas where changes are negative and statistically significant at the 5% level. Light shading is used to highlight where changes are negative and marginally significant, between the 5% and 10% level. [Source: Brown and Braaten, 1998]



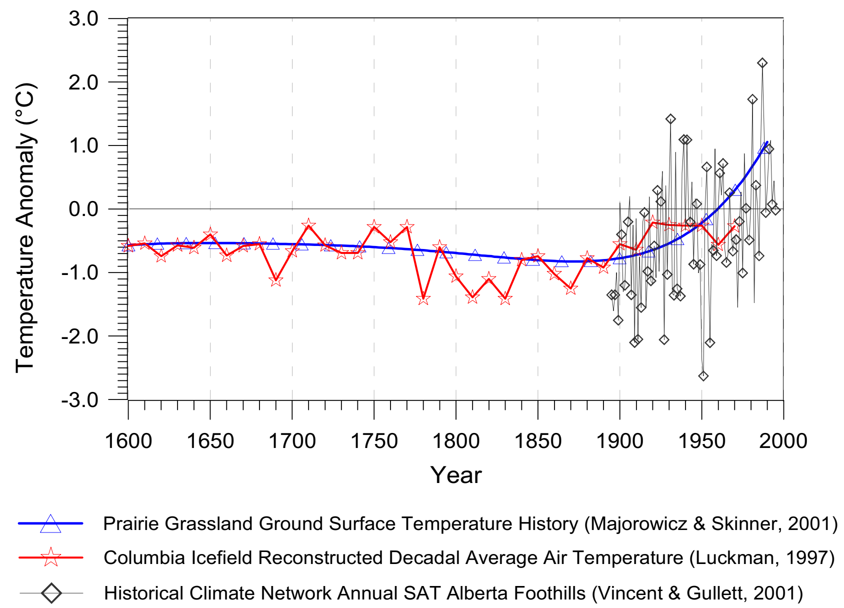

## Figure 2.9

Monthly sea ice extent for eastern Canada (Baffin Bay, Davis Strait, Labrador, Newfoundland) using sea ice area estimated from satellite passive microwave data. The open circles are for May of each year. [Courtesy of: T. Agnew, Meteorological Service of Canada]



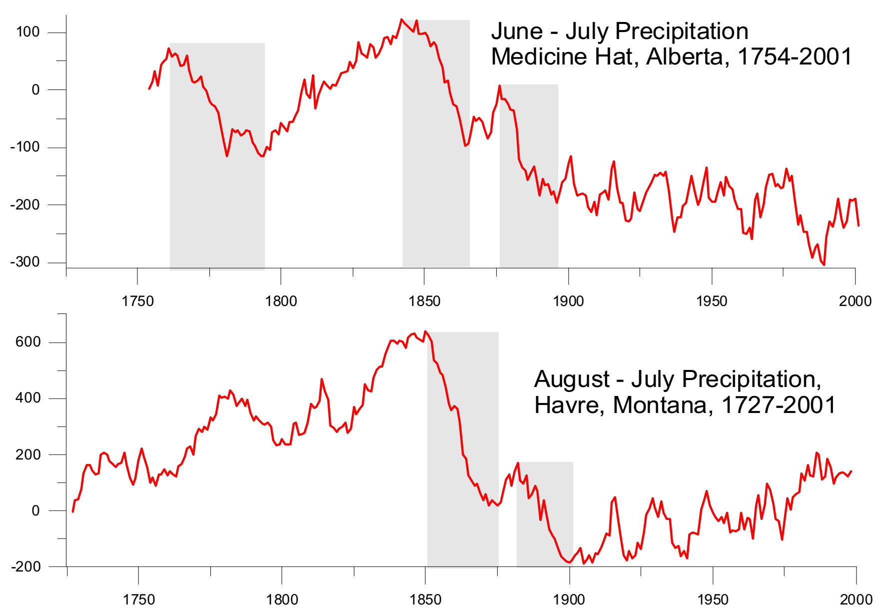

## Figure 2.10

Millennial Northern Hemisphere (NH) temperature reconstruction (blue) and instrumental data (red) from AD 1000 to 1999, adapted from Mann et al. (1999). Smoother version of the NH series (black), linear trend from AD 1000 to 1850 (purple-dashed) and two standard error limits (grey-shaded) are shown. [Source: IPCC, 2001a]




## Figure 2.11

Comparison of reconstructed ground surface temperature with reconstructed surface air temperature and instrumental surface air temperature. [Source: Majorowicz and Skinner, 2001]




## Figure 2.12

Cumulative departures of reconstructed precipitation from median values for two locations in the northern Great Plains. The shaded time periods suggest prolonged drought events absent from the 20th century and thus instrumental climate records. [Source: Sauchyn et al., 2003]

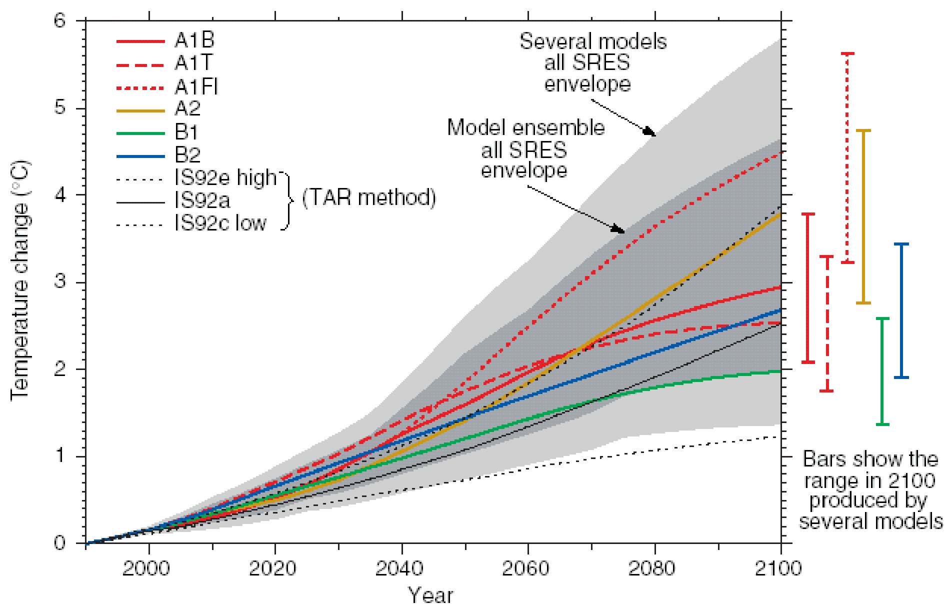
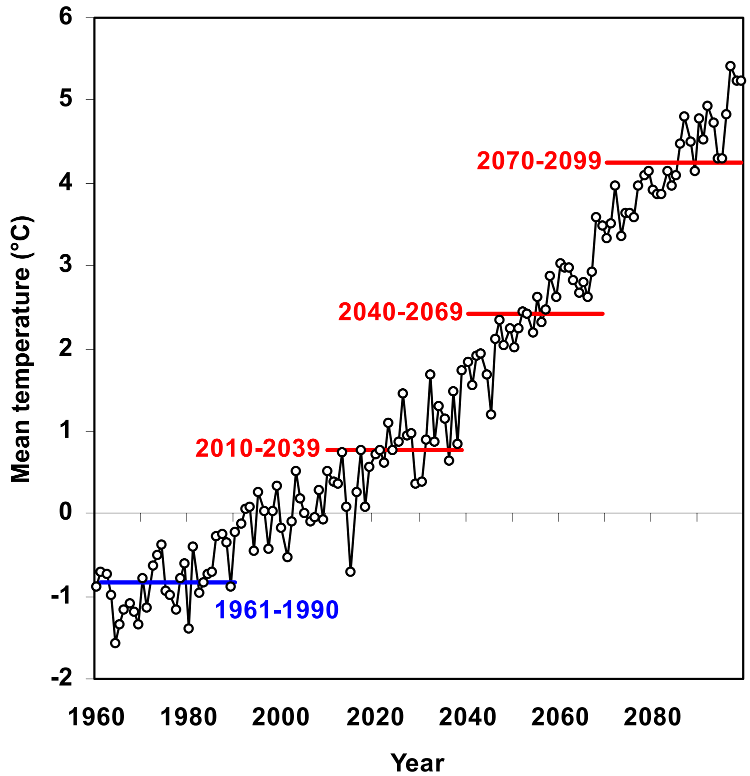



**Figure 3.1**

Global-mean temperature projections for the six illustrative SRES scenarios, derived using a simple climate model tuned to a number of complex models with a range of climate sensitivities. Also indicated for comparison are the results from three of the IS92 emissions scenarios (Leggett et al., 1992), of which IS92a - a business-as-usual emissions scenario - had been most widely used by the climate modelling and impacts communities until the advent of the SRES. [Source: IPCC, 2001a]




## Figure 3.2

Construction of climate change scenarios from GCM output. Illustrated is the time series of mean surface air temperature for the Canadian land area from the CGCM2 simulation forced by the SRES A2 emissions scenario. The blue line indicates the 30-year mean for the 1961-1990 baseline period, whilst the red lines indicate the 30-year mean values for the 2020s (2010-2039), the 2050s (2040-2069) and the 2080s (2070-2099). Scenarios are constructed by calculating the difference, or ratio, between the time means of the future and baseline periods, depending on the climate variable under consideration.

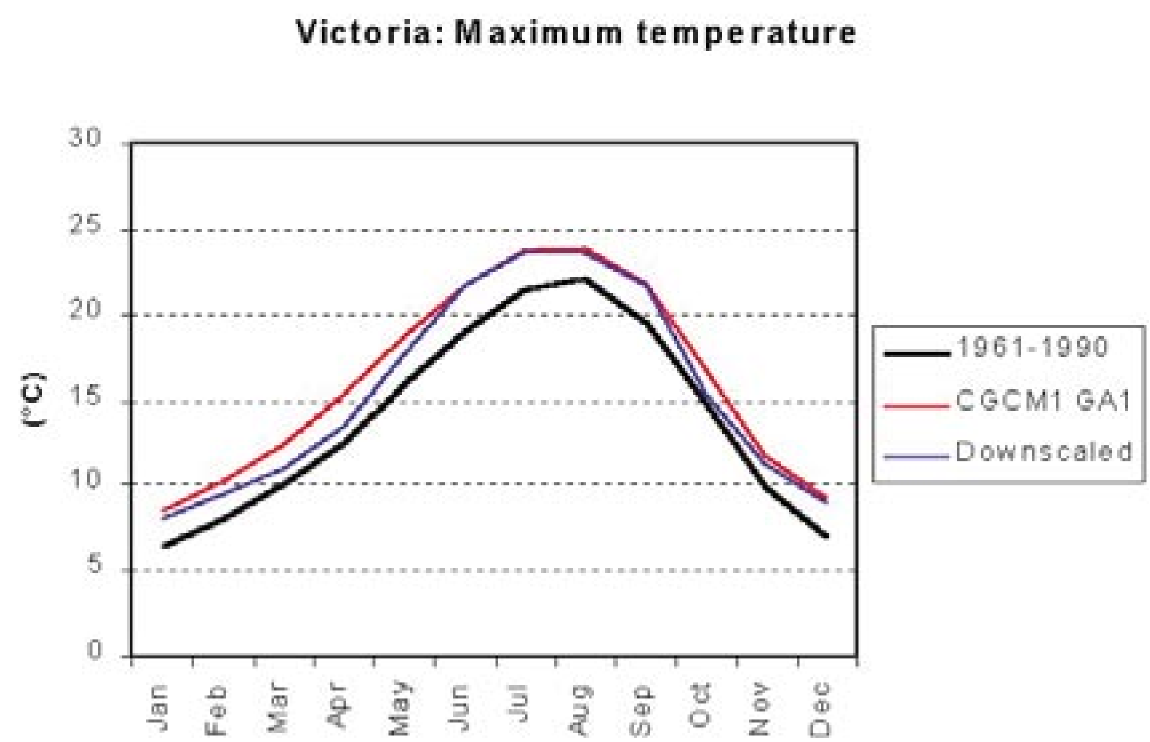



**Figure 3.3**

The effect of downscaling maximum temperature for Victoria, BC, for the 2050s using SDSM (Wilby et al., 2002). Illustrated are the 1961-1990 maximum temperature values (black line), maximum temperature values for the 2050s as a result of applying the CGCM1 GA1 climate change scenario (red line), and downscaled maximum temperature values for the 2050s calculated by driving the statistical downscaling model with large-scale climate information from the CGCM1 GA1 climate change experiment (blue line).

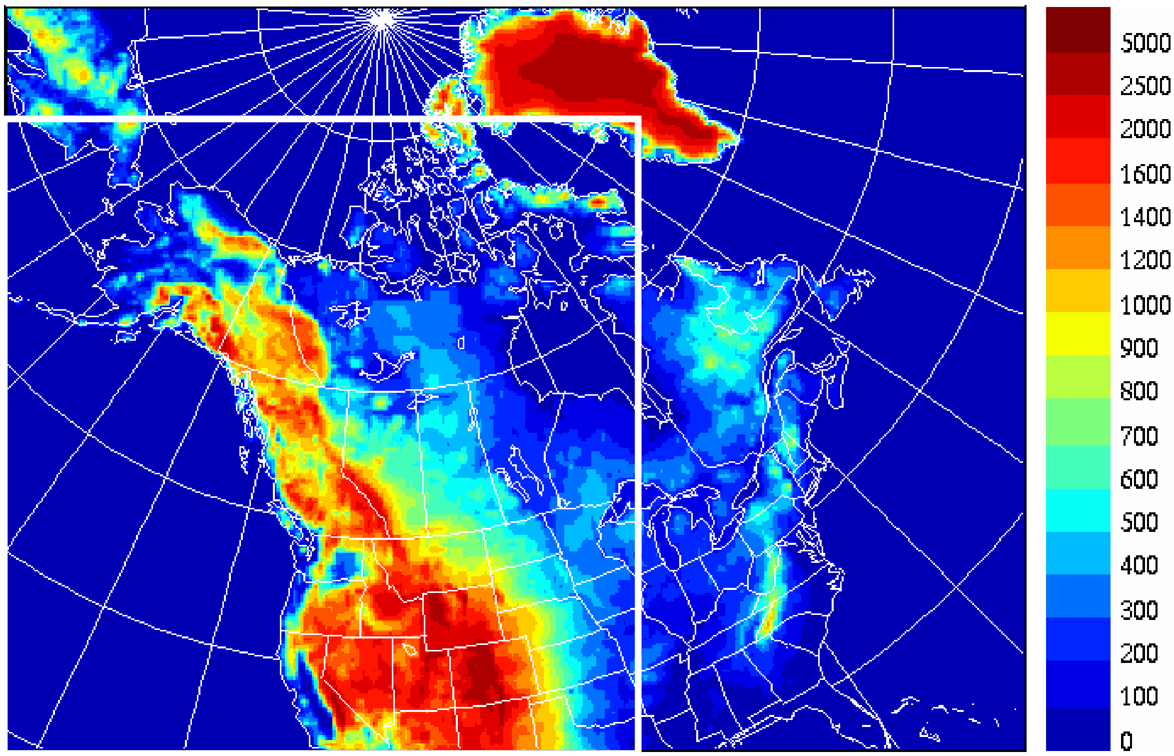



Figure 3.4

The topography field on the domain currently used to perform different climate simulations with the Canadian Regional Climate Model (CRCM). Simulations currently in production use Version 3.6.1 of the CRCM and include simulations of current climate (from January 1973 to December 1999 using NCEP reanalysis [NRA-1] and AMIP driving data for the atmosphere and ocean, respectively), and climate change experiments where the atmospheric and oceanic driving data are provided by CGCM2 (IS92a) for the period 1968-1994 and 2037-2063. The lower left area of the figure delimited by the white box is the domain previously used to perform climate change experiments with CRCM Version 3.5.1 (Laprise et al., 2003).

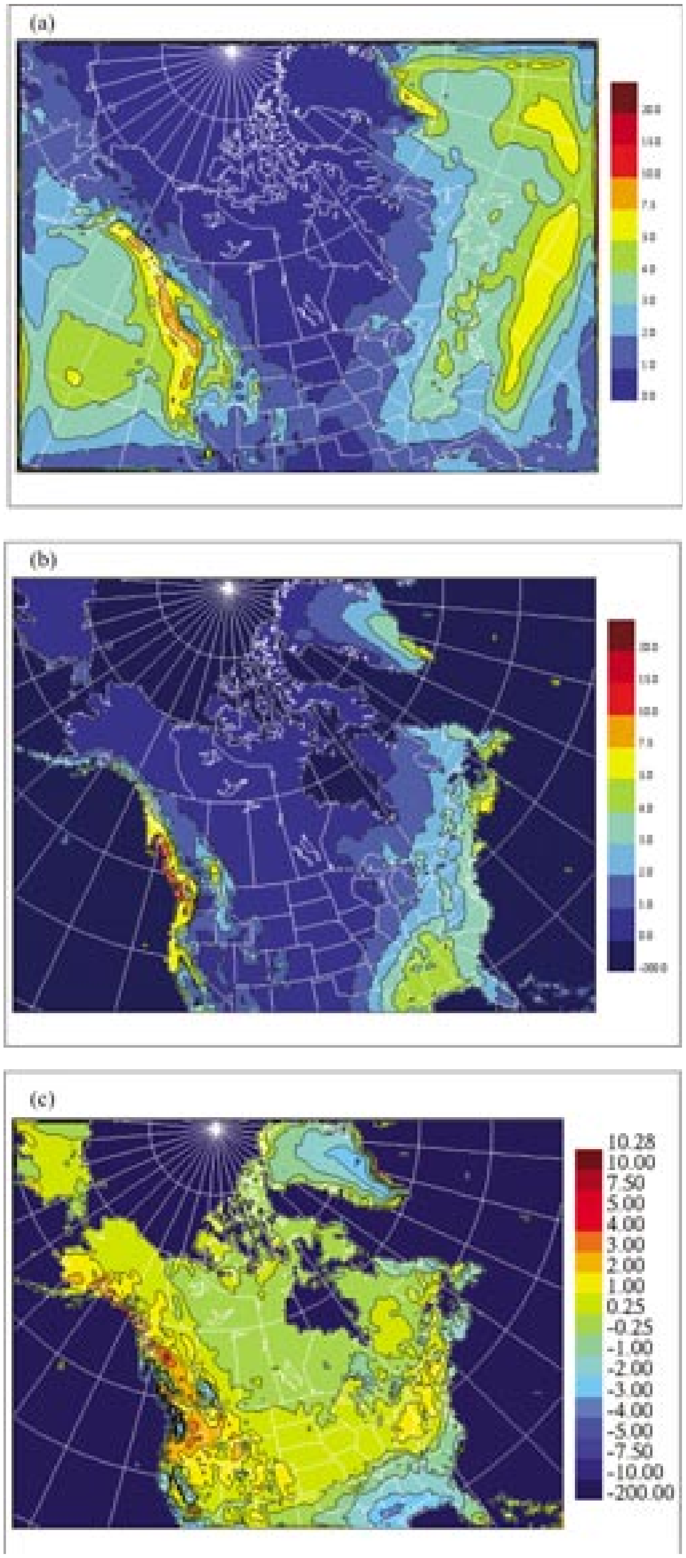
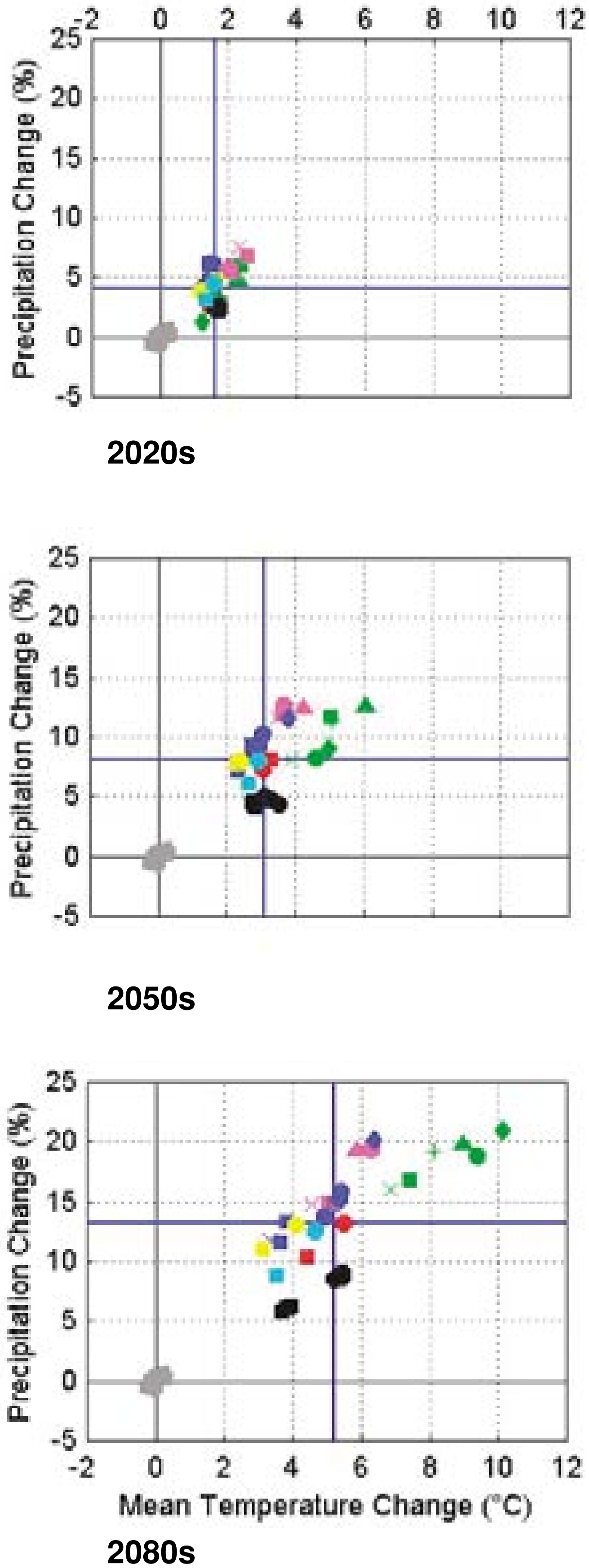


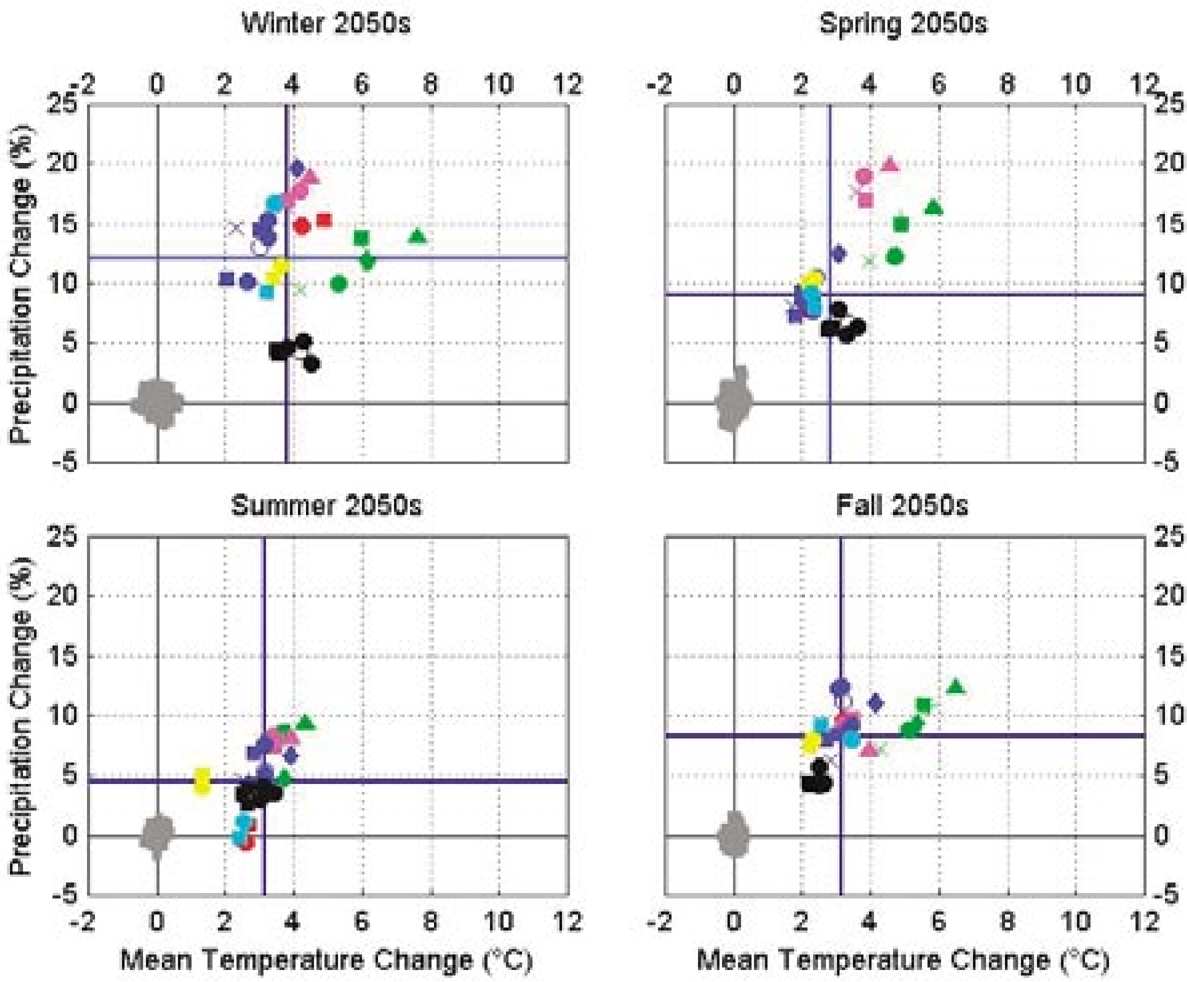

**Figure 3.5**

Results for the 5-year winter mean precipitation rate (mm/day) simulation for the 1975-1979 period. (a) Results from CRCM Version 3.6.1 driven by NCEP NRA-1 reanalysis data and AMIP ocean data. (b) Mean precipitation rate for the same period computed from the CRU (Climatic Research Unit, Norwich, UK) 2.02 monthly mean gridded time series at 0.5°×0.5° resolution (Mitchell et al., 2003). (c) The difference between the CRCM and CRU fields. Contours on (a) and (b) are 0, 1, 2, 3, 4, 5, 7.5, 10, 15 and 20 mm/day. The value -200 indicates where data are not available.



