CLIMATE CHANGE DIGEST

Projections for Canada's Climate Future

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Special Edition

Environment Canada
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Projections for Canada's climate future

A discussion of recent simulations with the Canadian Global Climate Model

by

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INTRODUCTORY COMMENTS AND ACKNOWLEDGEMENTS

Projections for Canada's Climate Future *was prepared to provide the Canadian climate impacts research community, policy makers and the general public with a summary of recent results from climate change experiments undertaken with the first version of the Canadian coupled climate model, to describe how they were achieved, and to discuss both their credibility and limitations. It is being published as the third of a series of 'special'* Climate Change Digest *reports aimed at explaining and assessing our current understanding (or lack thereof) of some of the more complex and controversial aspects of climate change science.*

This report was prepared by Henry Hengeveld, Senior Science Advisor on Climate Change with the Science Assessment and Policy Integration Branch, Meteorological Service of Canada (MSC), and edited by David Francis of Lanark House Communications (Toronto).

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CLIMATE MODELS AND THE CLIMATE SYSTEM

With the enormous growth in computer power that has occurred over the past two decades, researchers in both the physical and social sciences have turned increasingly to mathematical modelling as a way of exploring complex phenomena. Mathematical models link the various equations that describe the key relationships and processes within a system to simulate its behaviour. By changing the values of certain variables, scientists can study how the system responds to both external and internal changes. Because system processes can never be understood perfectly, models unavoidably simplify reality. Their results must thus be used with caution. However, models in many areas have now reached such a degree of reliability that they are used routinely for operational purposes as well as for research. At the present time, mathematical models are regularly used in such varied applications as the analysis of market behaviour, the preparation of weather forecasts, and the testing of nuclear weapons. In research they are especially useful for analyzing phenomena that cannot easily be studied within the laboratory or in the field.

> Researchers in both the physical and social sciences have turned increasingly to mathematical modelling as a way of exploring complex phenomena.

These models are particularly important in climate change research. Indeed, our present understanding of the climate system and how it is likely to respond to increasing concentrations of greenhouse gases in the atmosphere would be impossible without the existence of what are known variously as global climate models or general circulation models – powerful computer programs that simulate the functioning of the global climate system in three spatial dimensions and in time. Given the scientific expertise needed to construct these models and the expensive computer resources needed to run them, it is not surprising that only a handful of countries are currently involved in advanced climate modelling.

Canada, which has been actively involved in climate modelling since the 1970s, is one of these countries. This work, which involves a close collaboration between scientists from Environment Canada and the universities, is now based at the Canadian Centre for Climate Modelling and Analysis (CCCma) in Victoria, B.C. Over the years, Canadian climate modellers have made important contributions to our understanding of climate processes and climate change. As we enter a new century in which climate change could become one of humankind's greatest challenges, their work is becoming increasingly important as a basis for public understanding and decision making. This report will look at recent research activities at the CCCma and what they are revealing about the probable course of climate change over the next century. It includes a description of the CCCma's first coupled climate model and its capabilities, a review of the results and implications of recent climate change experiments, and a discussion of the reliability of these results. The CCCma experimental results will also be compared with those reported by other modelling groups. Finally, it will briefly review current and future developments in Canadian climate modelling research.

Present concerns about climate change arise from two basic and undisputed facts. The first is that greenhouse gases, such as carbon dioxide and methane, retard the rate at which the earth loses heat to space and thus contribute to the warming of the earth's atmosphere. The second is that concentrations of these gases are increasing as a result of human activities.

This increase, which is already quite substantial and which will continue until greenhouse gas emissions are drastically reduced, is expected to lead to a warming of the planet's lower atmosphere and surface. We cannot be certain how much it will warm, however, nor can we immediately determine how other aspects of climate might be affected, because the earth's climate system is bewilderingly complex. It is the result not only of processes within the atmosphere itself but also of interactions involving the world's oceans, land surfaces, living things, and polar ice masses. A significant change in any one of these elements can trigger important changes in others. These in turn may cause a variety of feedback effects that further modify the original change, in some cases offsetting or moderating it, in others, enhancing it.

To determine the likely effect of a change such as an increase in greenhouse gas concentrations on the climate system, it is necessary to look at how the system as a whole responds. To do this, climate models are essential, because they integrate the main processes that occur within the climate system and calculate the adjustments and readjustments of its various elements as they respond to the original change.