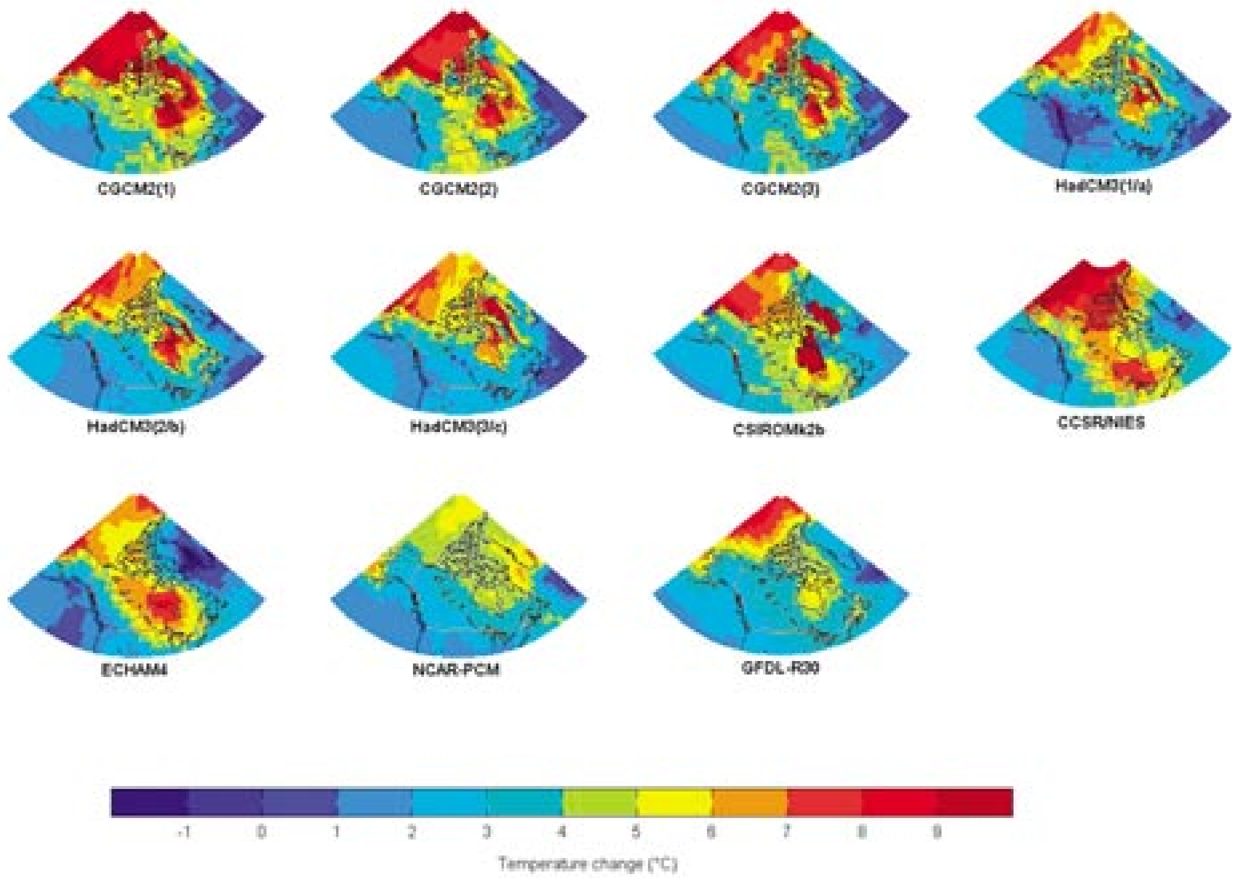

## Figure 4.1

Scatterplots indicating annual changes in mean temperature (°C) and precipitation (%) for the Canadian land area for the 2020s, 2050s and 2080s. Each symbol and colour represents a different GCM and SRES experiment: ◆ A1FI; + A1T; ▲ A1; ● A2; × B1; ■ B2; CGCM2 - black; CCSR/NIES - green; CSIROMk2 - pink; ECHAM4 - red; NCAR-PCM - yellow; HadCM3 - blue; GFDL-R30 - cyan. Closed symbols indicate individual experiments, whilst open symbols represent ensemble-means (i.e., the average of a number of individual experiments using identical SRES forcing). Blue lines indicate the median changes in mean temperature and precipitation and may be used to determine which scenarios are warmer, wetter, cooler or drier than other scenarios in the suite illustrated. Grey squares centred on the origin represent simulated-natural variability estimates of mean temperature and precipitation change, when compared to the 1000-year mean from the CGCM2 control experiment.




## Figure 4.2

As for Figure 4.1, but for seasonal changes for the 2050s only.




## Figure 4.3

Scenarios of winter mean temperature change (°C) for the 2050s (with respect to 1961-1990) as simulated by seven global climate models for the A2 emissions scenario. Three A2 experiments were undertaken with both CGCM2 and HadCM3.

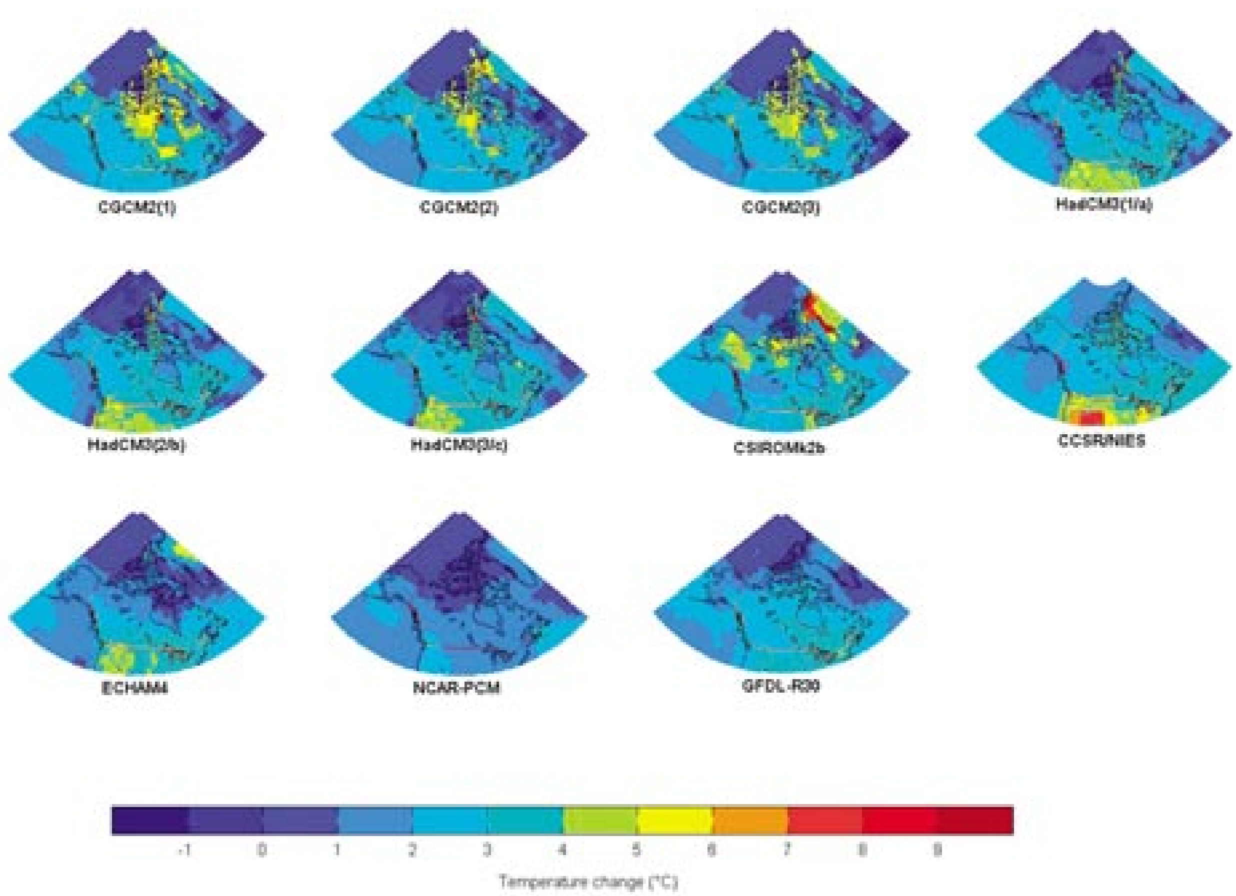
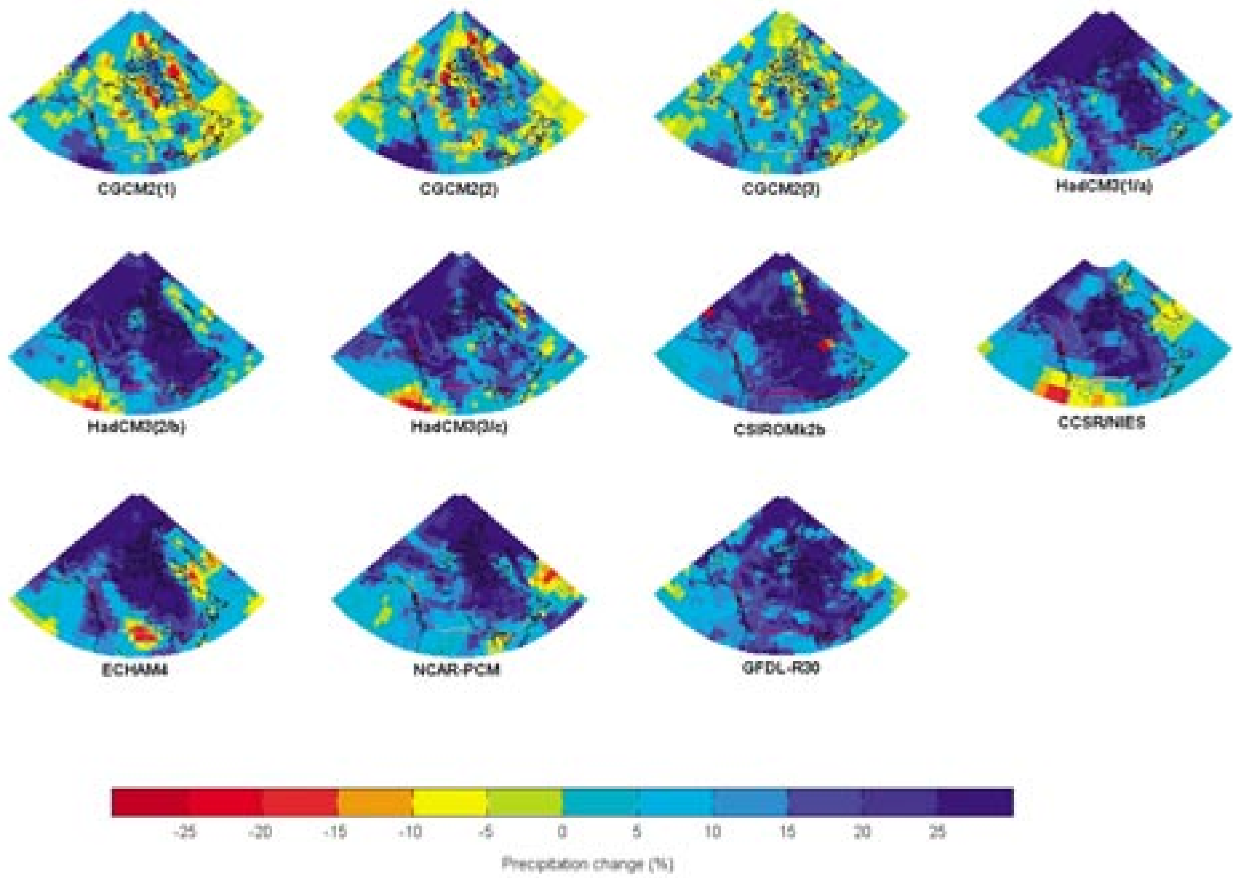


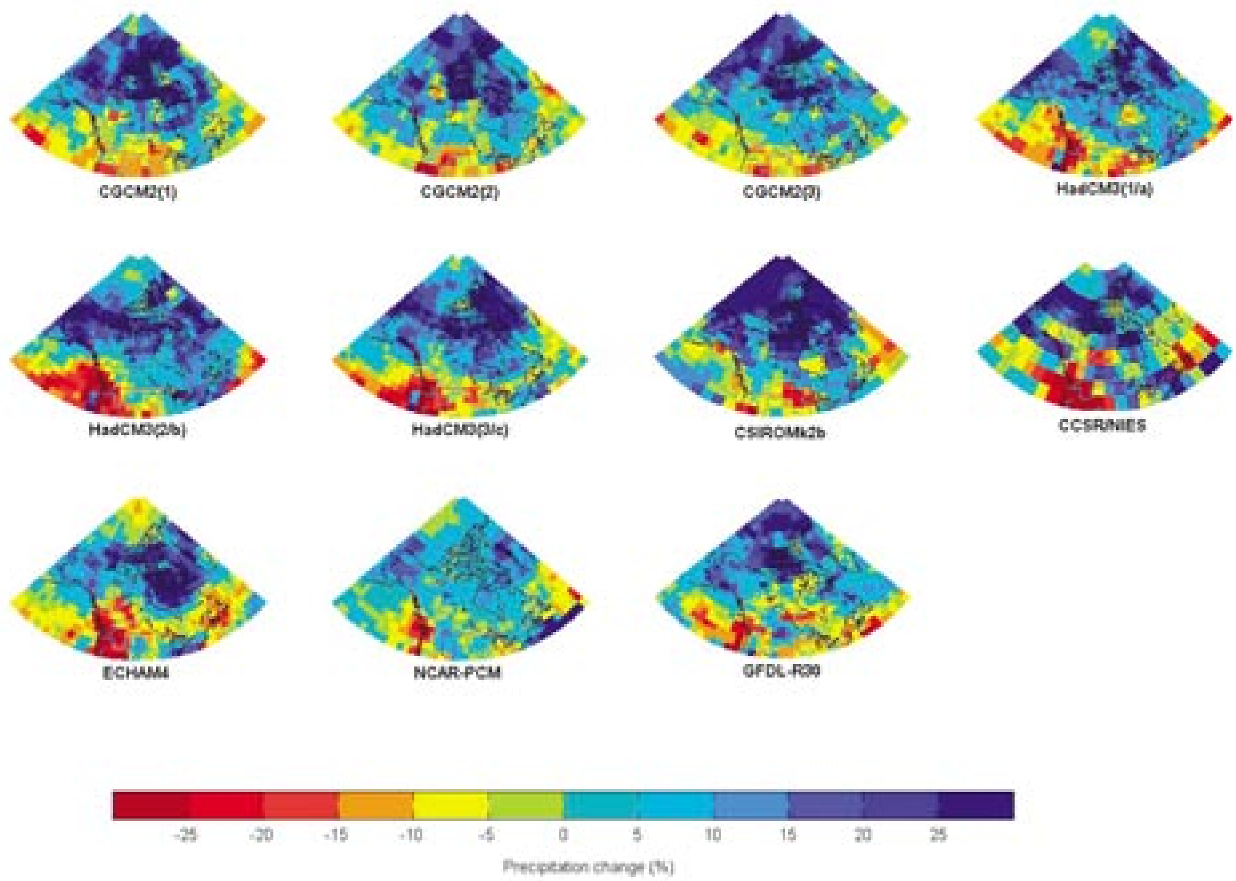

**Figure 4.4**

Scenarios of summer mean temperature change (°C) for the 2050s (with respect to 1961-1990) as simulated by seven global climate models for the A2 emissions scenario. Three A2 experiments were undertaken with both CGCM2 and HadCM3.



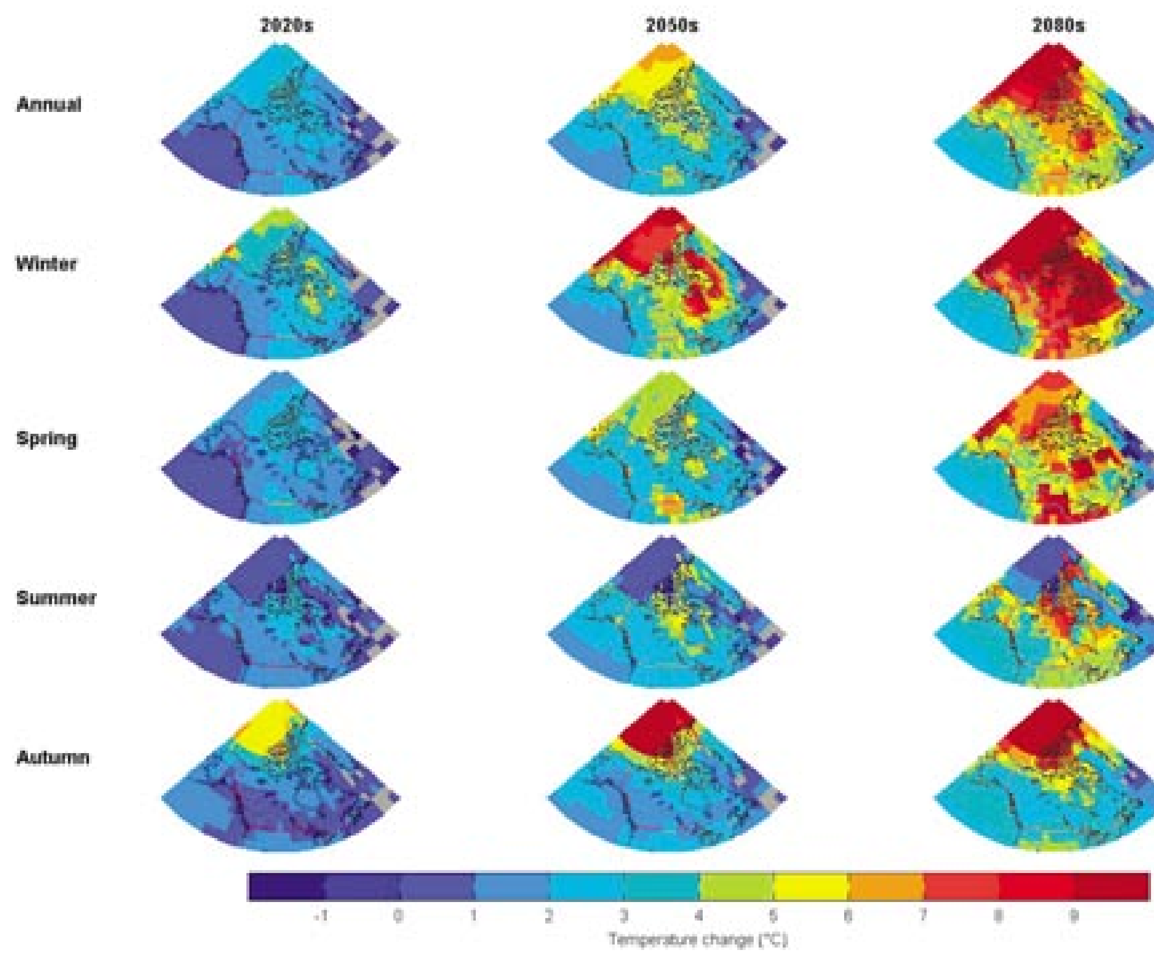

## Figure 4.5

Scenarios of winter precipitation change (%) for the 2050s (with respect to 1961-1990) as simulated by seven global climate models for the A2 emissions scenario. Three A2 experiments were undertaken with both CGCM2 and HadCM3.



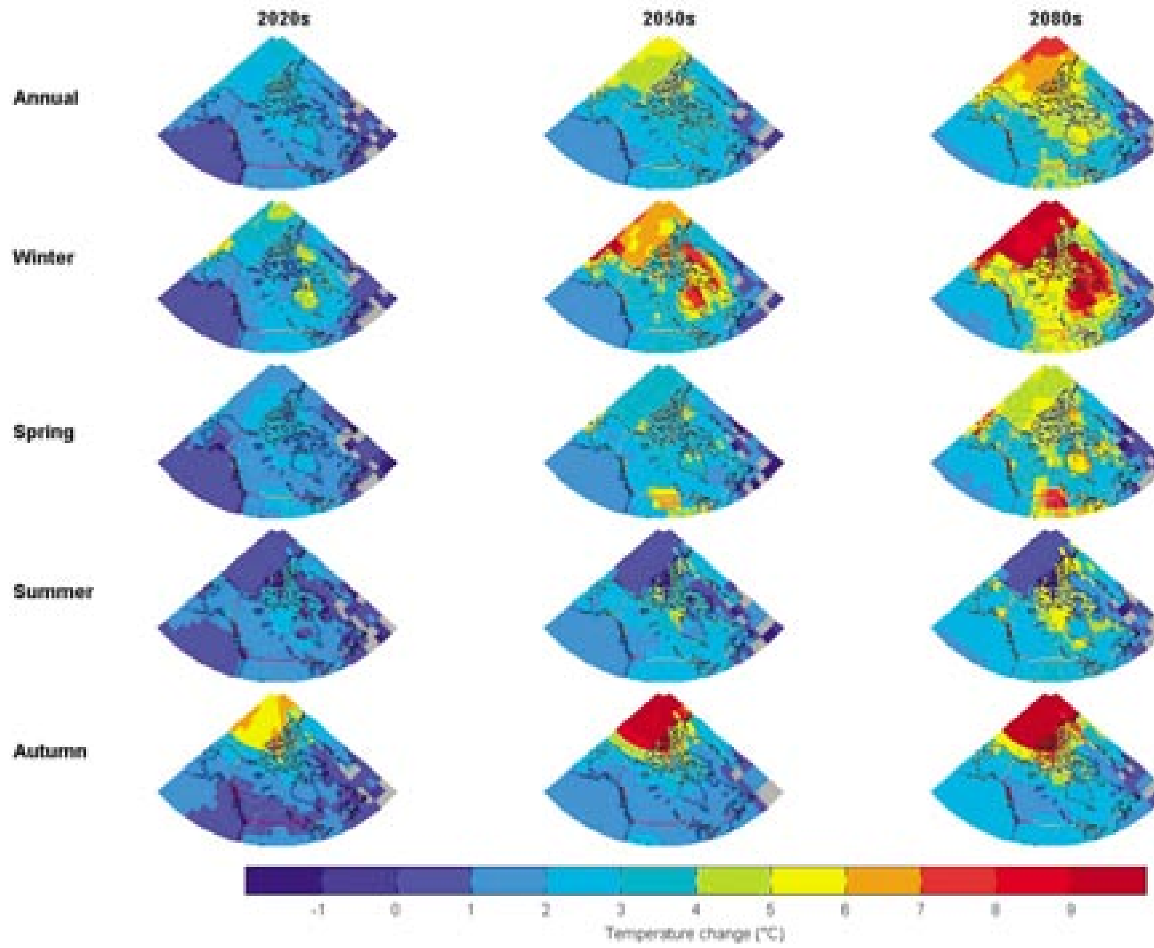

## Figure 4.6

Scenarios of summer precipitation change (%) for the 2050s (with respect to 1961-1990) as simulated by seven global climate models for the A2 emissions scenario. Three A2 experiments were undertaken with both CGCM2 and HadCM3.



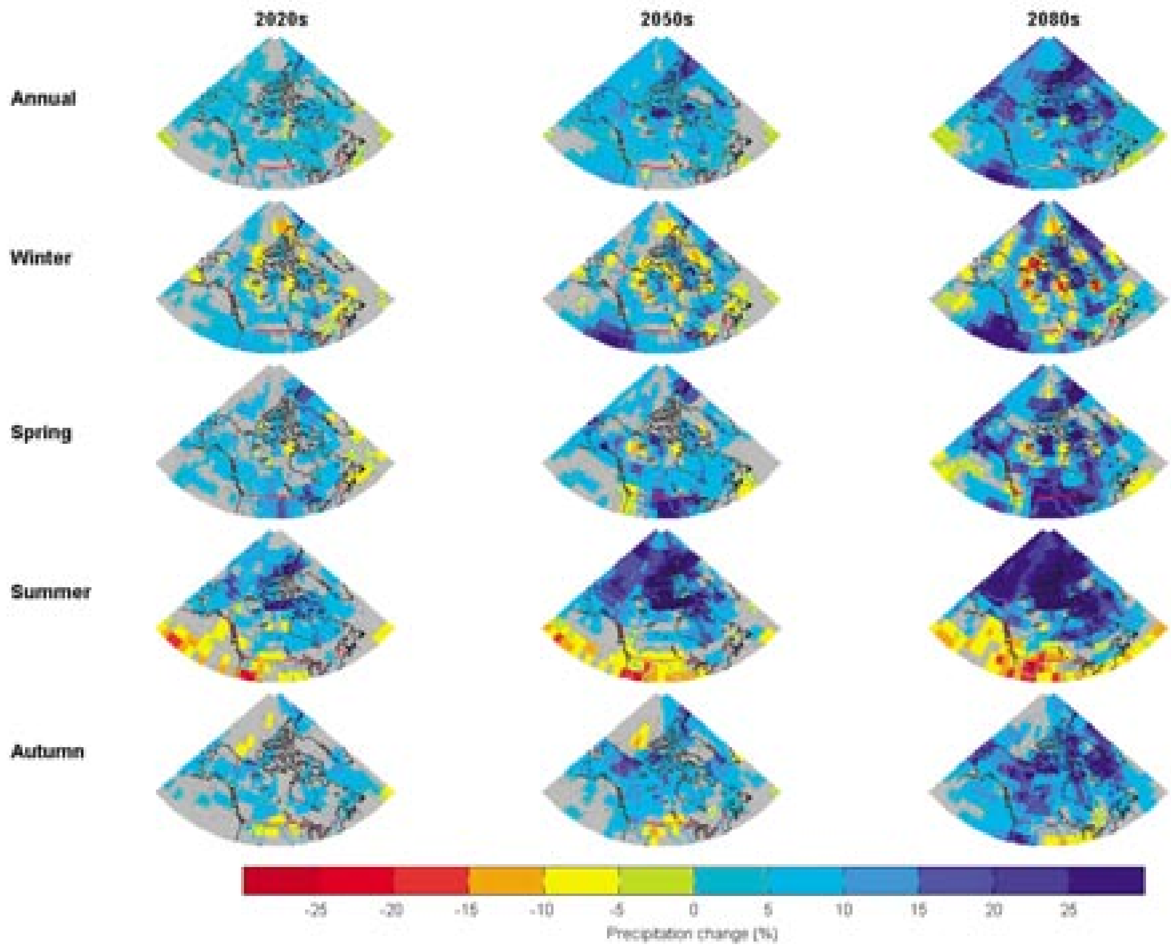

## Figure 4.7

CGCM2-derived A2 ensemble-mean scenarios of annual and seasonal mean temperature change (°C) for the 2020s, 2050s and 2080s (with respect to 1961-1990). Grey shaded areas indicate where the projected changes lie within a measure of natural climate variability, in this case one standard deviation of model-simulated 30-year average climates.



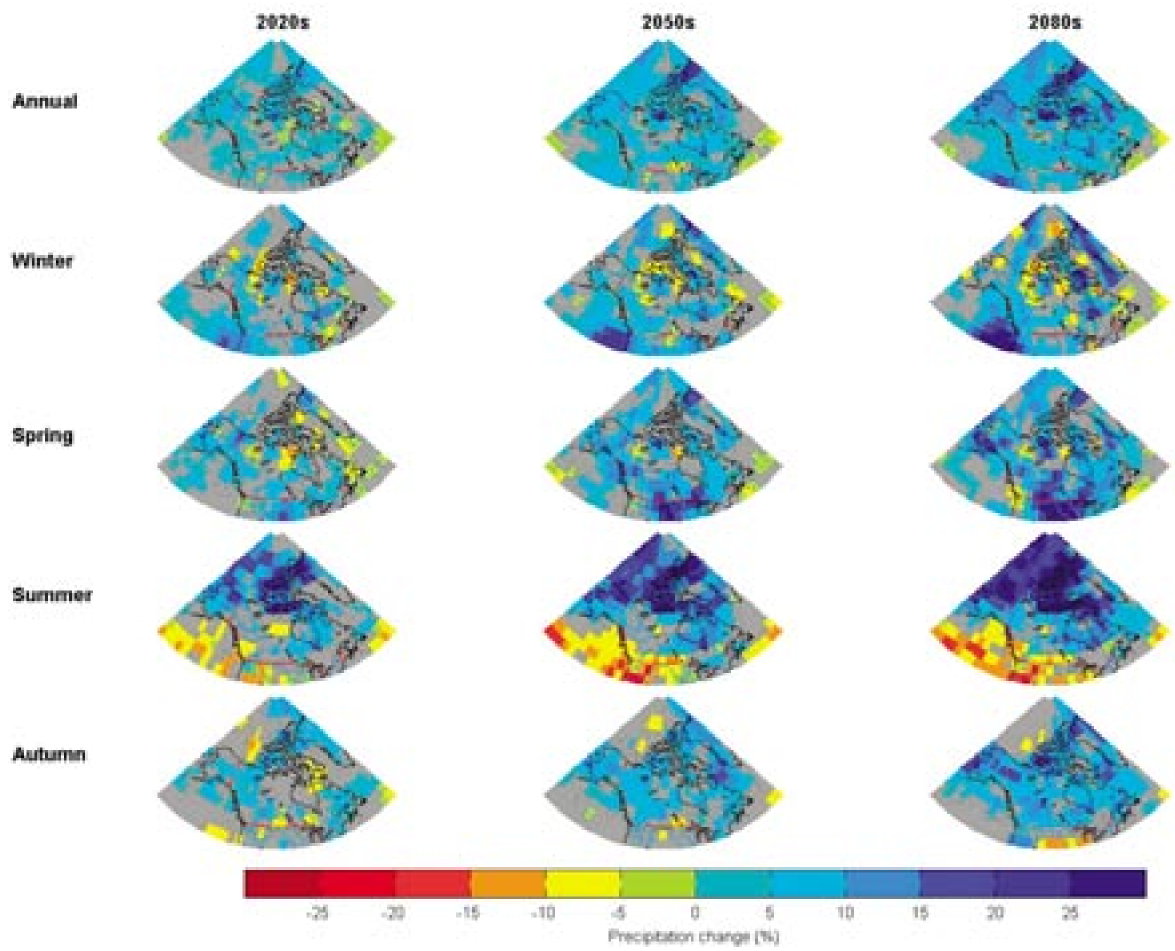

## Figure 4.8

As for Figure 4.7, but for B2 ensemble-mean scenarios.




## Figure 4.9

CGCM2-derived A2 ensemble-mean scenarios of annual and seasonal precipitation change (%) for the 2020s, 2050s and 2080s (with respect to 1961-1990). Grey shaded areas indicate where the projected changes lie within a measure of natural climate variability, in this case one standard deviation of model-simulated 30-year average climates.




## Figure 4.10

CGCM2-derived B2 ensemble-mean scenarios of annual and seasonal precipitation change (%) for the 2020s, 2050s and 2080s (with respect to 1961-1990). Grey shaded areas indicate where the projected changes lie within a measure of natural climate variability, in this case one standard deviation of model-simulated 30-year average climates.

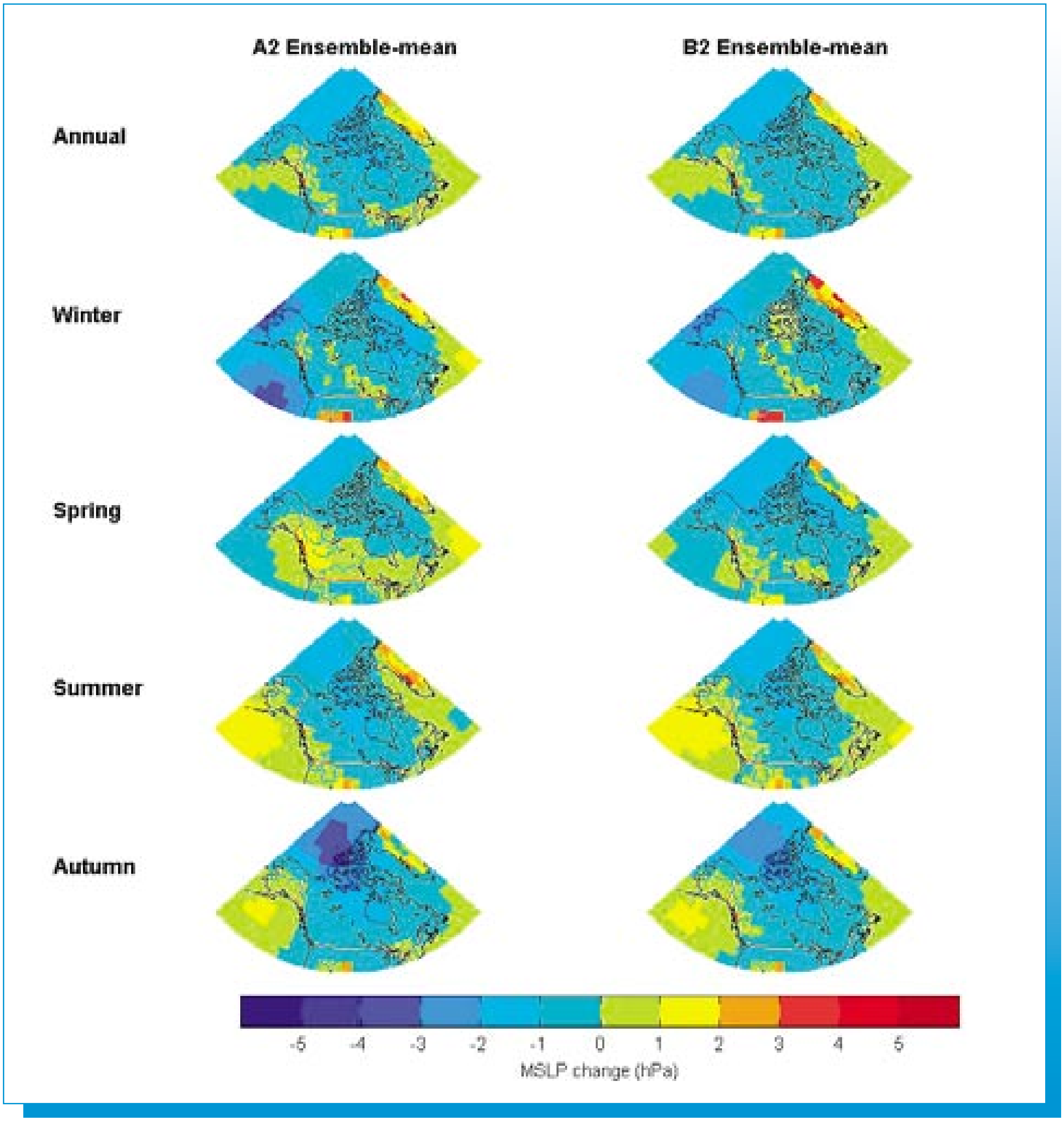



**Figure 4.11**

Annual and seasonal changes in mean sea level pressure (hPa) for the CGCM2-derived A2 and B2 ensemble-mean scenarios for the 2050s (with respect to 1961-1990).

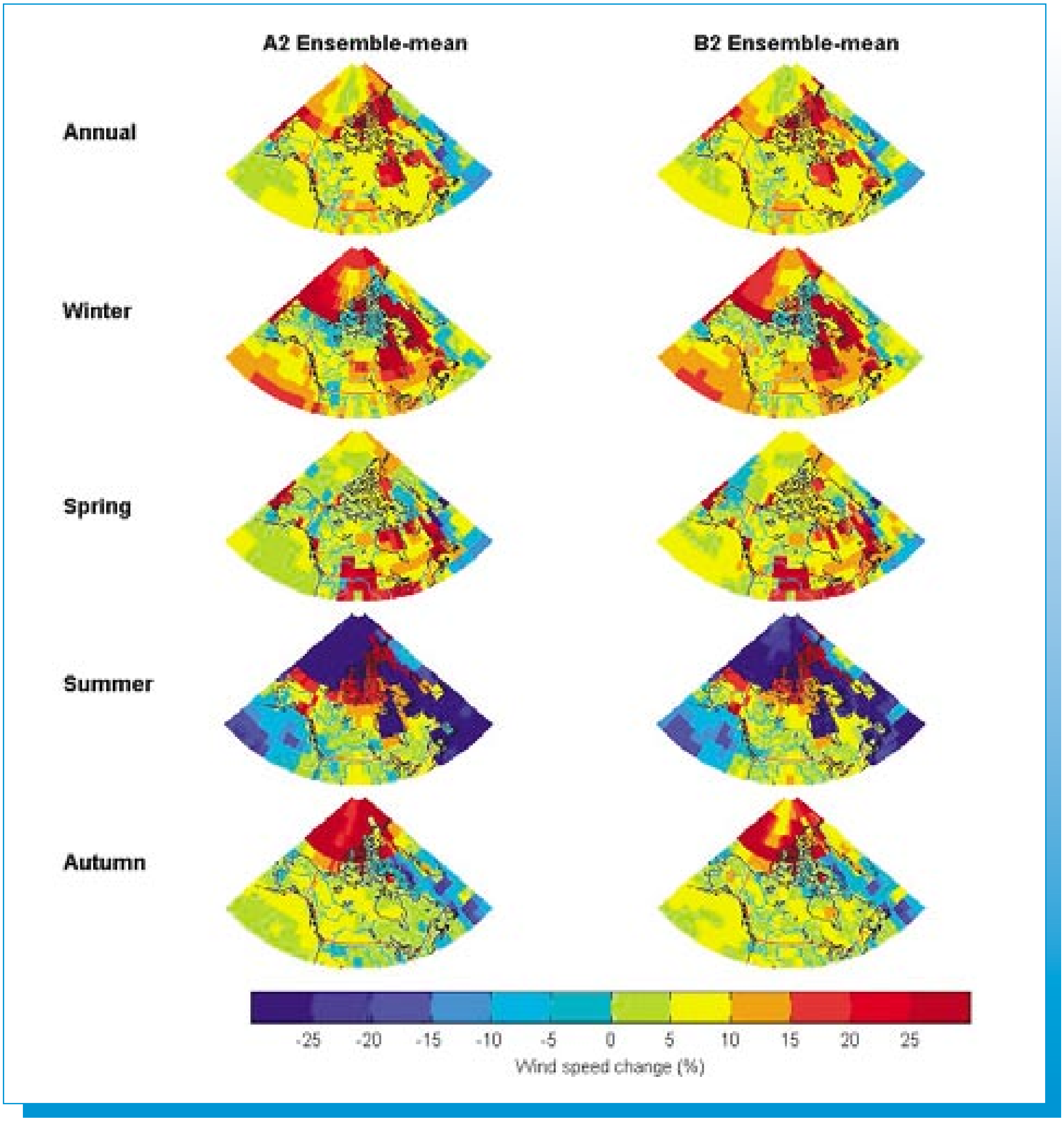



**Figure 4.12**

Annual and seasonal changes in wind speed (%) for the CGCM2-derived A2 and B2 ensemble-mean scenarios for the 2050s (with respect to 1961-1990).

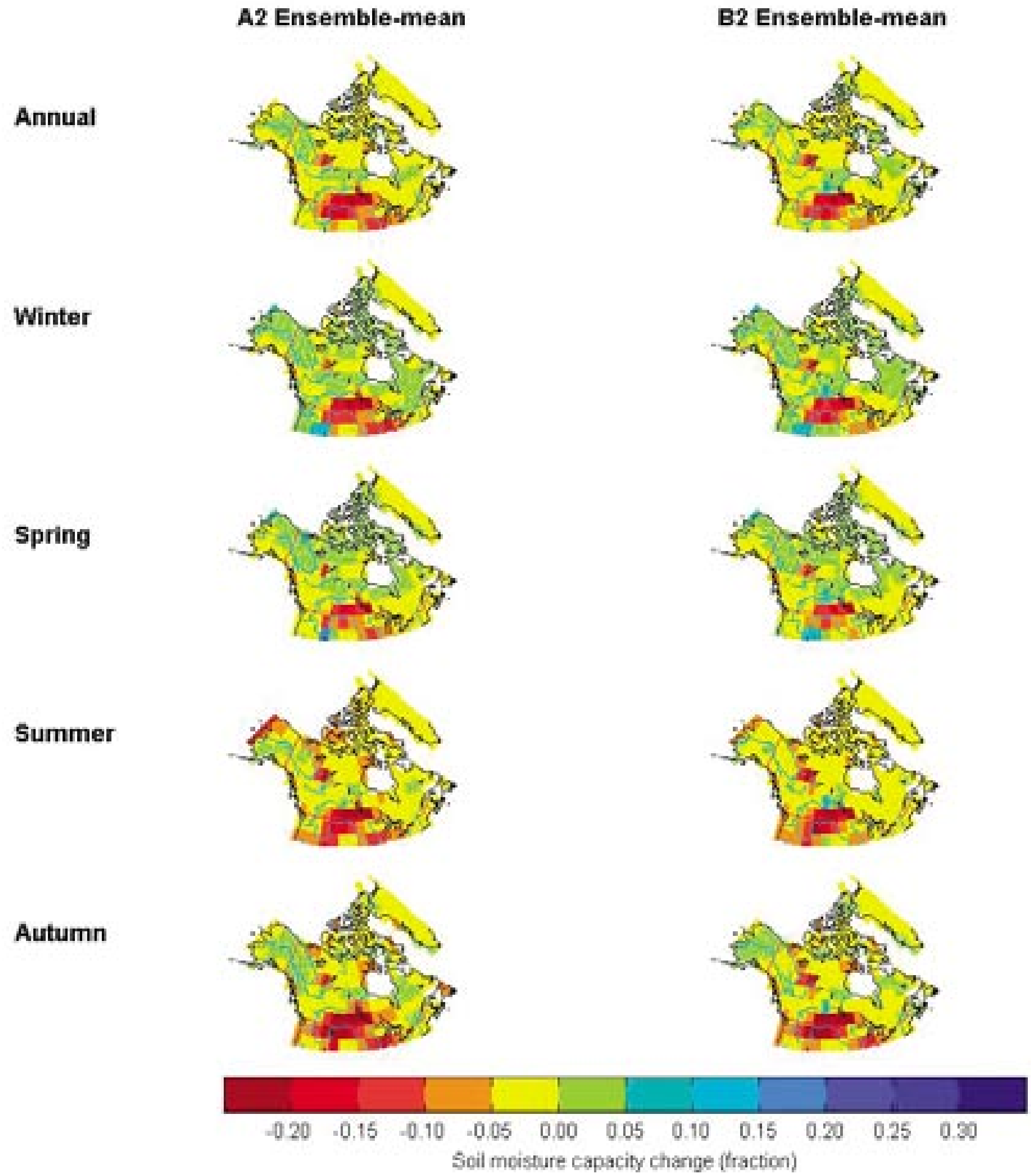



**Figure 4.13**

Annual and seasonal changes in soil moisture capacity (fraction) for the CGCM2-derived A2 and B2 ensemble-mean scenarios for the 2050s (with respect to 1961-1990).

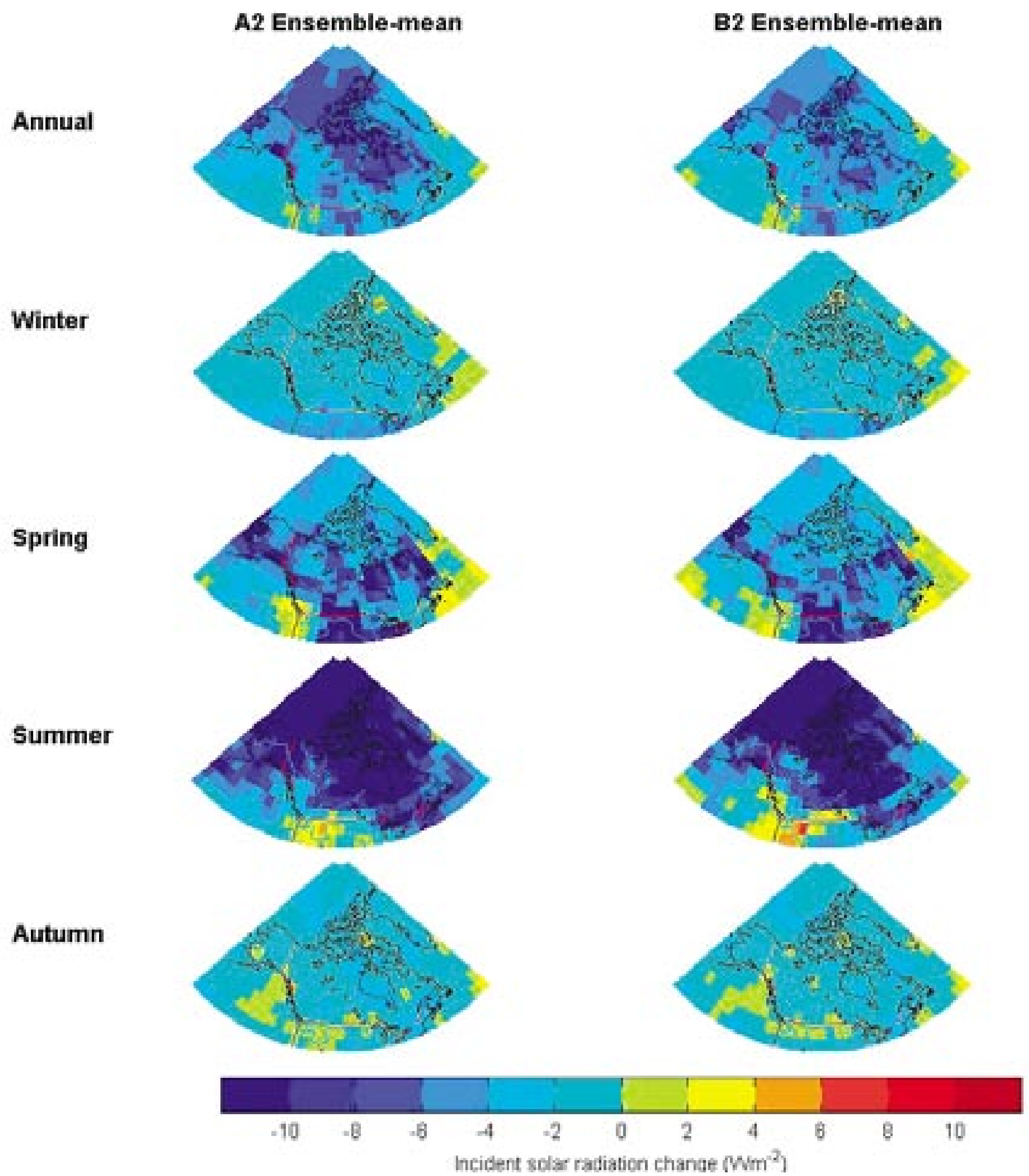



Figure 4.14

Annual and seasonal changes in incident solar radiation ($Wm^{-2}$) for the CGCM2-derived A2 and B2 ensemble-mean scenarios for the 2050s (with respect to 1961-1990).