The first models that could perform such tasks appeared in the late 1970s. They simulated the workings of the earth's atmosphere in three dimensions, representing the operation of climatic processes not only at the earth's surface but also at various levels above it. Because of the limited computer power available at the time, however, their simulation of the climate system was necessarily simplistic. Oceans, which play a major role in transporting heat from one part of the globe to another, were described in a highly simplified fashion, and their interactions with the atmosphere were represented only in a very generalized way. Clouds, whose effects on the heating of the atmosphere vary with their structure, altitude, and coverage of the sky (as well as with the time of day), were also poorly represented and could not respond to changes in other atmospheric conditions. The representation of the water cycle, which has important implications for clouds, precipitation, soil moisture, and greenhouse warming, was equally crude. In addition, early models suffered from coarse resolution; that is, they could only represent variations in the simulated climate variables at scales of about 800 km or greater. As a result, the precision with which they could represent many climatic processes was limited.

By the late 1980s, however, advances in modelling techniques, understanding of climatic processes, and computer power made possible the development of a second generation of GCMs. Although these models still used highly simplified oceans, their representation of interactions between the upper ocean and the atmosphere was much improved. In addition, spatial resolutions had been enhanced, the description of the water cycle had become more detailed, and sea ice and clouds now responded to changes in the model's climate. With these models, researchers were able to explore what they called equilibrium climate change, that is, the changes in climate that would result after the climate system had stabilized in response to a given change – usually a doubling – in greenhouse gas concentrations. These models gave valuable insights into the sensitivity of the climate system to higher concentrations of greenhouse gases, but they still could not satisfactorily simulate what is known as transient climate change, that is, the behaviour of the climate system while it is changing rather than after it has changed. The ability to model transient change is very important, because it provides a closer approximation to how we observe the climate system from year to year and decade to decade and hence allows a more rigorous test of how well the model approximates the historical behaviour of the real system.

To simulate transient climate change, models needed a much better representation of ocean processes and hence still more computer power. By the late 1980s and early 1990s various modelling groups had begun to meet these requirements, and a much more sophisticated third generation of climate models began to emerge. Known as coupled atmospheric-ocean general circulation models (AOGCMs) or, more simply, as coupled climate models, they include an atmospheric GCM that is fully coupled to a detailed three-dimensional model of the ocean. This feature, in combination with other refinements, gives them the ability to model climate much more realistically.

At the present time, there are more than 20 such models in use or under development around the world. The Canadian Centre for Climate

Modelling and Analysis completed the construction of its first coupled model, known as CGCM1, in the mid-1990s and has since run a series of transient climate change experiments with it. The results of these experiments have been made available to the Intergovernmental Panel on Climate Change (IPCC) data distribution centre for international use in research into climate change impacts. In 1999, the U.S. National Academy of Science also identified CGCM1 as one of the current leading performers in climate system simulation and recommended that its results be used in the U.S. National Climate Change Assessment.

THE CANADIAN COUPLED CLIMATE MODEL

CGCM1 provides a good illustration of both the advanced features and the continuing limitations of state-of-the-art climate models at the end of the twentieth century. It is made up of four key components:

1. An *atmospheric general circulation model*, known as GCMII, with 10 vertical levels and a horizontal resolution of approximately 3.7° of latitude and longitude (about 400 km). This resolution is similar to that used in most atmospheric GCMs, although some now achieve resolutions better than 300 km. Cloud cover and cloud characteristics respond interactively to other changes in the climate system.
2. An *ocean general circulation model* capable of reproducing the large-scale features of the ocean circulation as well as important water properties such as temperature and salinity. Known as the modular ocean model (MOM), it was originally developed by the Geophysical Fluid Dynamics Laboratory in Princeton, New Jersey, and has been modified for use in CGCM1. It has 29 vertical layers and a horizontal resolution of about 200 km, about twice that of the atmospheric model. Its resolution is still inadequate, however, to describe fully all of the many processes that control the behaviour of the oceans.
3. A *thermodynamic sea ice model* that allows ice to grow and melt in response to heat exchanges with the ocean and the atmosphere. Openings in the ice cover are represented by a relationship with the amount of ice present. This ice model was also used in earlier equilibrium experiments with CCCma's second-generation GCM.
4. A simple *land surface model* that calculates runoff and soil moisture on the basis of the balance between precipitation, surface evaporation, and the water holding capacity of the soil. The soil water holding capacity varies with location, depending on soil type and properties. While vegetation is not included directly in the model, some of its effects are approximated by specifying different soil depths and evapotranspiration rates at different locations.