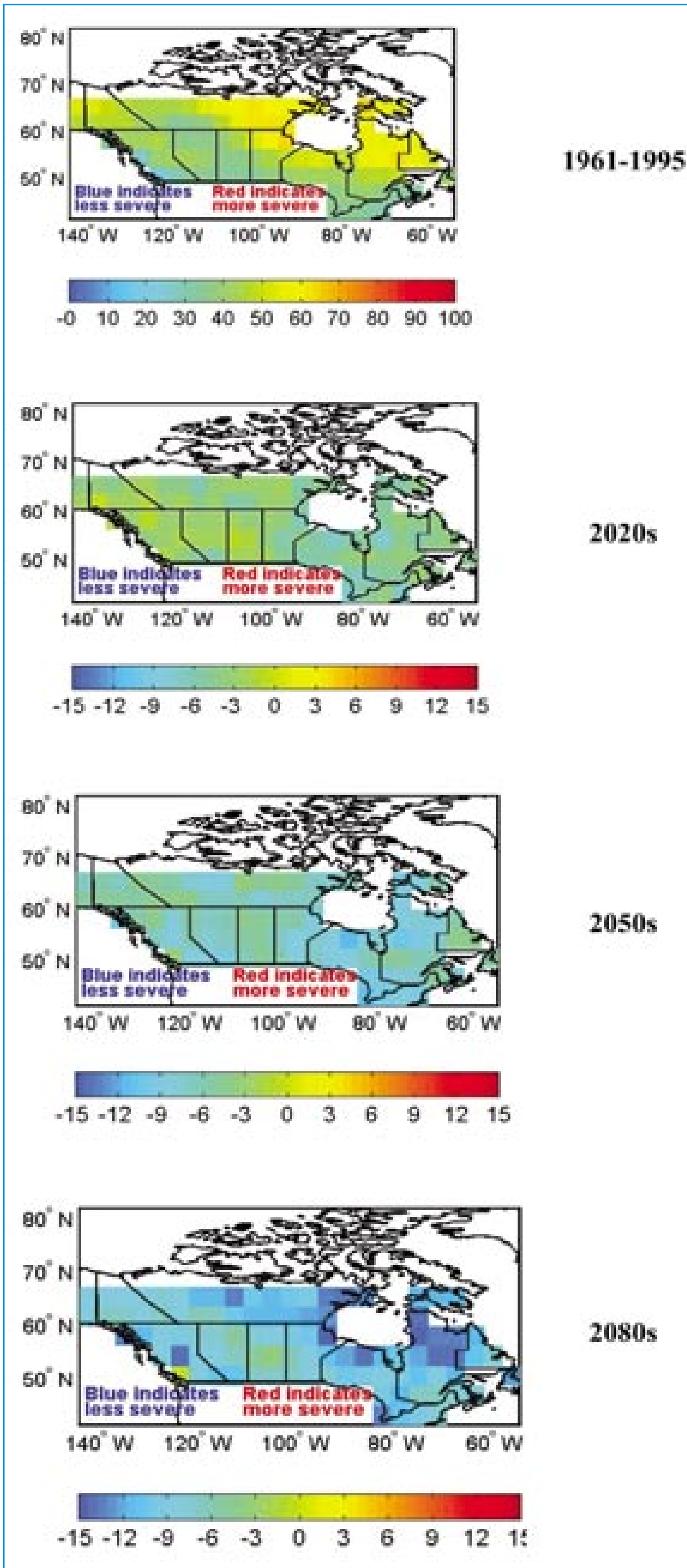



**Figure 4.15**

The Climate Severity Index across Canada (on a scale of 0 to 100) for 1961-1995 and projected changes in the index according to the CGCM1 IS92a scenario for the 2020s, 2050s and 2080s.

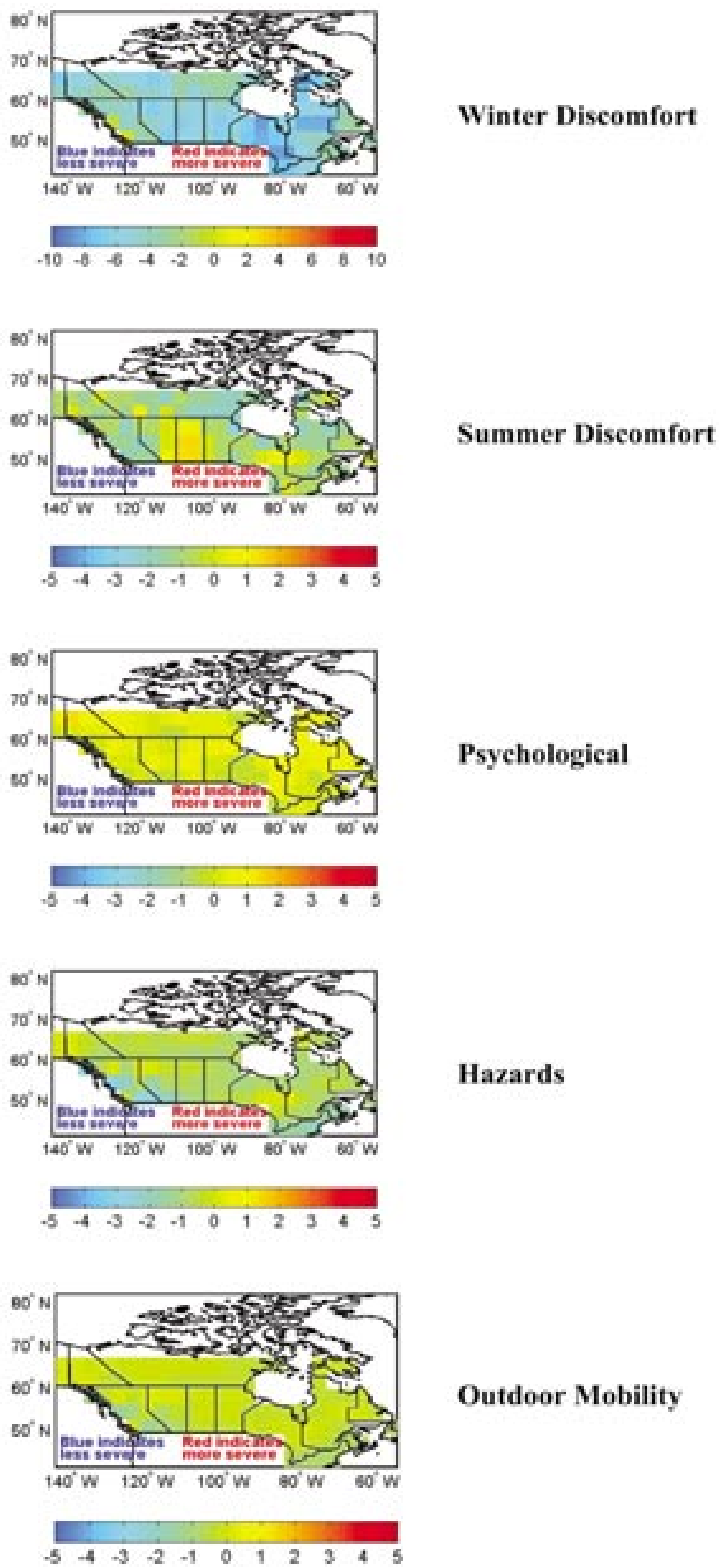
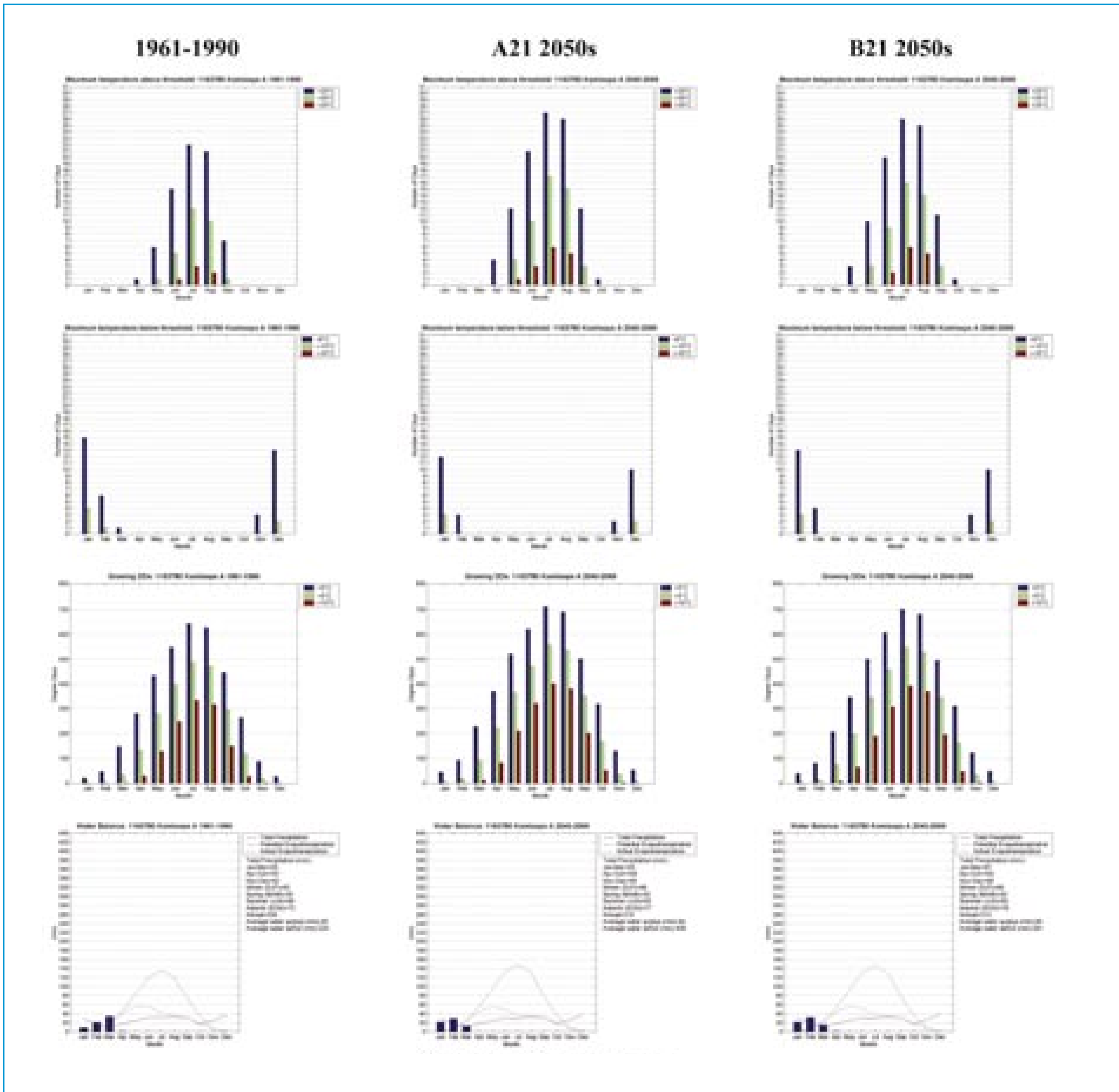



**Figure 4.16**

Changes in the five components of the Climate Severity Index from 1961-1995 to the 2050s.



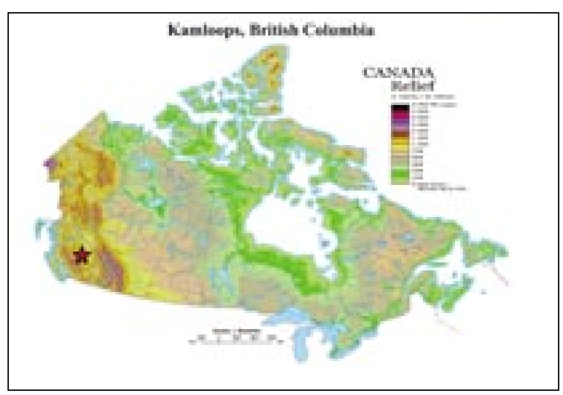
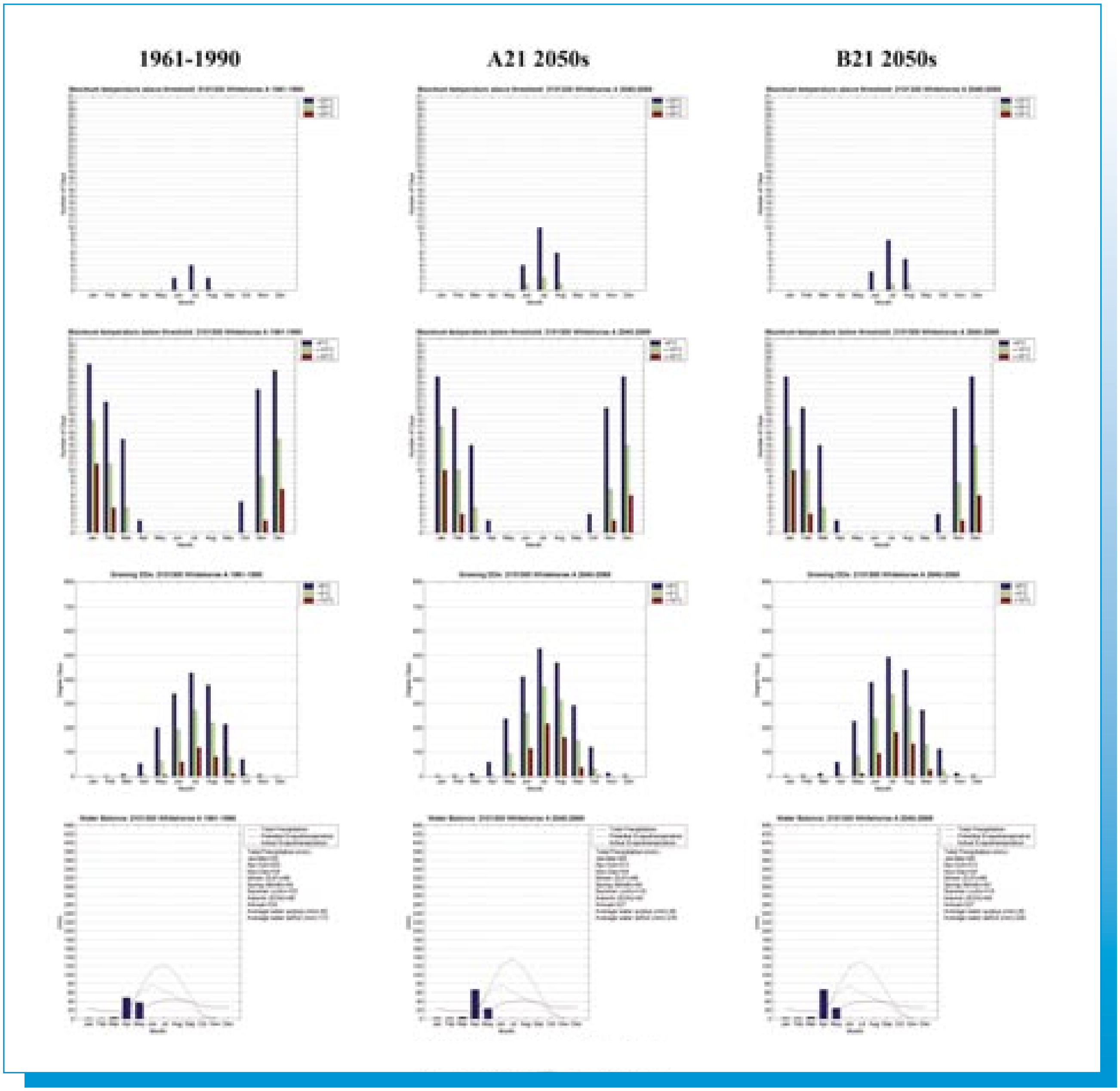
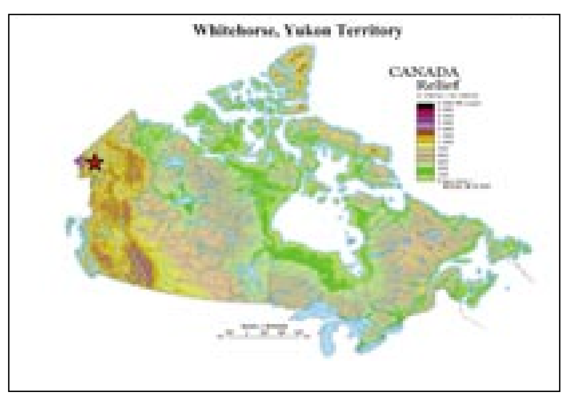




**Figure 4.17**

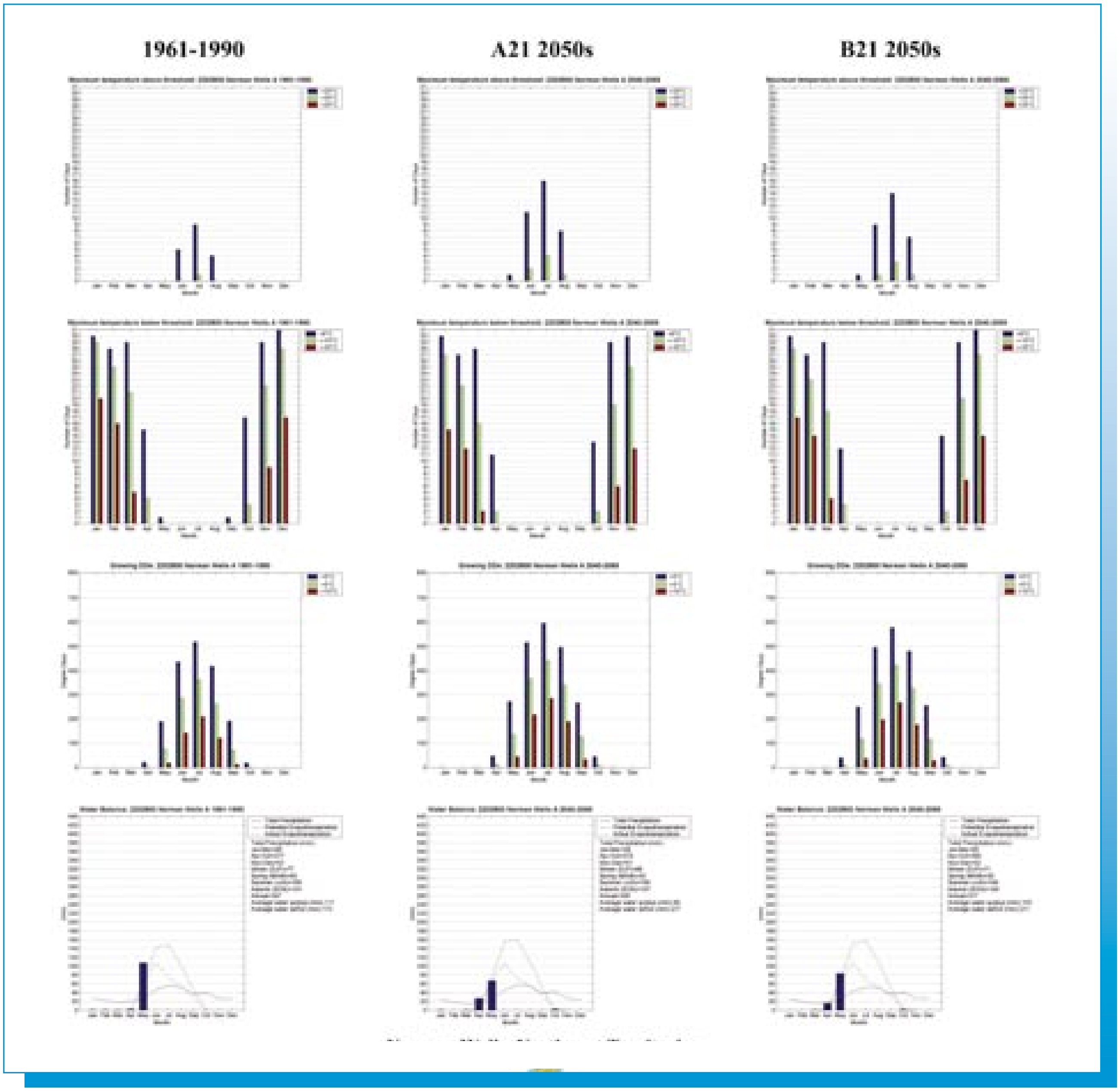
Components of the bioclimate profiles for 1961-1990 and for the CGCM2-derived A21 and B21 scenarios for the 2050s for Kamloops, BC. Components include: number of days with maximum temperatures above and below specific threshold temperatures, growing degree days above threshold temperatures of 0, 5 and 10°C, and monthly water balance (blue bars indicate water surplus). The location of the station is given in the map below the graphics.




## Figure 4.18

As for Figure 4.17, but for Whitehorse, YT.



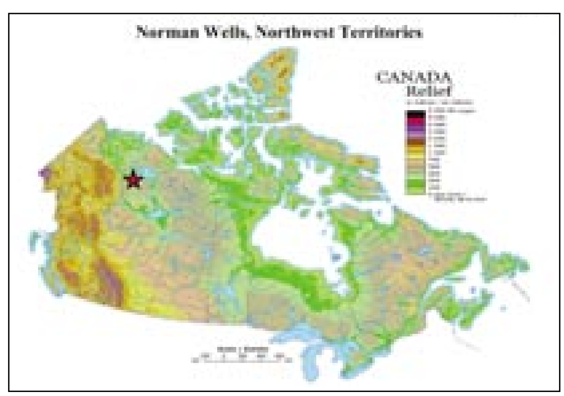




**Figure 4.19**

As for Figure 4.17, but for Norman Wells, NWT.

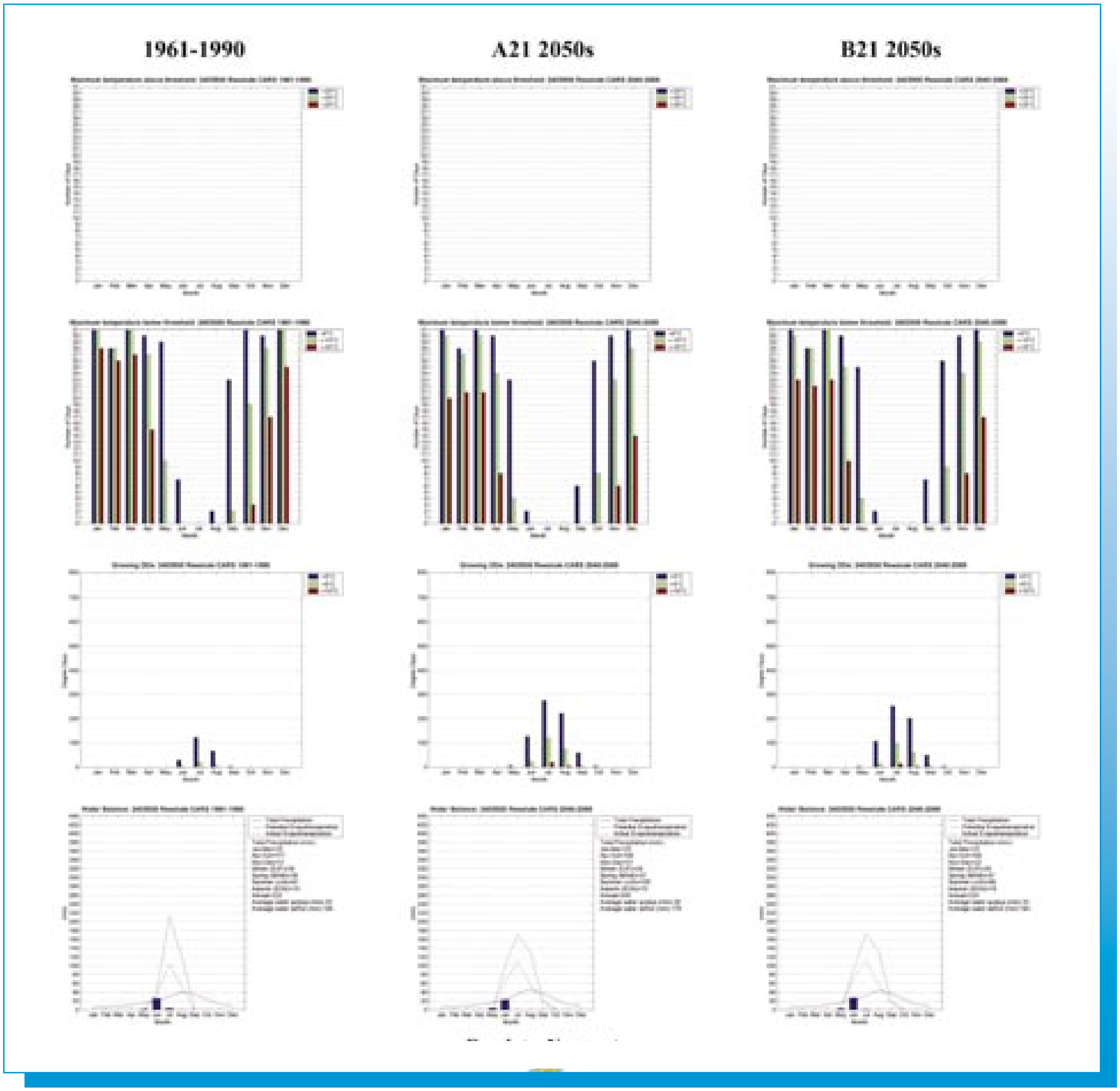
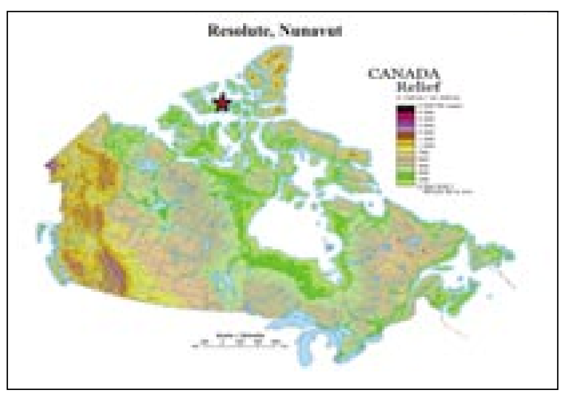
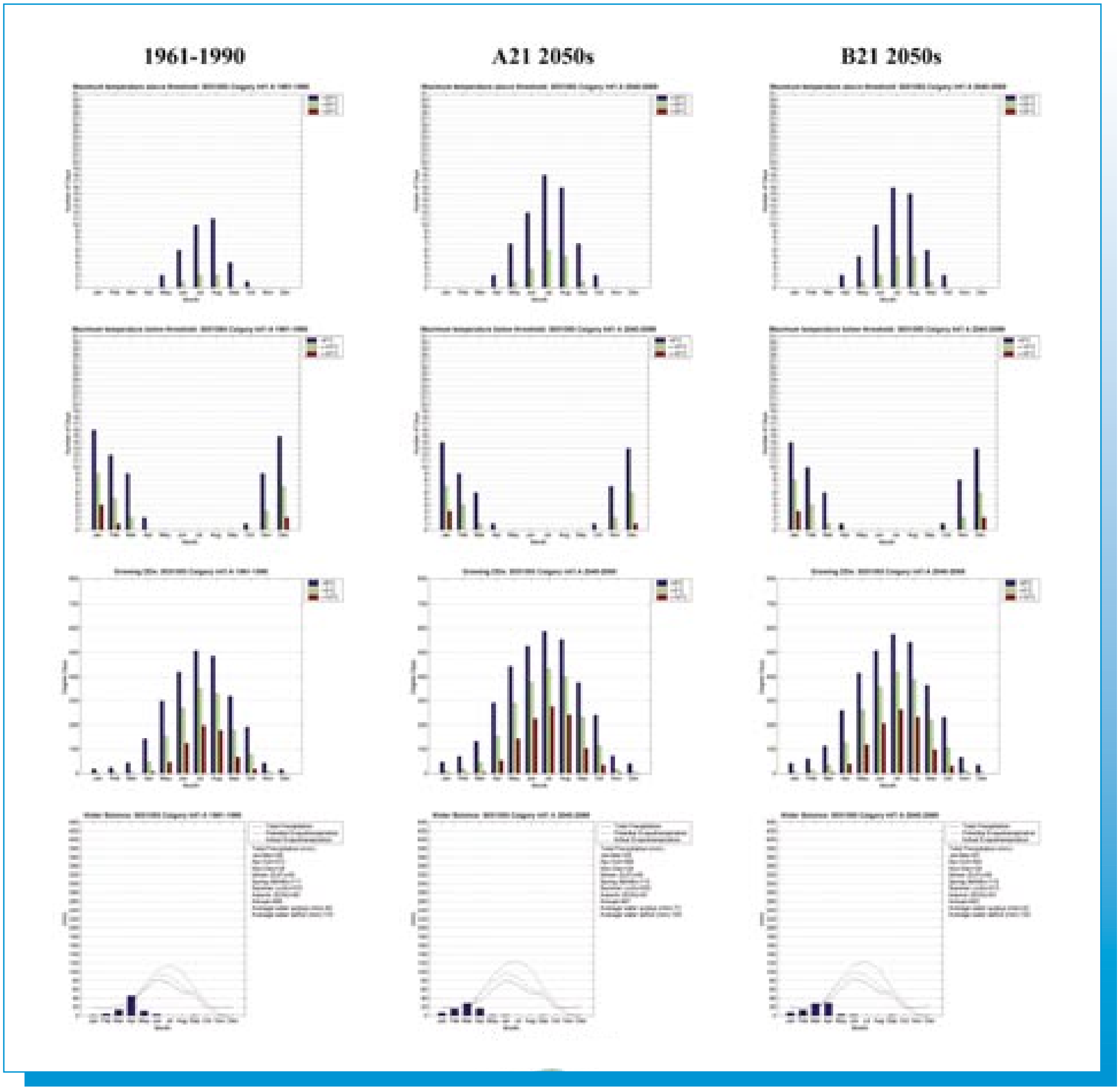



**Figure 4.20**

As for Figure 4.17, but for Resolute, NU.





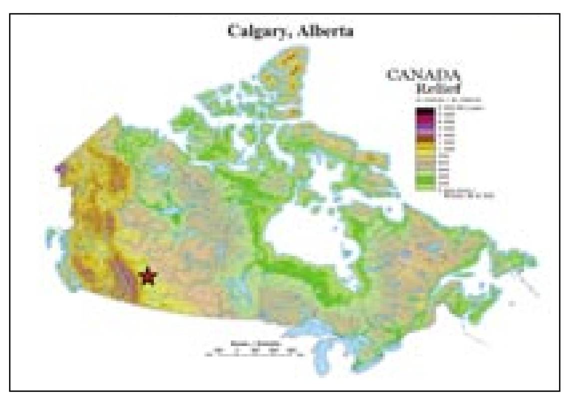
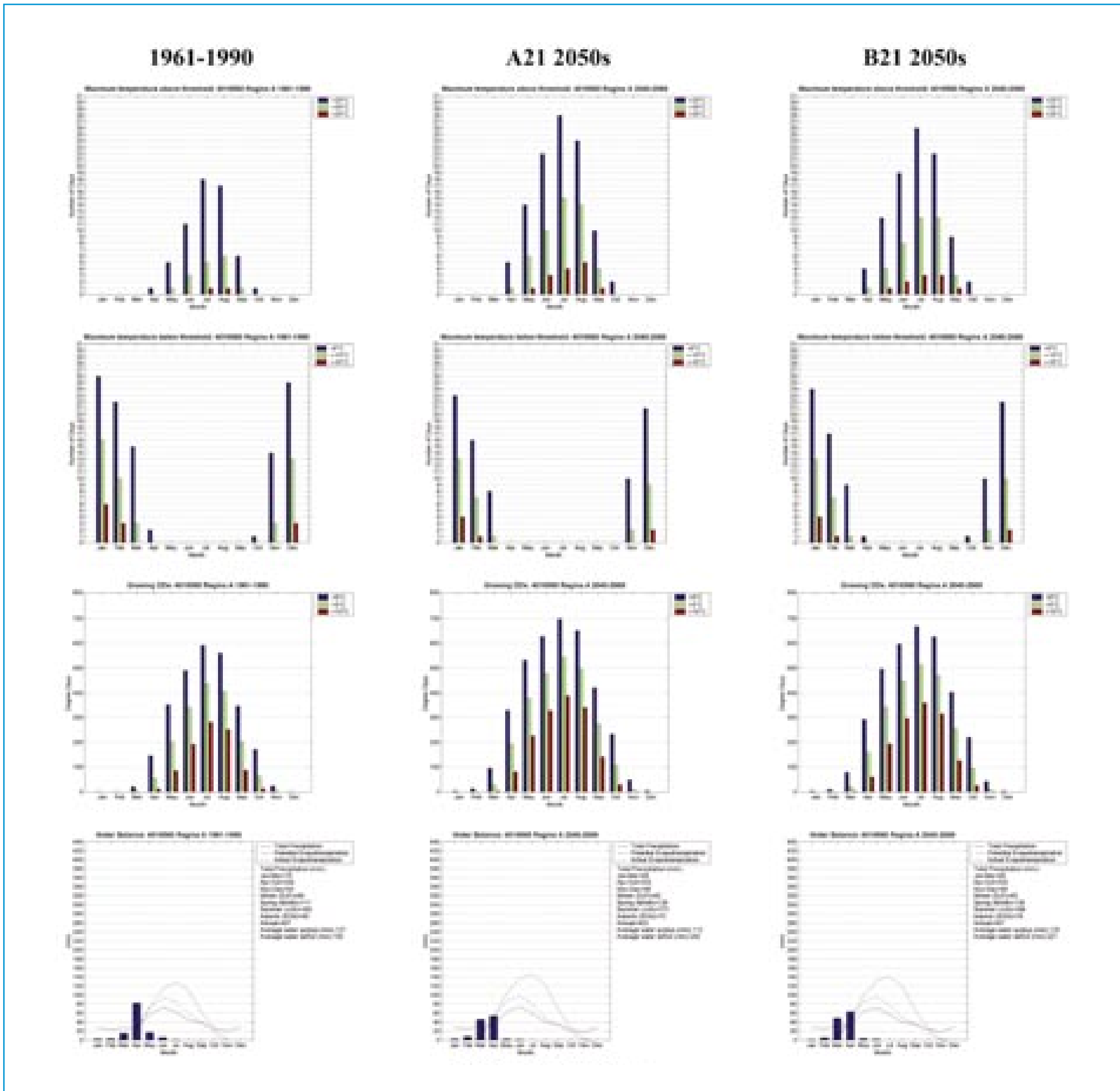




**Figure 4.21**

As for Figure 4.17, but for Calgary, AB.




# Figure 4.22

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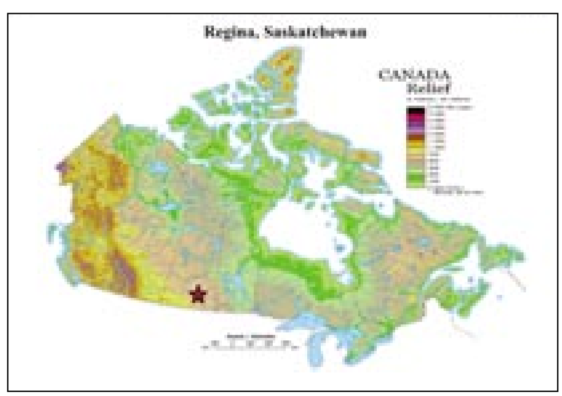
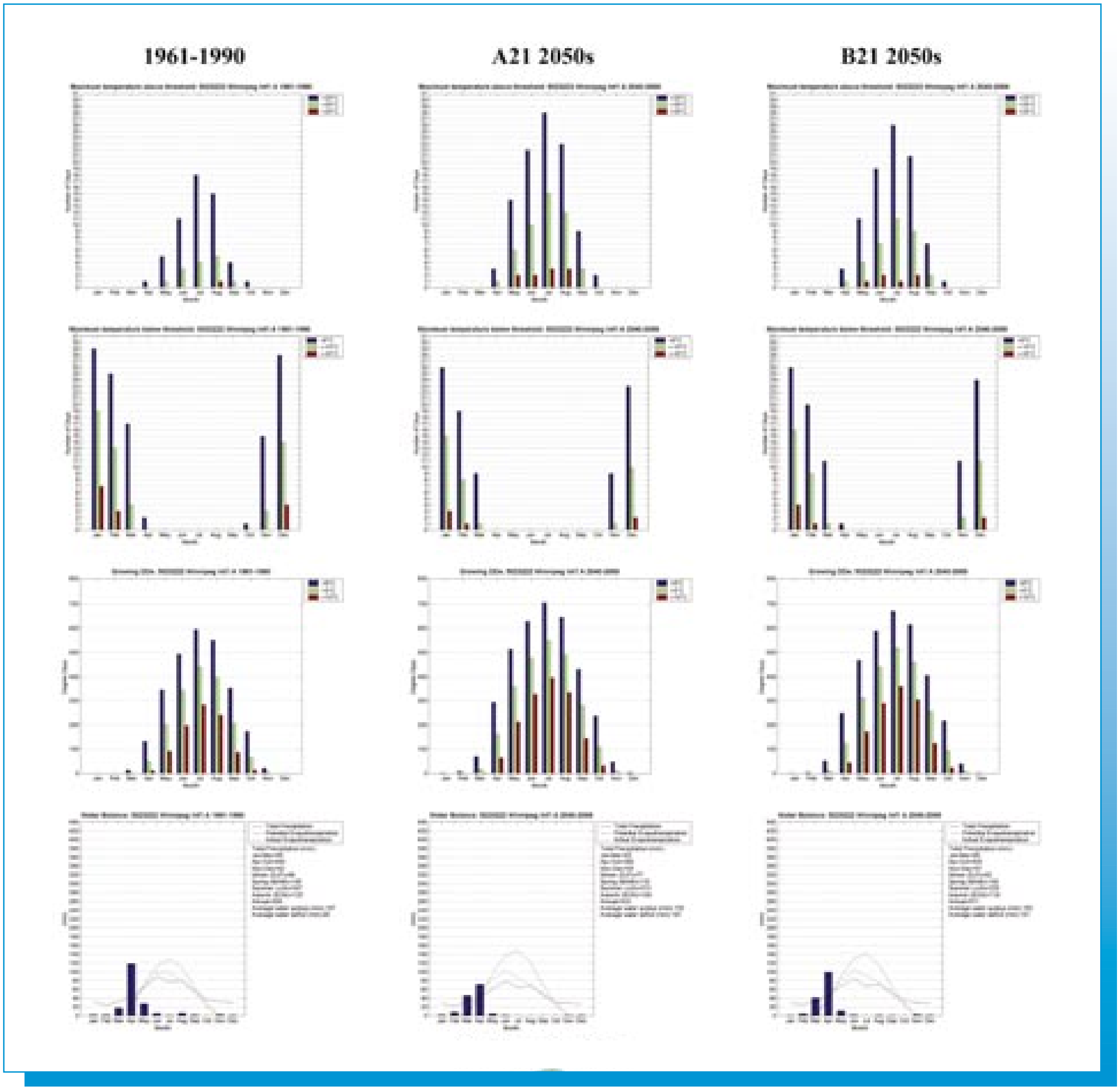




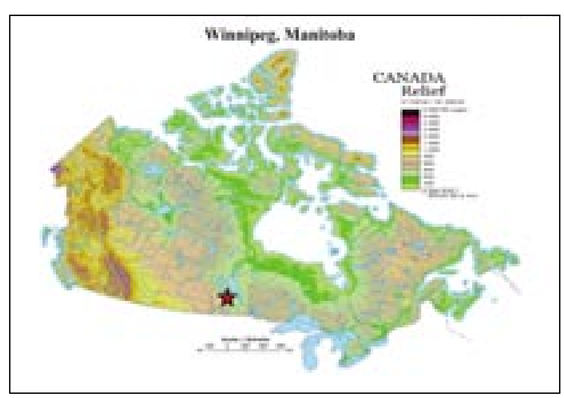
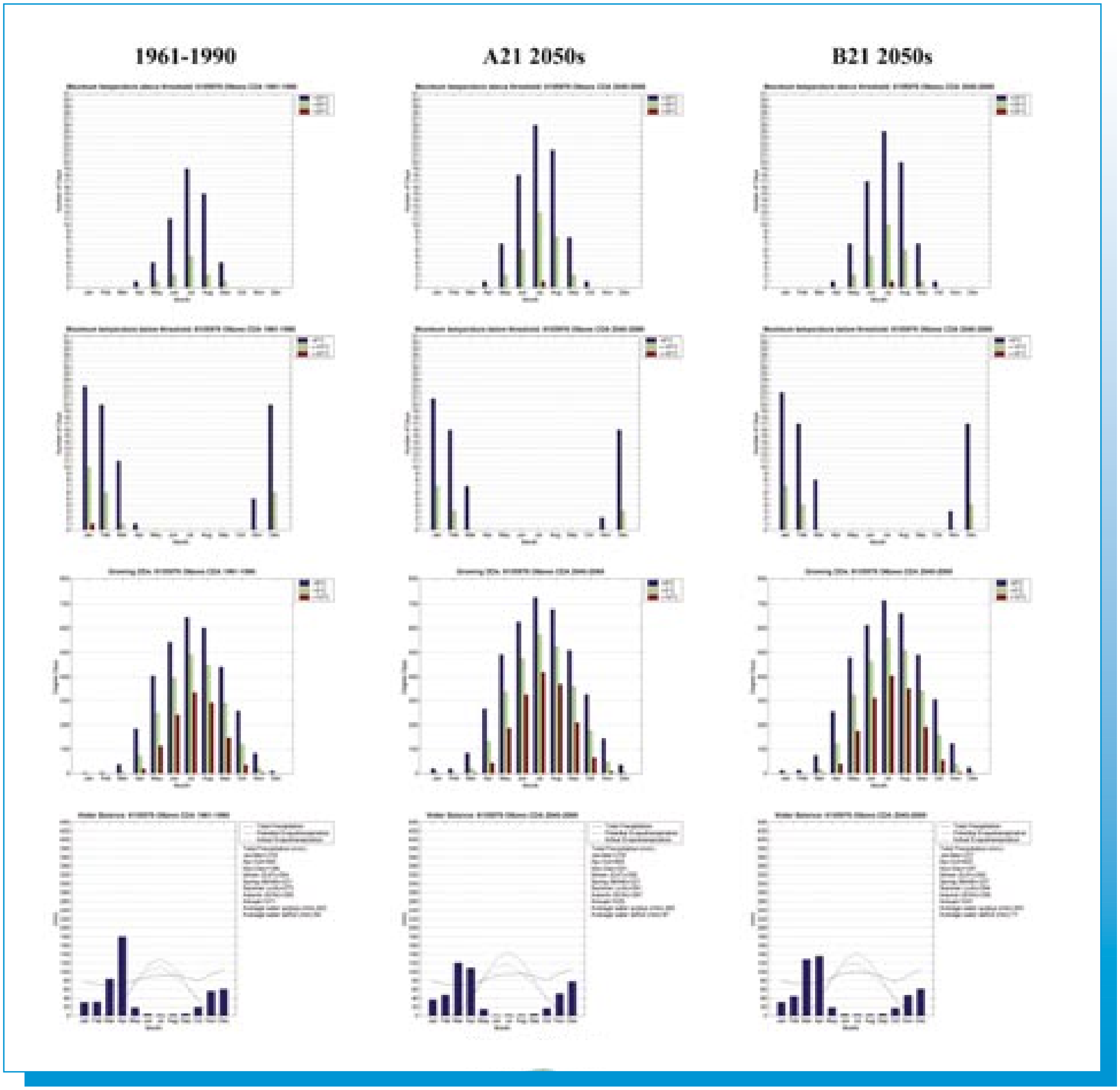




**Figure 4.23**

As for Figure 4.17, but for Winnipeg, MB.




## Figure 4.24

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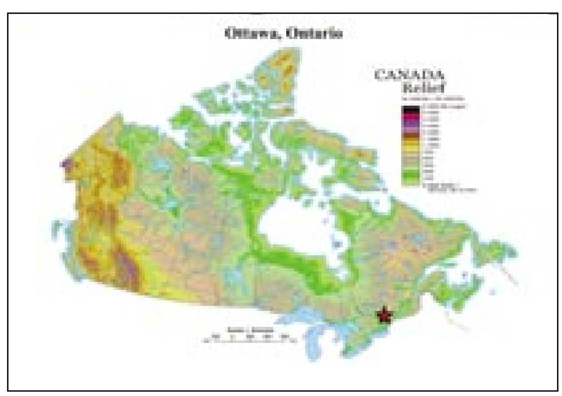
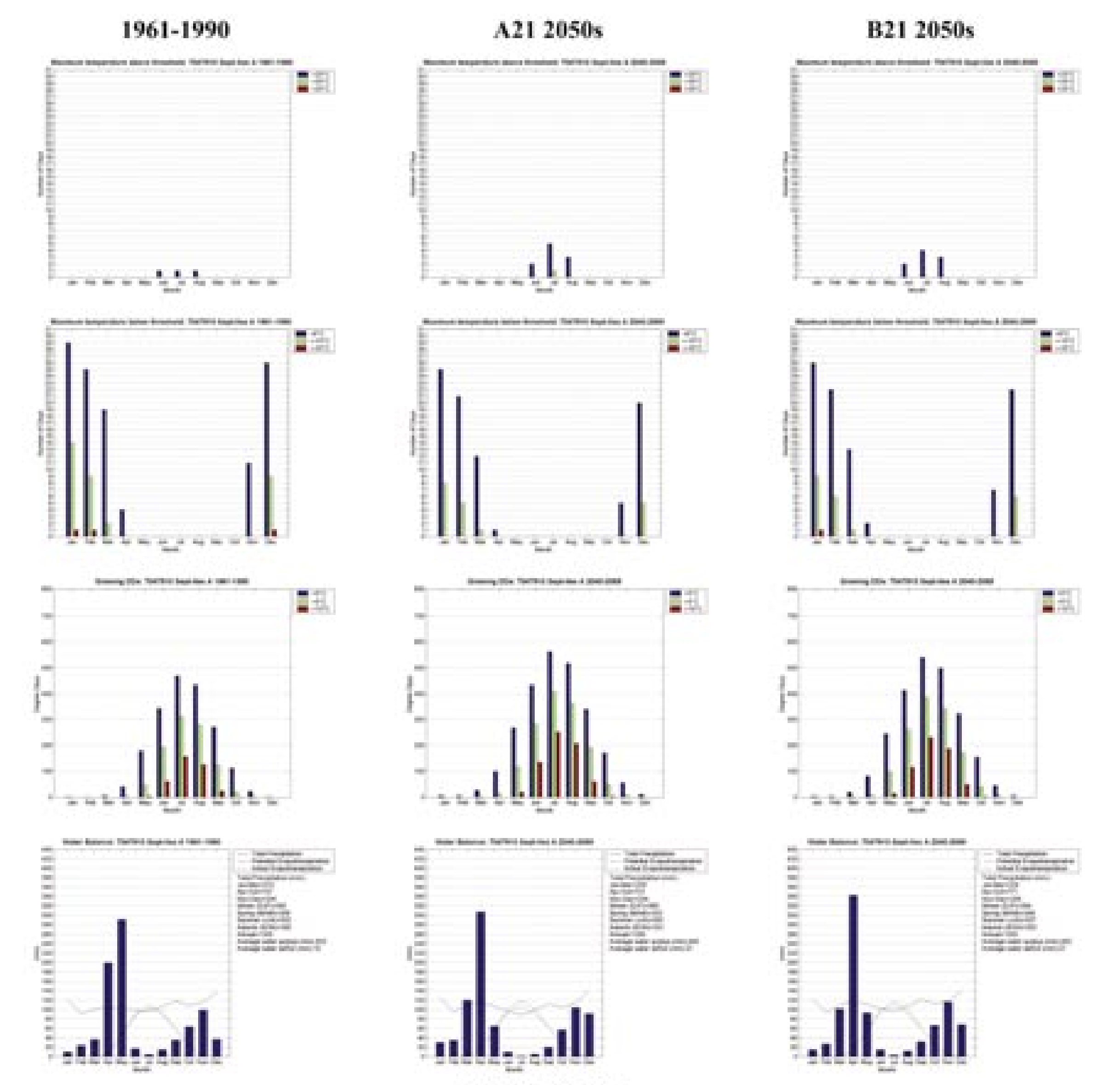
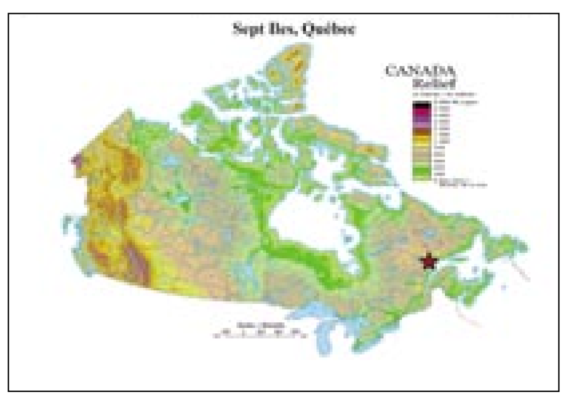





## Figure 4.25

As for Figure 4.17, but for Sept Iles, PQ.