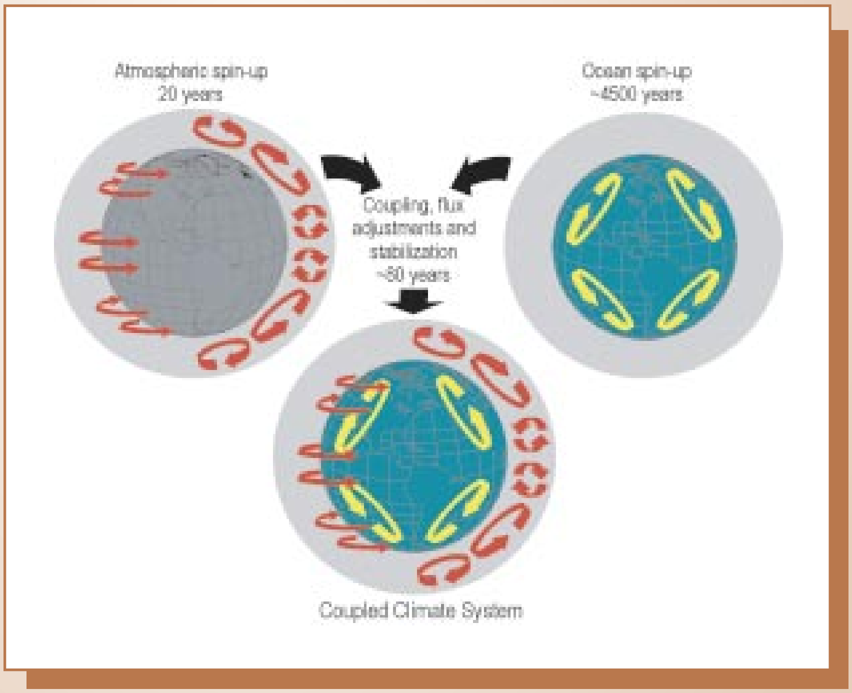
To operate the model, the ocean and atmospheric models are first individually "spun up" to an "equilibrium" condition equivalent to our present climate, and the components are then coupled together so that the atmosphere and ocean interact on a daily basis. However, errors in the modelled flow of heat and moisture between the ocean and atmosphere can cause the model to drift with time and produce unrealistic results. These errors are thought to be linked to omissions and inaccuracies in some of the models' approximations of ocean and atmospheric processes.

Modelling groups have resorted to two different ways of dealing with the drift problem. Some assume that the drift will remain the same throughout their climate change experiments and can thus be subtracted out of the results once the rate of drift has been determined in simulations of the present climate. Most groups, including the CCCma, though, attempt to eliminate the drift by making adjustments to the flow of heat and fresh water between the ocean and the atmosphere. These flux adjustments, as they are called, are then used in any experiment that the model runs. While both methods have their advantages and disadvantages, researchers cannot rule out the possibility that either of them could introduce unforeseen errors into experimental results. Researchers at CCCma and elsewhere have given a high priority to reducing and eventually eliminating the need for flux adjustments in future models.

Spinning up the Coupled Climate Model

General circulation models simulate the climate system using mathematical equations that describe the earth's radiation budget, its translation into heat and motion, and the operation of the water cycle. However, before they can be used for climate studies, these models must first be "spun up" to achieve an approximate state of equilibrium within the simulated climate system. For the atmosphere, this spin-up process can be completed within a few years of simulated time. However, the oceans, which respond much more slowly, require several thousand years of spin-up to reach a state of approximate equilibrium.