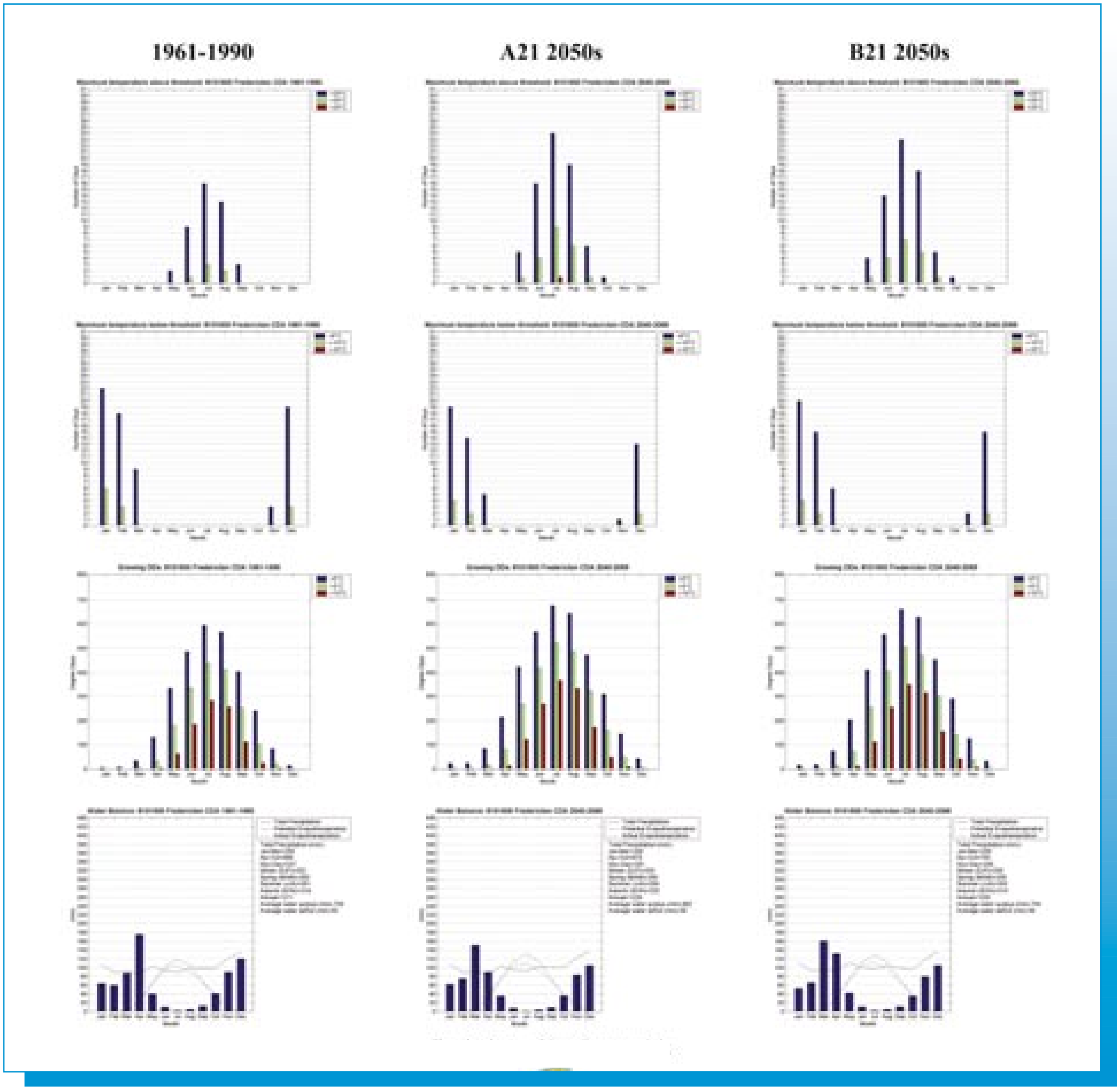
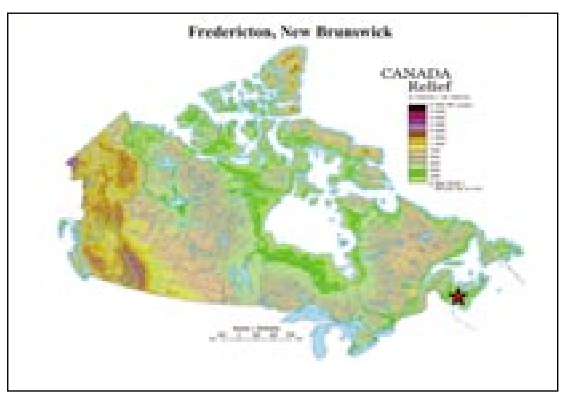
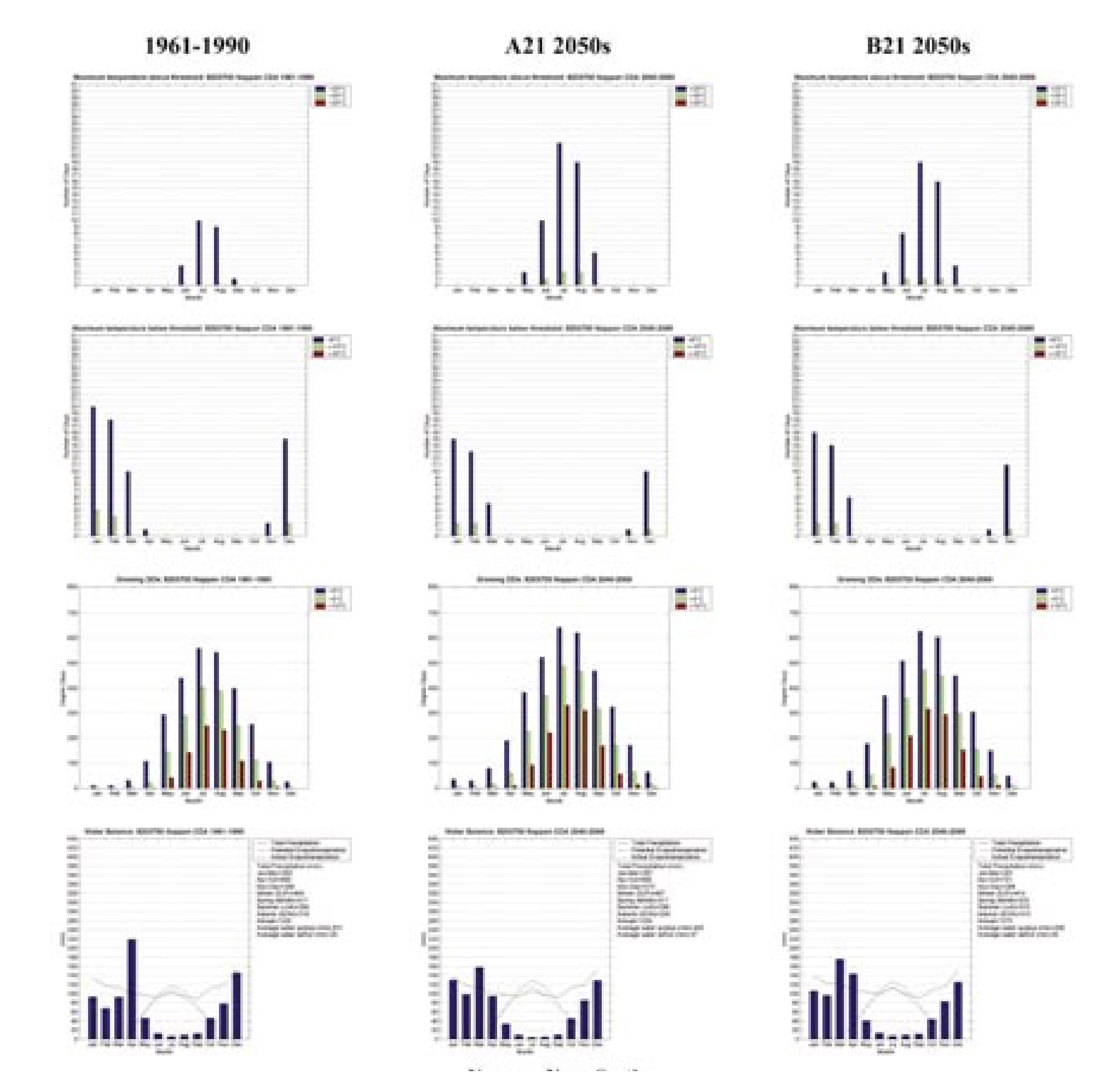



**Figure 4.26**

As for Figure 4.17, but for Fredericton, NB.






## Figure 4.27

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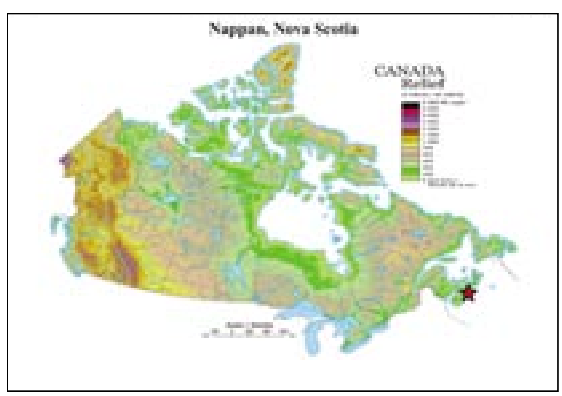
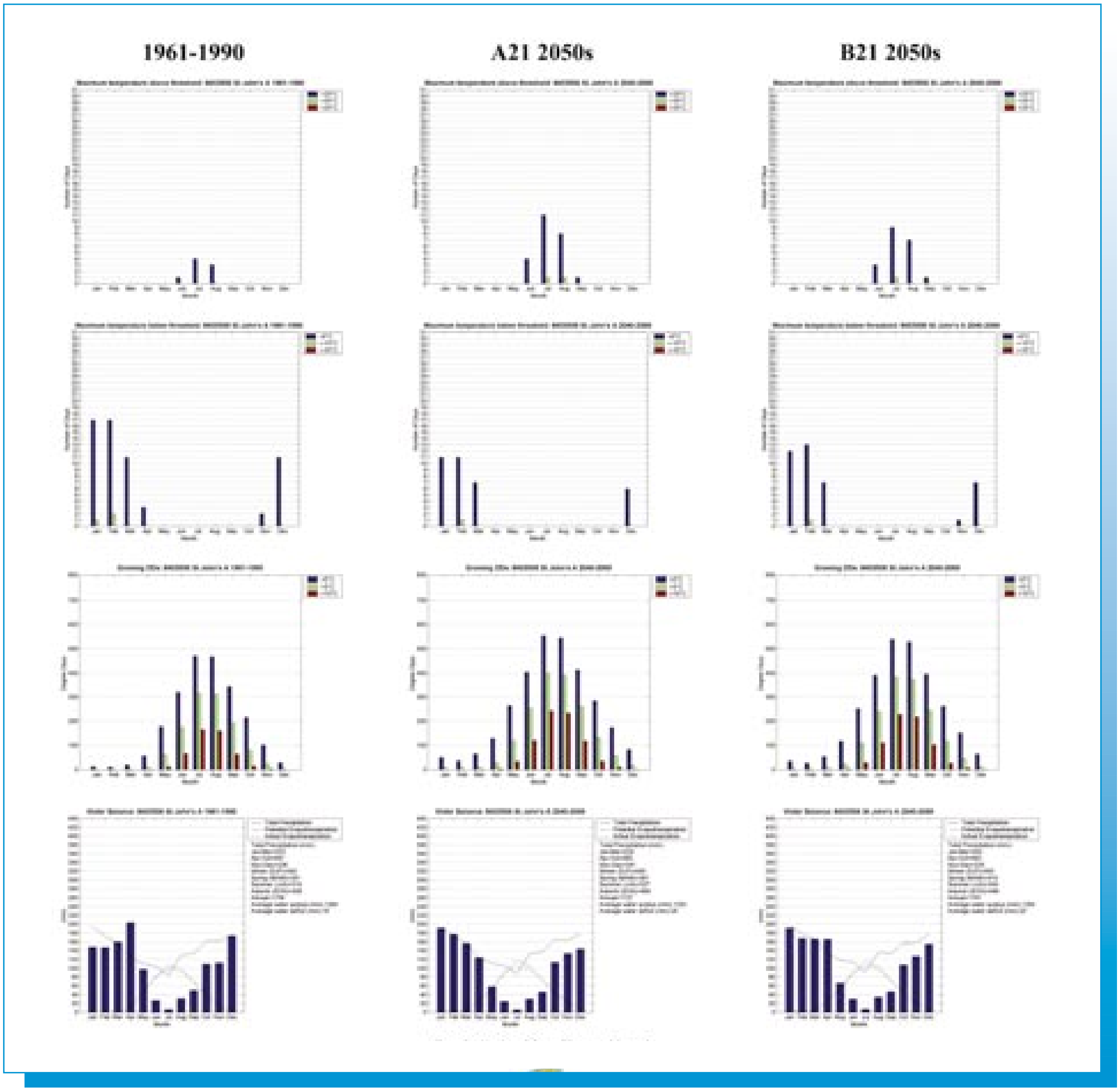
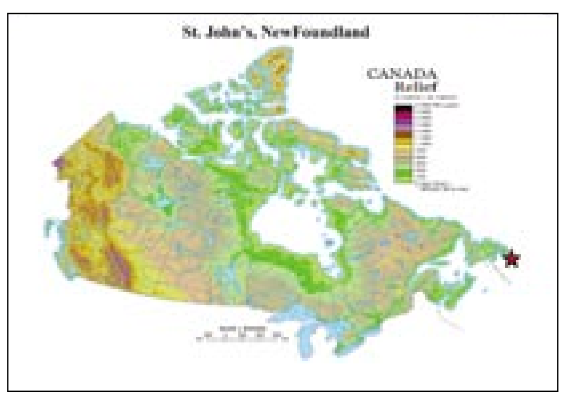
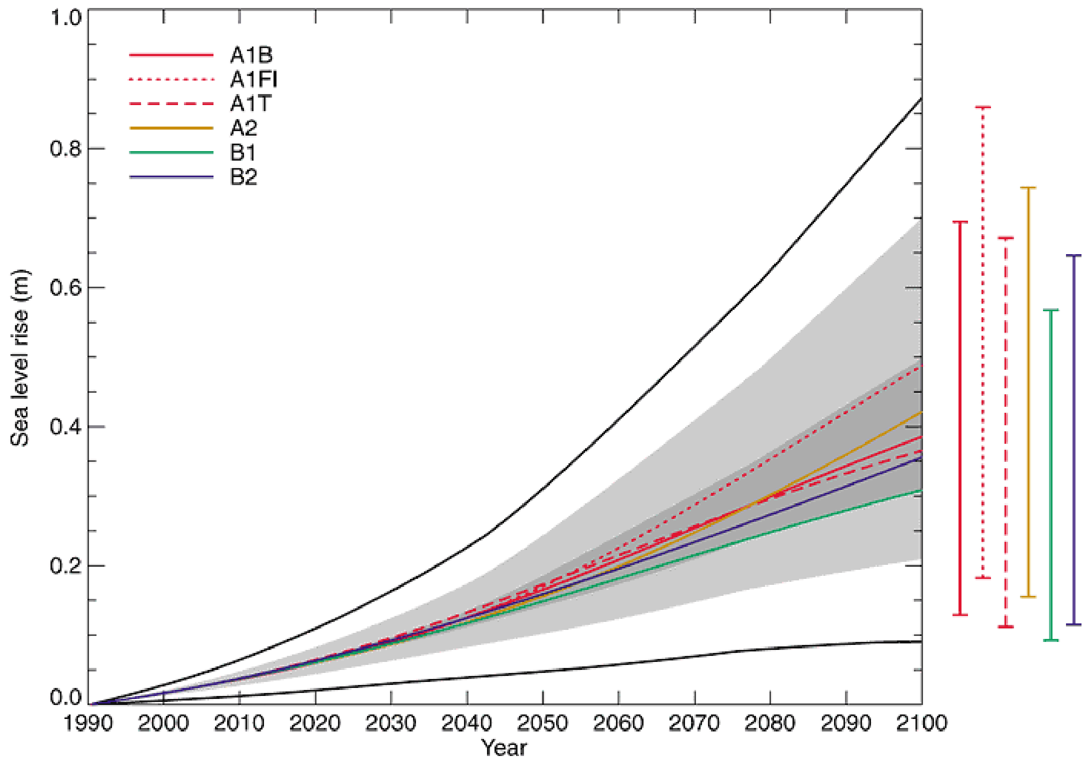




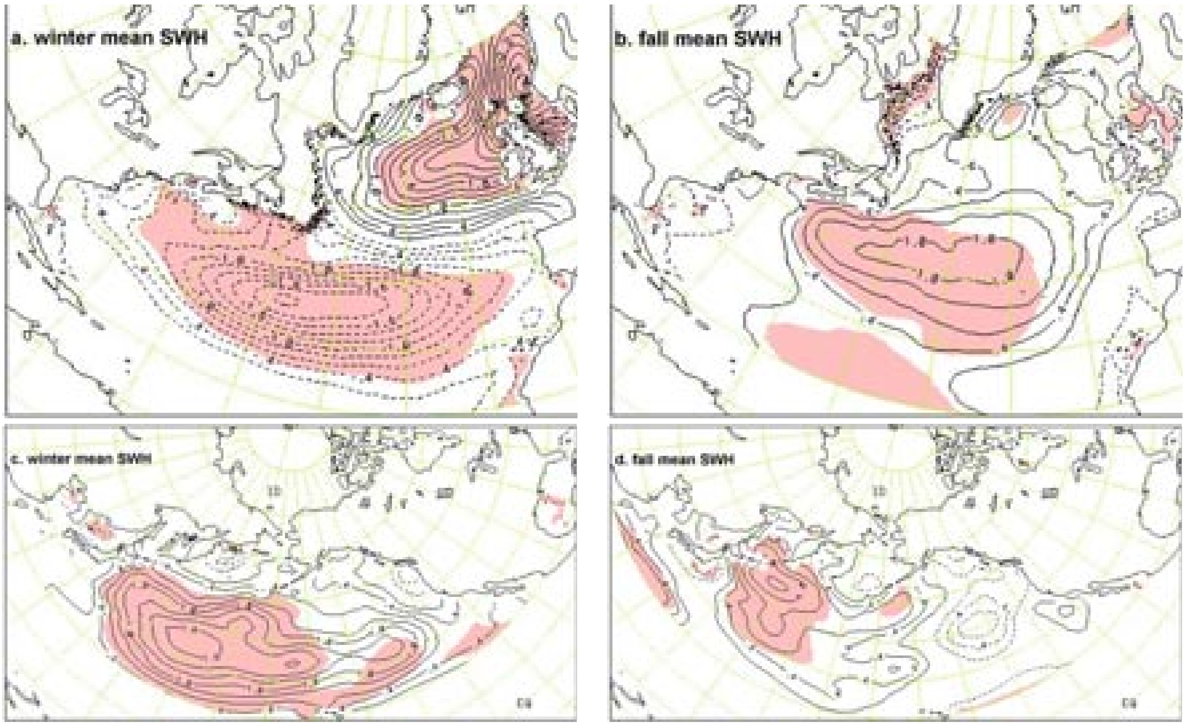

## Figure 4.28

As for Figure 4.17, but for St. John's, NFLD.




## Figure 5.1

Global average sea level rise, 1990 to 2100 for the SRES scenarios. Thermal expansion and land ice changes were calculated using a simple climate model calibrated separately for each of seven AOGCMs, and contributions from changes in permafrost, the effect of sediment deposition and the long-term adjustment of the ice sheets to past climate changes were added. Each of the six lines appearing in the key is the average of AOGCMs for one of the six illustrative scenarios. The region in dark shading shows the range of all AOGCMs for all 35 scenarios. The region delimited by the outermost lines shows the range of all AOGCMs and scenarios including uncertainty in land-ice changes, permafrost changes and sediment deposition. Note that this range does not allow for uncertainty relating to ice-dynamical changes in the West Antarctic ice sheet. The bars show the range in 2100 of all AOGCMs for the six illustrative scenarios. [Source: IPCC, 2001a]




## Figure 5.2

Changes (cm/yr) in winter (JFM) and fall (OND) mean significant wave height in the North Atlantic (upper panels) and the North Pacific (lower panels) during 1958-1997. Solid and dashed lines are positive and negative contours, respectively (zero contours are not shown). Shading indicates areas of significant changes at the 5% level. [Source: Wang and Swail, 2003]

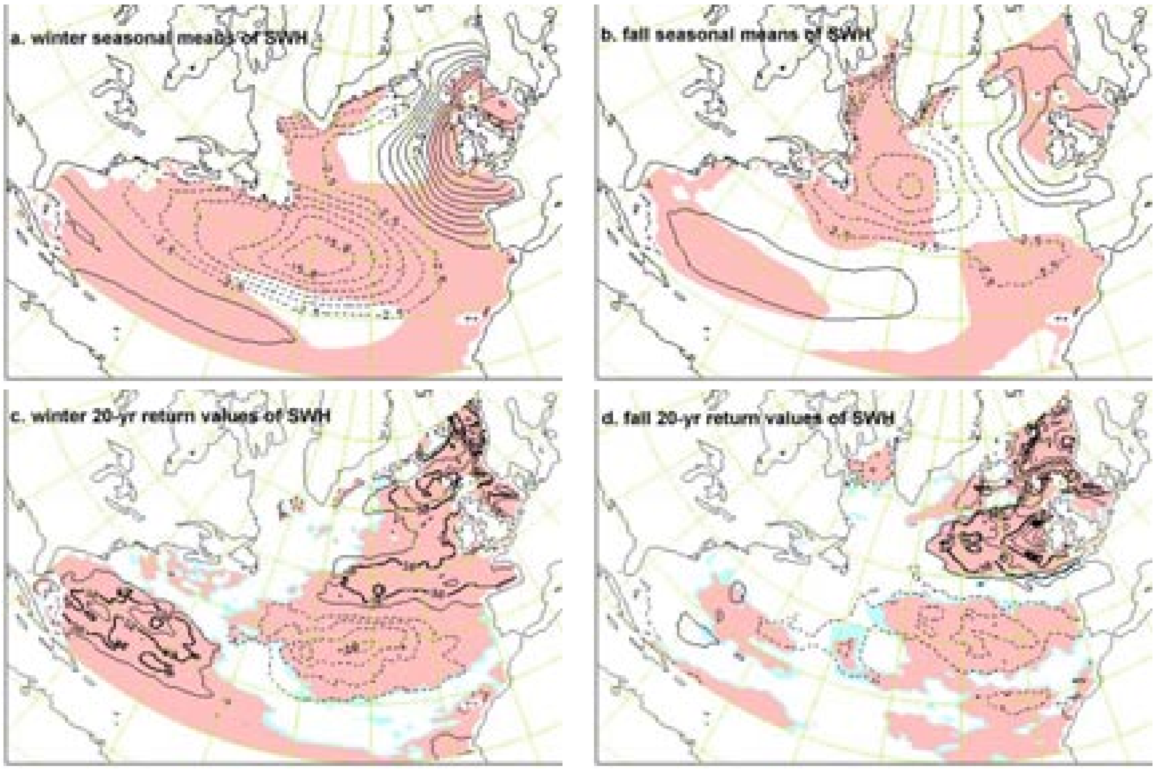
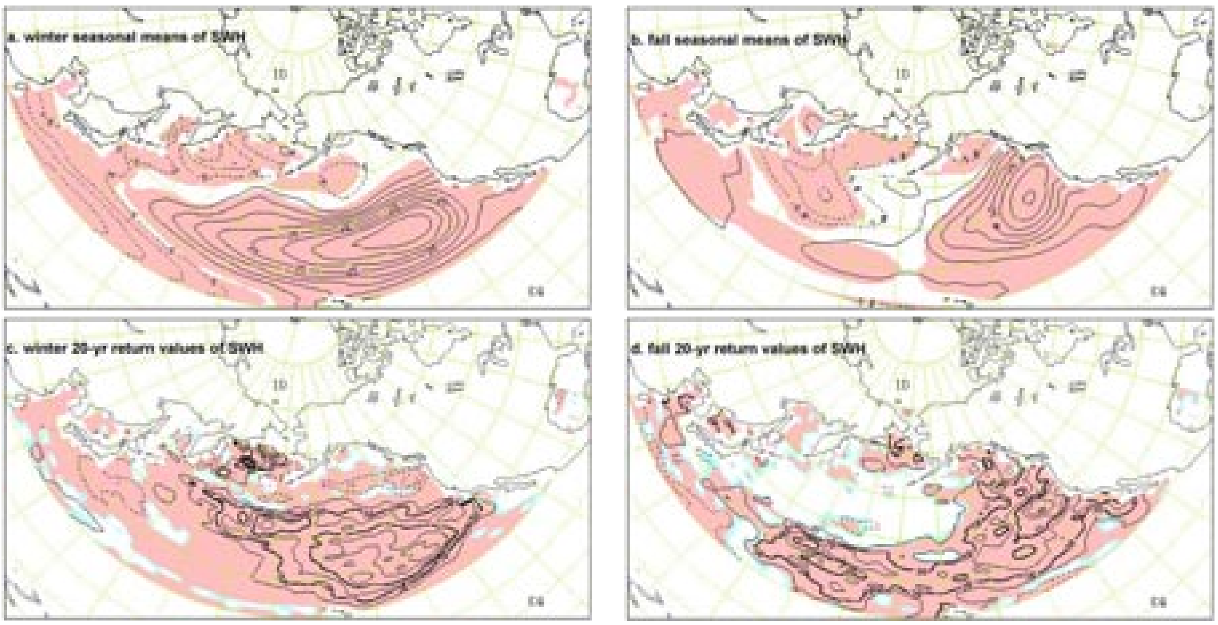



**Figure 5.3**

Changes in seasonal means (upper panels) and 20-year return values (lower panels) of winter and fall significant wave height in the North Atlantic in the period from 1990 to 2080 (2080s-1990s), as projected with the SRES A2 forcing scenario. The contour interval is 2.5cm for the means and 15cm for the 20-year return values. Solid and dashed lines are positive and negative contours, respectively (zero contours are not drawn). Pink/cyan shading indicate areas of significant quadratic/linear trends. [Source: Wang et al., 2003b]




## Figure 5.4

As Figure 5.3, but for significant wave height in the North Pacific. [Source: Wang and Swail, 2003]

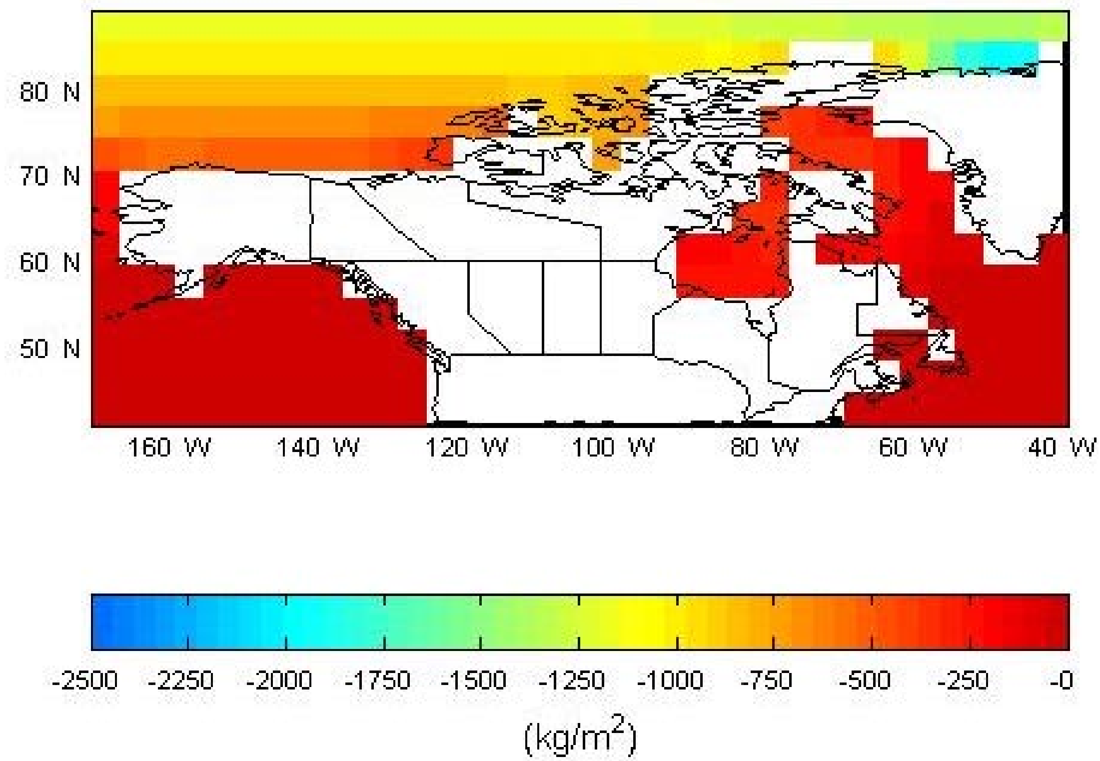



**Figure 5.5**

Winter change in sea-ice thickness for the 2080s, as indicated by the CGCM2 SRES A2 ensemble-mean climate change scenario. 100kgm$^{-2}$ is roughly equivalent to 10cm depth, assuming an average ice density. All changes are with respect to the 1961-1990 baseline. [Image source: The CCIS Project web site: http://www.cics.uvic.ca/scenarios]

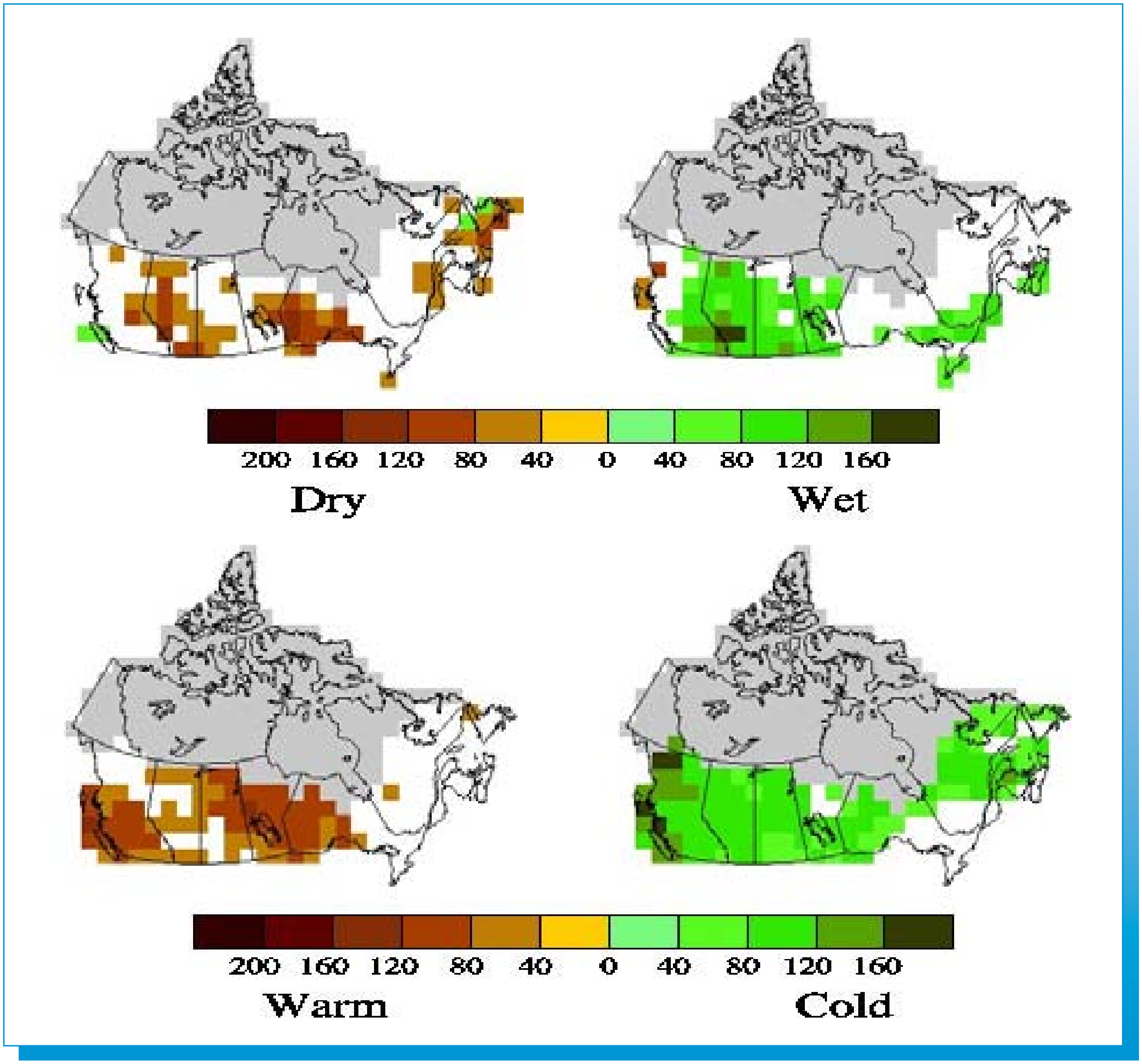



Figure 6.1

Risks of winter season extreme precipitation (upper panel) and temperature (lower panel) departures (in % more than average) during El Niño and La Niña episodes in the 20th century. Coloured areas show where the probability of increased risk of extremes occurring by chance is less than 5%. Areas with insufficient data are shaded grey.

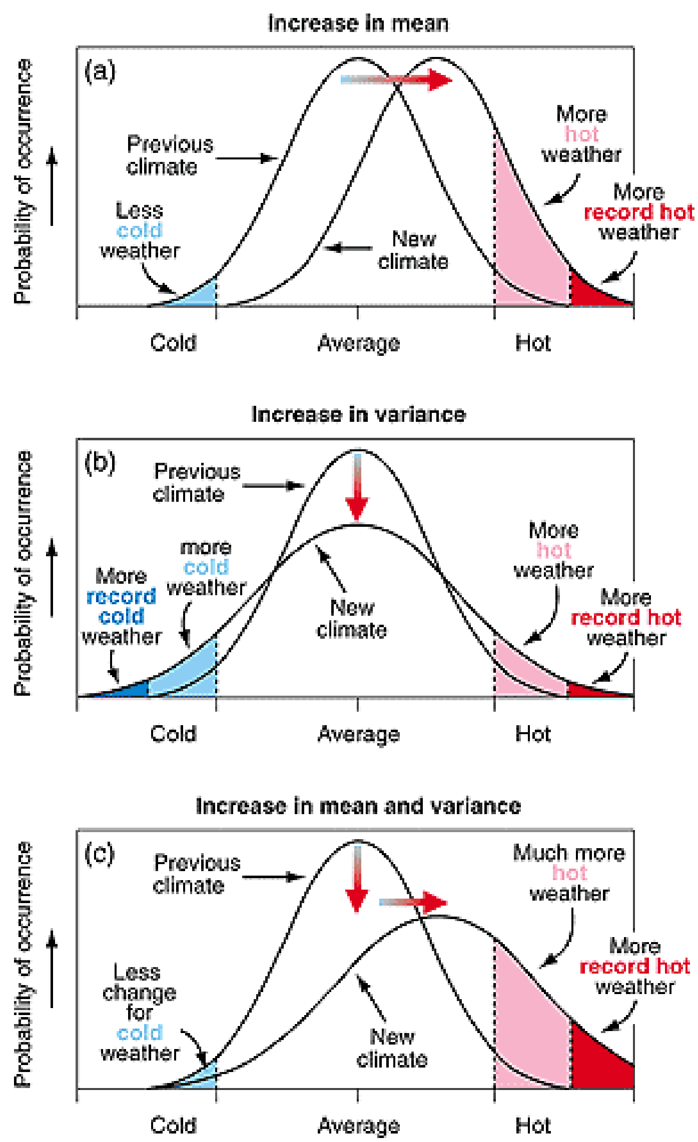



**Figure 6.2**

Schematic showing the effect on extreme temperatures when (a) mean temperature increases, (b) the variance increases, and (c) when both the mean and variance increase for a normal distribution of temperature. [Source: IPCC, 2001a]

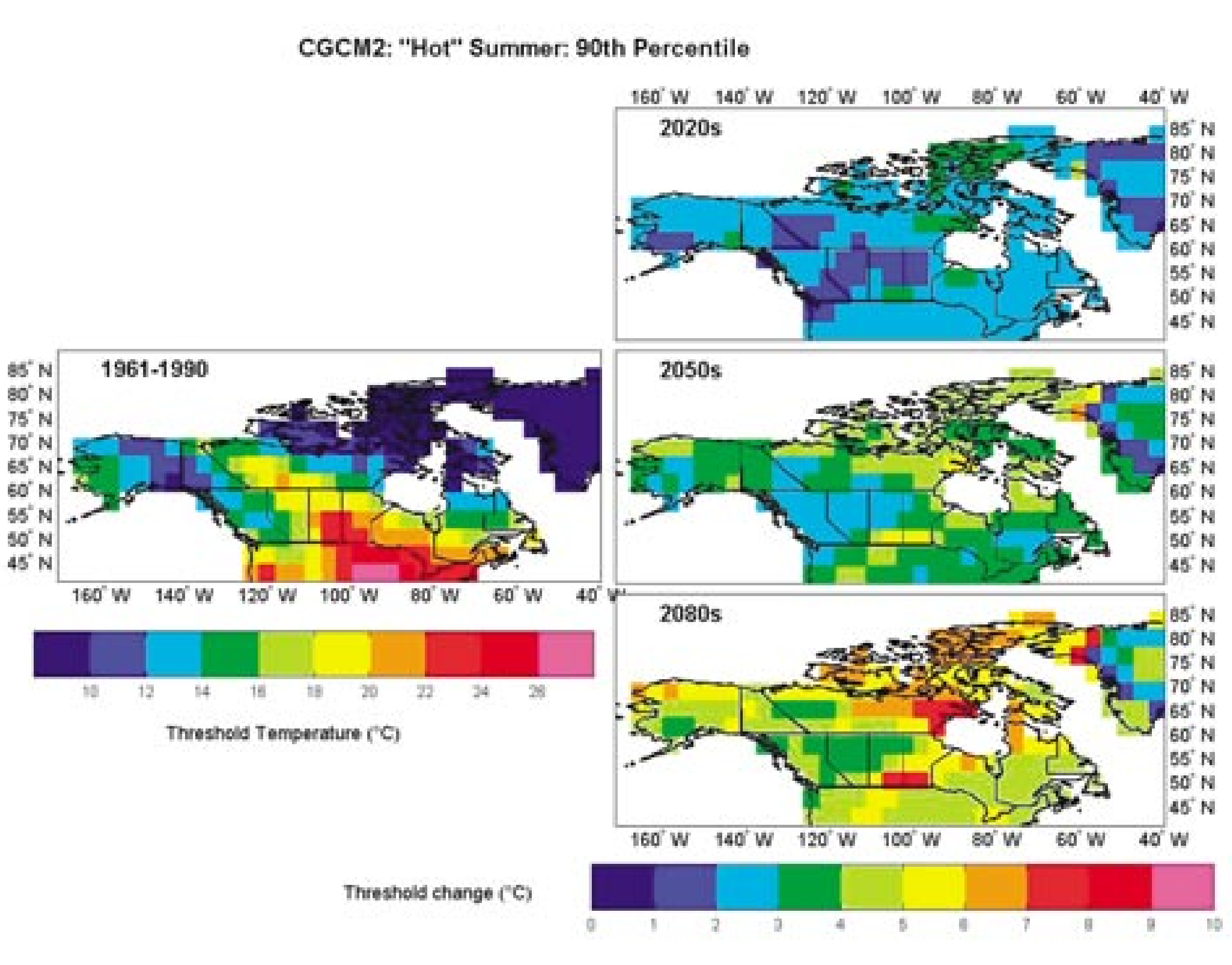



**Figure 6.3**

Changes in the maximum threshold temperature (°C) defining a 'hot' summer (using the 90th percentile) from the pooled CGCM2 A2 experimental results.

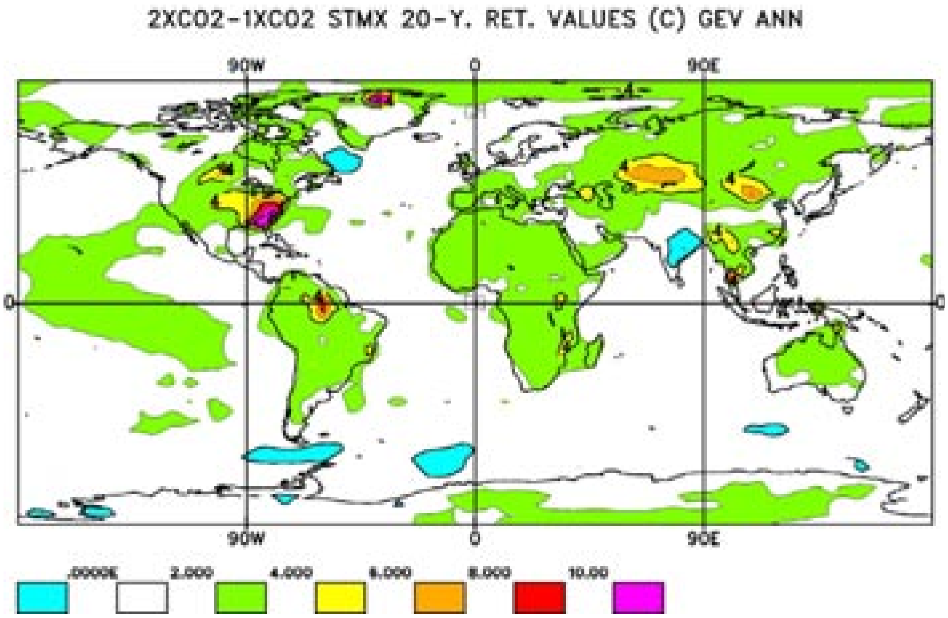



**Figure 6.4**

Changes (in °C) in 20-year return values for daily maximum screen temperature simulated in the greenhouse gas (GHG+A) runs in 2040-2060 relative to the reference period 1975-1995. [Reproduction of Figure 7a in Kharin and Zwiers (2000)]

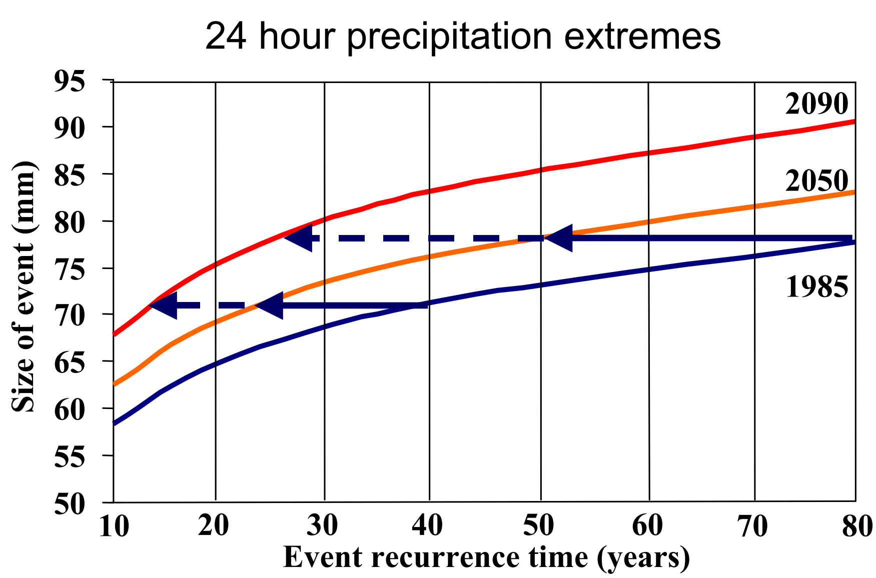
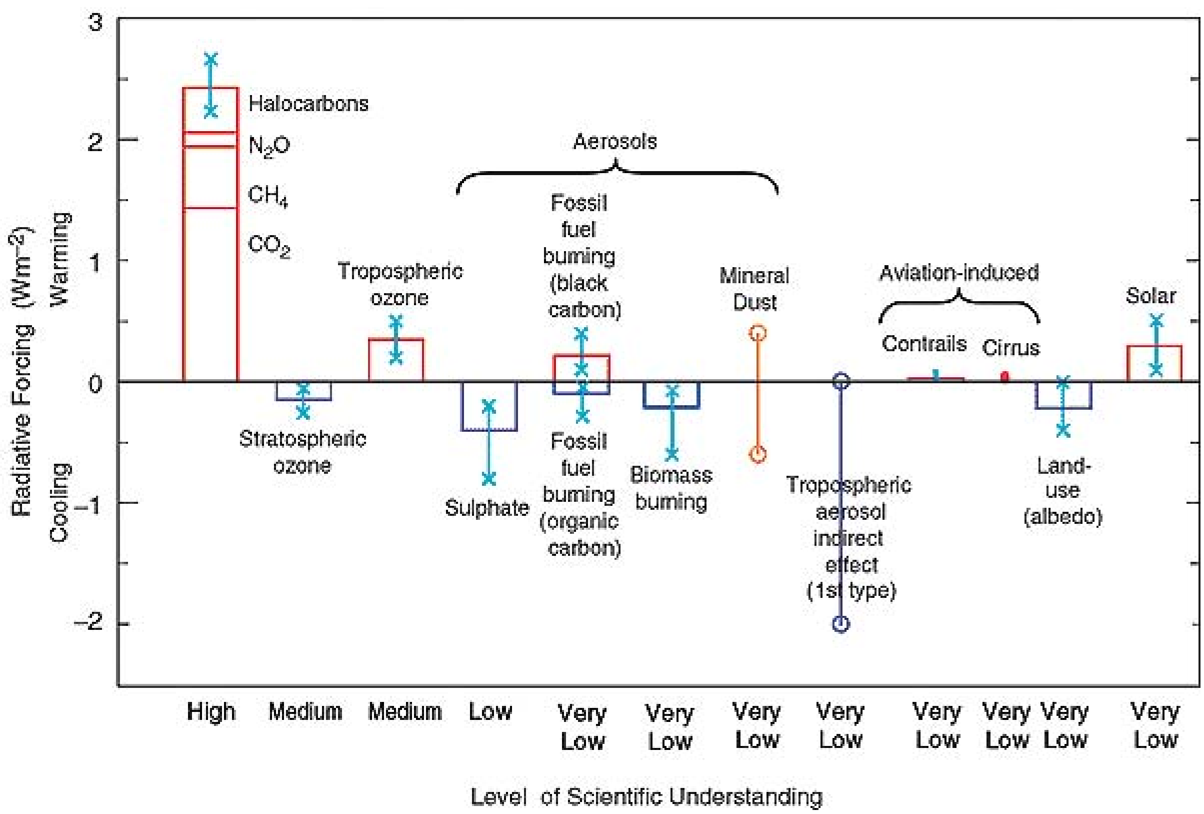


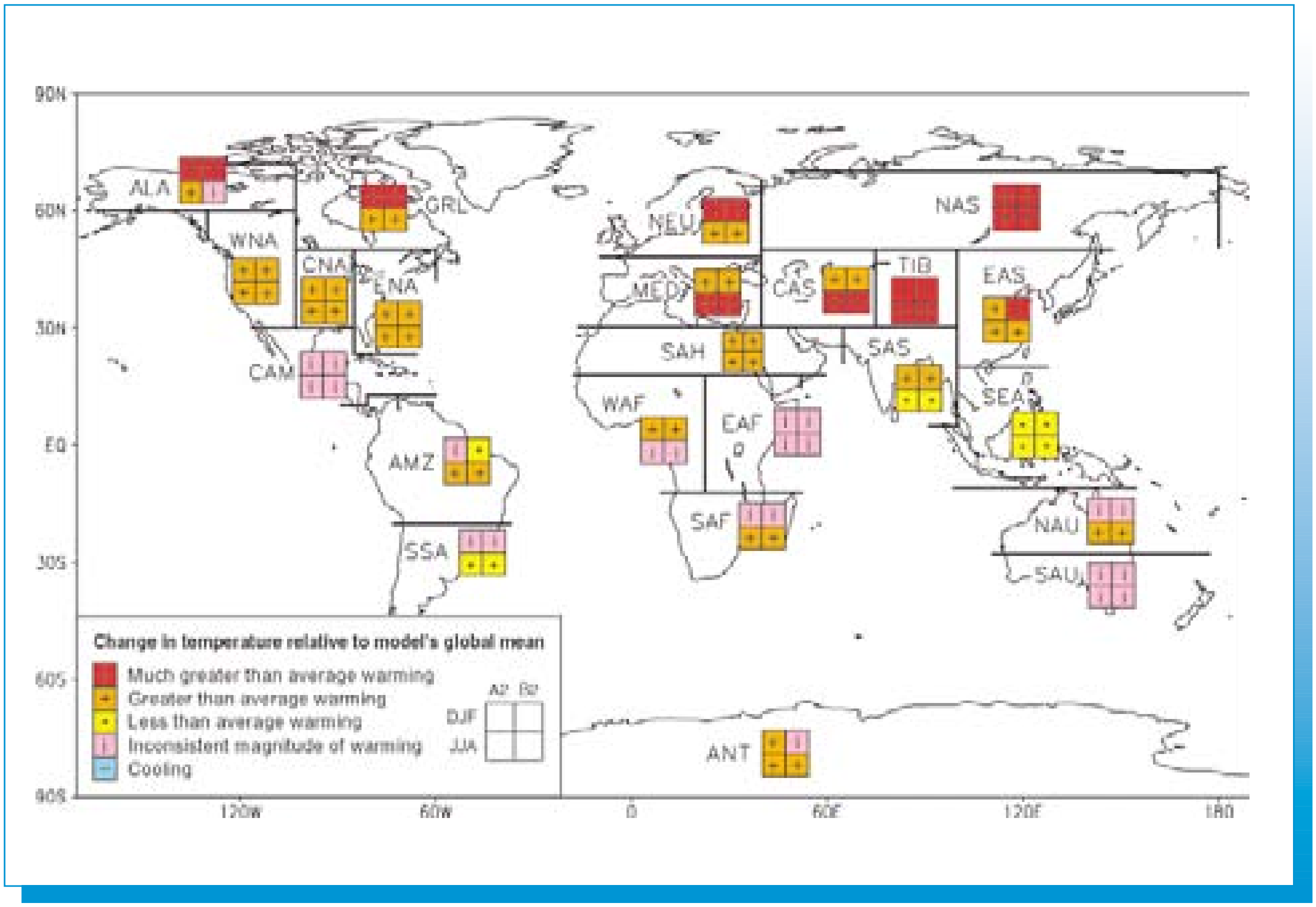

**Figure 6.5**

This diagram shows the size (in mm) of extreme events (represented as annual maximum 24-hour precipitation) averaged over Canada and their corresponding recurrence time (in years) for current (1995) and CGCM1-projected future (2050 and 2090) climates. It clearly indicates a reduction in the waiting period for the recurrence of the same extreme event in the future. For example, extreme precipitation with a 40-year return period in the current climate will occur in less than 25 years , and about 15 years on average by the middle and the end of the 21st century, respectively. [Figure courtesy of Francis Zwiers, Meteorological Service of Canada]



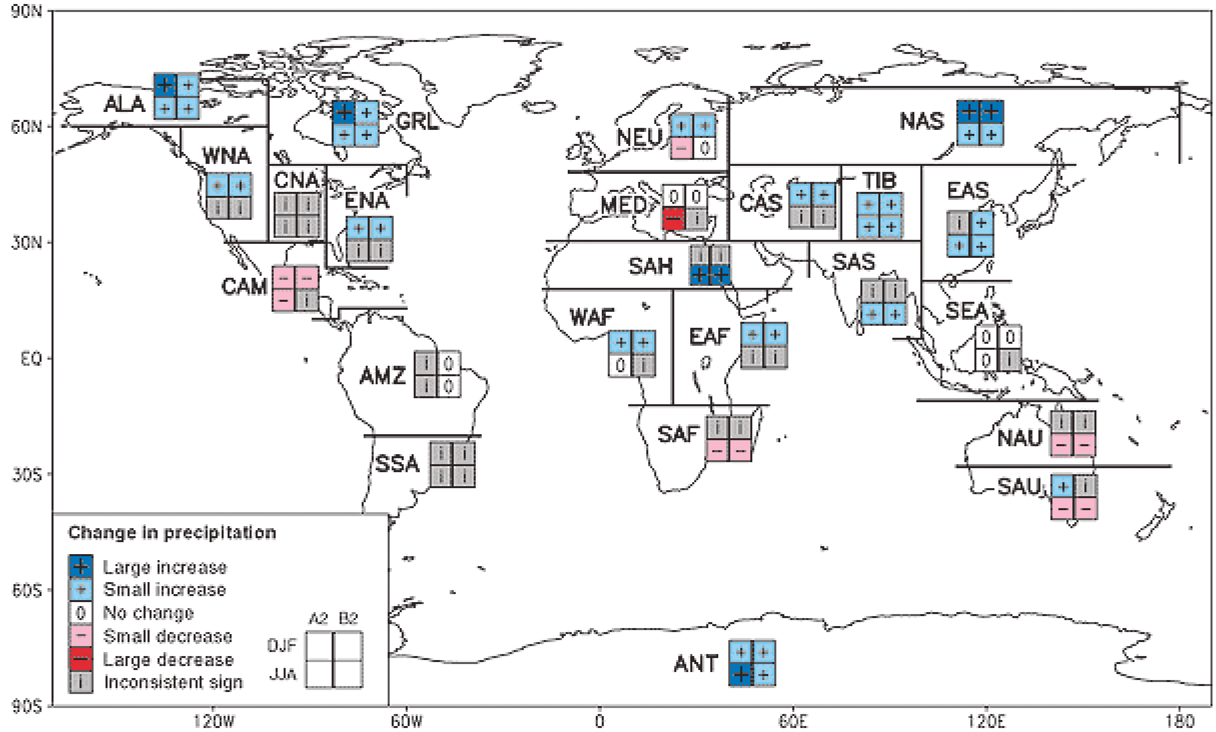

## Figure 7.1

Global, annual-mean radiative forcings (Wm$^{-2}$) due to a number of agents for the period from pre-industrial (1750) to present (late 1990s; about 2000). The height of the rectangular bar denotes a central or best estimate value, whilst its absence denotes no best estimate is possible. The vertical line about the rectangular bar with "x" delimiters indicates an estimate of the uncertainty range, for the most part guided by the spread in the published values of the forcing. A vertical line without a rectangular bar and with "o" delimiters denotes a forcing for which no central estimate can be given owing to large uncertainties. The uncertainty range specified here has no statistical basis. A "level of scientific understanding" index is accorded to each forcing, with high, medium, low and very low levels, respectively. This represents the subjective judgement about the reliability of the forcing estimate, involving factors such as the assumptions necessary to evaluate the forcing, the degree of knowledge of the physical/chemical mechanisms determining the forcing, and the uncertainties surrounding the quantitative estimate of the forcing. The well-mixed greenhouse gases are grouped together into a single rectangular bar with the individual mean contributions due to $CO_2$, $CH_4$, $N_2O$ and halocarbons shown. Fossil fuel burning is separated into the "black carbon" and "organic carbon" components with its separate best estimate and range. The sign of the effects due to mineral dust is itself an uncertainty. The indirect forcing due to tropospheric aerosols is poorly understood. The same is true for the forcing due to aviation via its effects on contrails and cirrus clouds. Only the "first" type of indirect effect due to aerosols as applicable in the context of liquid clouds is considered here. The "second" type of effect is conceptually important, but there exists very little confidence in the simulated quantitative estimates. The forcing associated with stratospheric aerosols from volcanic eruptions is highly variable over the period and is not considered for this plot. All the forcings shown have distinct spatial and seasonal features such that the global, annual means appearing on this plot do not yield a complete picture of the radiative perturbation. They are only intended to give, in a relative sense, a first-order perspective on a global, annual mean scale and cannot be readily employed to obtain the climate response to the total natural and/or anthropogenic forcings. [Source: Figure 9 in the IPCC Technical Summary of the Working Group I Report in IPCC (2001a)].



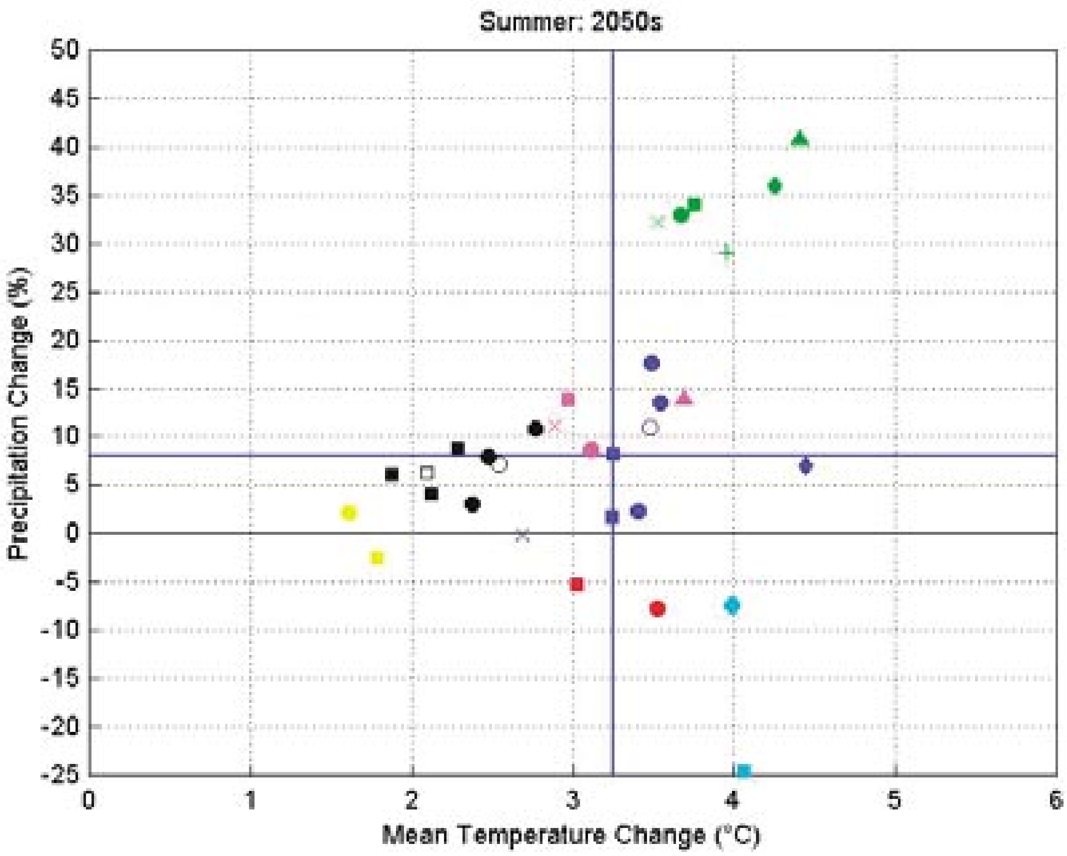

## Figure 7.2a

Analysis of inter-model consistency in regional relative warming (warming relative to each model's global average warming) for the A2 and B2 emissions scenarios. Regions are classified as showing either agreement on warming in excess of 40% above the global average ("Much greater than average warming"), agreement on warming greater than the global average ("Greater than average warming"), agreement on warming less that the global average ("Less than average warming"), or disagreement amongst models on the magnitude of regional relative warming ("Inconsistent magnitude of warming"). There is also a category for agreement on cooling (which never occurs). A consistent result from at least seven of the nine models is deemed necessary for agreement. The global annual average warming of the models used spans 1.2 to 4.5°C for A2 and 0.9 to 3.4°C for B2, and therefore a regional 40% amplification represents warming ranges of 1.7 to 6.3°C for A2 and 1.3 to 4.7°C for B2. [Source: Figure 21 in the IPCC Technical Summary of the Working Group I Report in IPCC (2001a)].



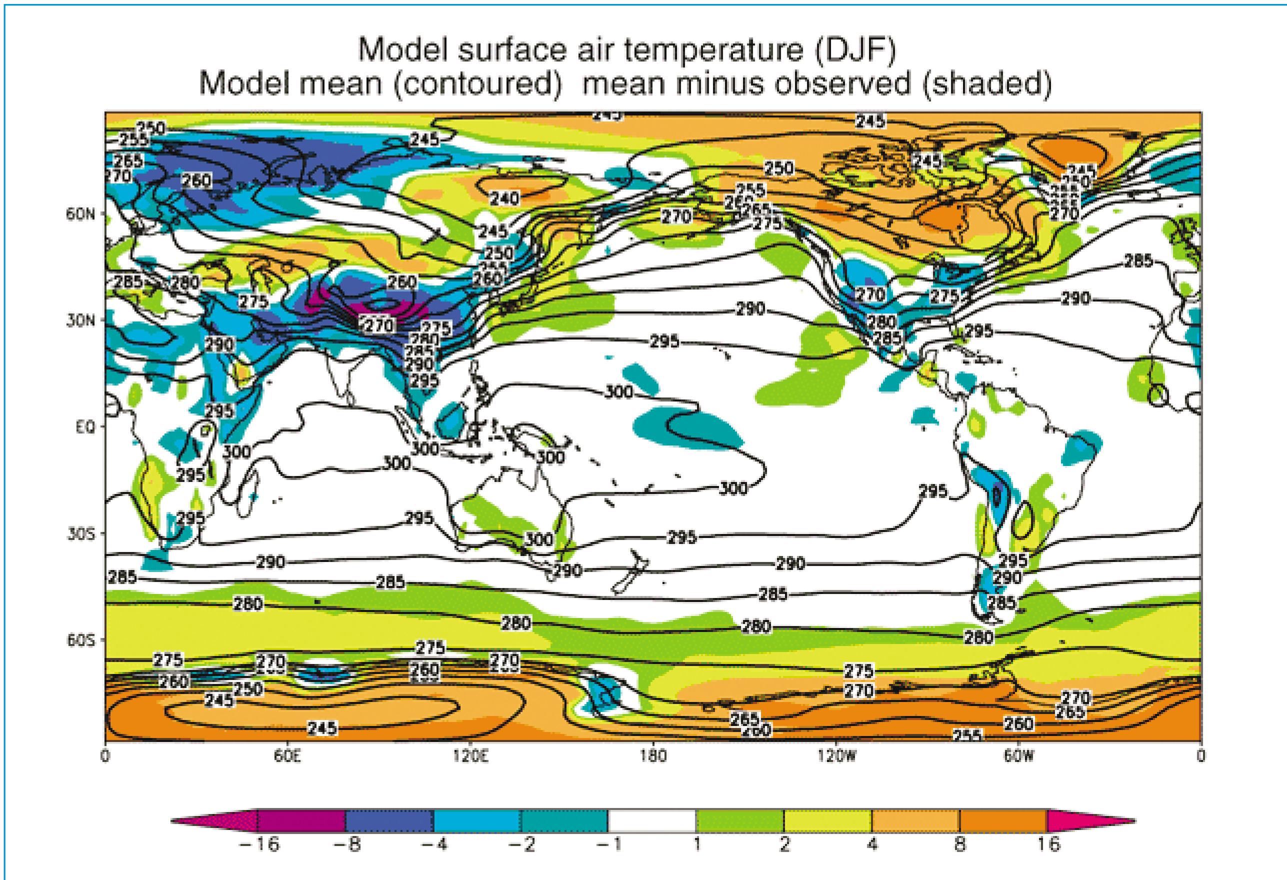

## Figure 7.2b

Analysis of inter-model consistency in regional precipitation change for the A2 and B2 emissions scenarios. Regions are classified as showing either agreement on increase with an average change of greater than 20% ("Large increase"), agreement on increase with an average change between 5 and 20% ("Small increase"), agreement on a change between -5 and +5% or agreement with an average change between -5 and 5% ("No change"), agreement on decrease with an average change between -5 and -20% ("Small decrease"), agreement on decrease with an average change of less than -20% ("Large decrease"), or disagreement ("Inconsistent sign"). A consistent result from at least seven of the nine models is deemed necessary for agreement. [Source: Figure 21 in the IPCC Technical Summary of the Working Group I Report in IPCC (2001a)].



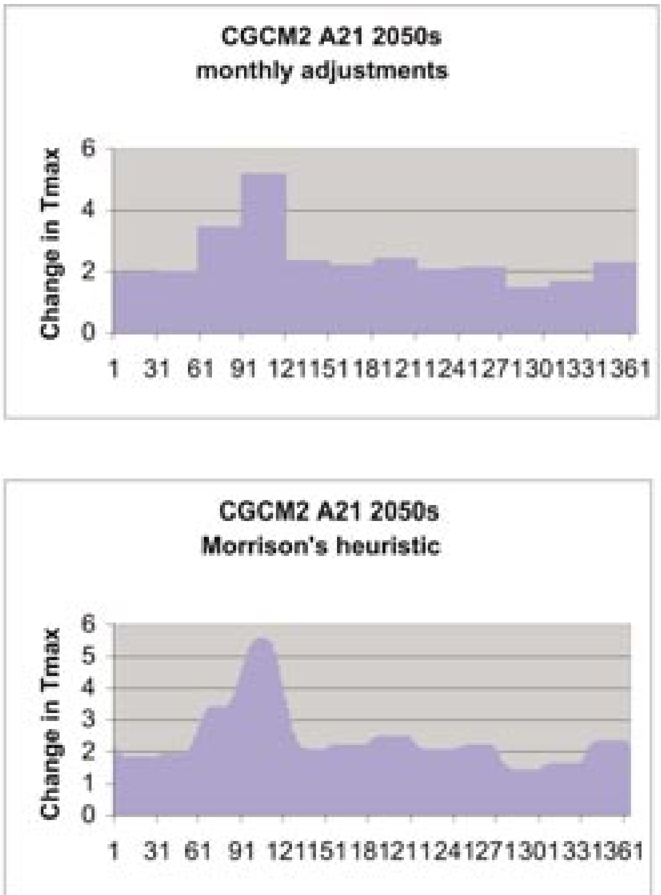

## Figure 7.3

Scatter plot of changes in mean temperature and precipitation for the Ottawa region for the 2050s summer season, as projected for all available climate change scenarios based on GCM climate change experiments undertaken with the SRES emissions scenarios. The blue lines represent the median changes in mean temperature and precipitation based on this suite of climate change scenarios, and give an indication of which scenarios indicate warmer, cooler, wetter or drier conditions when compared with the complete suite of scenarios illustrated here. Each symbol and colour represents a different GCM and SRES experiment: ◆ A1FI; + A1T; ▲ A1; • A2; × B1; ■ B2; CGCM2 - black; CCSR/NIES - green; CSIROMk2 - pink; ECHAM4 - red; NCAR-PCM - yellow; HadCM3 - blue; GFDL-R30 - cyan. Closed symbols indicate individual experiments, whilst open symbols represent ensemble-means (i.e., the average of a number of individual experiments using identical SRES forcing).



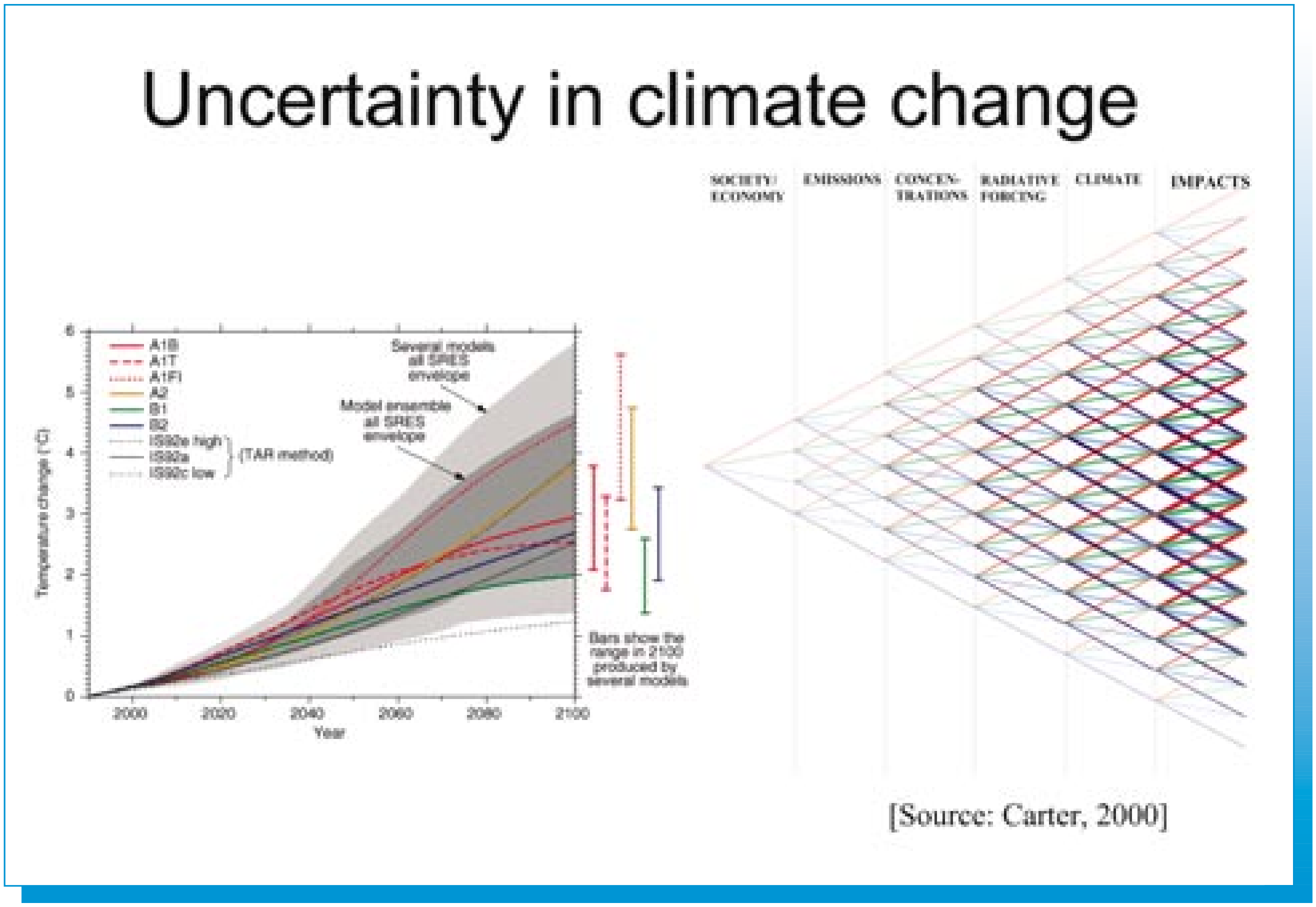

## Figure 8.1

December-January-February climatological surface air temperature in Kelvin simulated by the CMIP1 model control runs averaged over all models. Differences between "average" model and observations are shaded [Source: IPCC, 2001a]




## Figure 8.2

The effect of applying Morrison's smoothing technique to monthly GCM adjustments. The top figure shows the Canadian model CGCM2 A2 monthly adjustments for the 2050s. The abrupt changes at the monthly boundaries are removed at the bottom after applying the smoothing technique.
[Source: Taylor et al., 2003]




## Figure 8.3

The cascade of uncertainties.

# List of acronyms

| | |
|---|---|
| AMIP | Atmospheric Model Intercomparison Project |
| AO | Arctic Oscillation |
| AOGCMs | Atmosphere-ocean GCMs, i.e., coupled GCMs |
| BAHC | Biospheric Aspects of the Hydrological Cycle |
| BCPs | Bioclimate Profiles |
| CCAF | Climate Change Action Fund |
| CCCma | Canadian Centre for Climate Modelling and Analysis |
| CCIS | Canadian Climate Impacts Scenarios |
| CCRS/NIES | Centre for Climate Research Studies/National Institute for Environmental Studies |
| CGCM1 | Canadian Coupled Global Climate Model |
| CMIP | Coupled Model Intercomparison Project |
| CRCM | Canadian Regional Climate Model |
| CSI | Climate Severity Index |
| CSIRO | Commonwealth Scientific and Industrial Research Organisation |
| DDC | Data Distribution Centre |
| ECHAM | Max Planck Institute for Meteorology |
| ENSO | El Niño-Southern Oscillation |
| GCM | Global Climate Model |
| GFDL | Geophysical Fluid Dynamics Laboratory |
| GHG | Greenhouse Gas |
| HadCM | Hadley Centre for Climate Prediction and Research |
| HSDs | Heat Stress Days |
| IGBP | International Geosphere-Biosphere Programme |
| IPCC | Intergovernmental Panel on Climate Change |
| MICE | Modelling the Impact of Climate Extremes |
| MSLP | Mean Sea Level Pressure |
| NAO | North Atlantic Oscillation |

| | |
|---|---|
| NCAR | National Centre for Atmospheric Research |
| NCEP | National Centres for Environmental Prediction |
| NRA | NCEP/NCAR reanalysis |
| PAGES | Past Global Changes |
| PDO | Pacific Decadal Oscillation |
| PRUDENCE | Prediction of Regional scenarios and Uncertainties for Defining EuropeaN Climate change risks and Effects |
| RA | Redundancy analysis |
| RCM | Regional Climate Model |
| SDSM | Statistical DownScaling Model |
| SLP | Sea Level Pressure |
| SRES | Special Report on Emissions Scenarios |
| STARDEX | STAtistical and Regional Dynamical Downscaling of Extremes for European regions |
| SWH | Significant Wave Height |
| TGCIA | Task Group on Scenarios for Climate Impact Assessment |
| VIA | Vulnerability, Impacts and Adaptation |