To save valuable computing time, the atmospheric and oceanic components of a coupled model are usually spun up separately before being connected, although some basic interactions between the atmosphere and the oceans must still be programmed into each component during the spin-up. In the case of CGCM1, the atmospheric component is first coupled to a non-circulating "slab" ocean system with sea surface temperatures that approximate actual observed values and then run until it approaches equilibrium. The atmospheric model is then run for a further 20 years so that researchers can calculate the average flux of energy and fresh water between the atmosphere and the ocean surface and estimate surface winds over the ocean. This information is then used in spinning up the ocean model, which is run for a simulated period of more than 4500 years to allow it to reach an equilibrium that is close to actual observed conditions. At this point, the two components are coupled together. However, because of the separate spin-up processes, there remain important differences between the atmospheric model's estimate of the amount of heat and moisture being transferred to and from the oceans and the ocean model's estimate of these transfers. If these fluxes don't balance, they can cause a large drift with time in the simulated climate. As a result, a flux adjustment, based initially on the differences in these values, is applied to the coupled system.



The two model components are then allowed to interact fully and to adapt to each other for a simulated period of a decade or so. Additional refinements are subsequently made to minimize any drift remaining in the coupled system. The system is then run for an additional 70 years to allow initial ripples in the system to fade away. Once it has stabilized, the model is run in this "control" mode for up to 1000 simulated years to produce statistical output useful for studying the natural variability of the model's climate. This information is also used in assessing the model's ability to approximate the real climate system, and as a reference against which to compare results from climate change experiments with the model.

CGCM1 PERFORMANCE EVALUATION

The need for flux adjustments is a reminder that models are simplified approximations of a very complex reality, and that their results must be interpreted with caution. That is why modelling groups put considerable effort into evaluating the reliability of their models. Such assessments not only indicate where the model's performance is acceptable and where it is weak but also help investigators interpret experimental results and refine the model's components.

The performance of a model can be evaluated in a variety of ways. One basic test is its ability to reproduce the principal characteristics of the present climate. Other important checks include the model's ability to simulate past climatic changes as well as its performance in relation to other climate models.

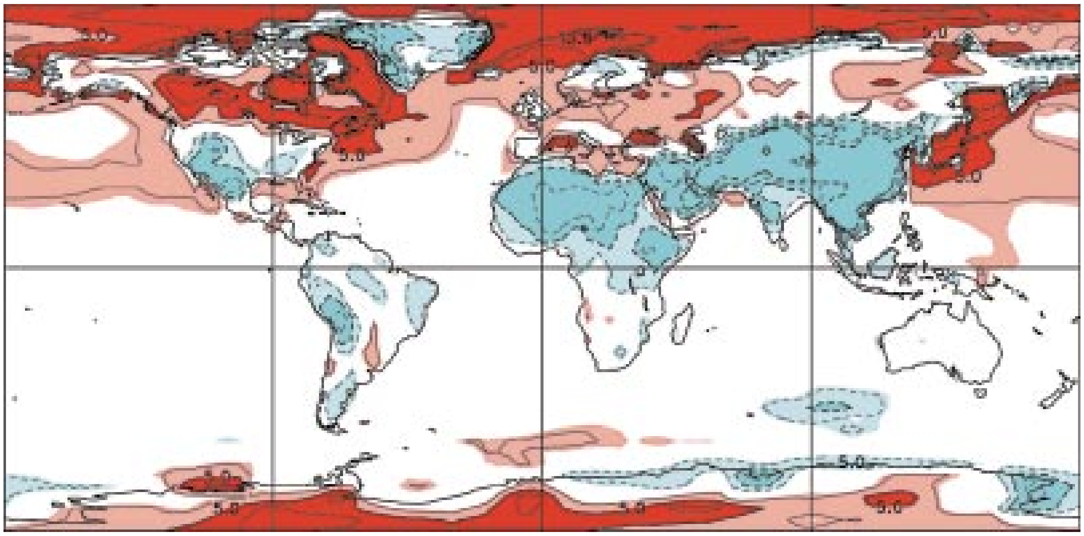
Model Intercomparisons

Model comparisons with observed climate and with results of other models are carried out within the World Climate Research Programme, primarily through the Atmospheric Model Intercomparison Project and the more recent Coupled Model Intercomparison Project. Results from these comparisons and other studies confirm that CGCM1 provides a generally realistic description of the global-scale features of the world's climate system. More specifically:

- The CGCM1 model climate is quite stable, with a very slow residual drift of 0.15°C per century (about ten times smaller than the temperature changes expected during the coming decades as a result of human impacts on the climate system).

Figure 1

Discrepancies in Modelled vs Observed Surface Temperature



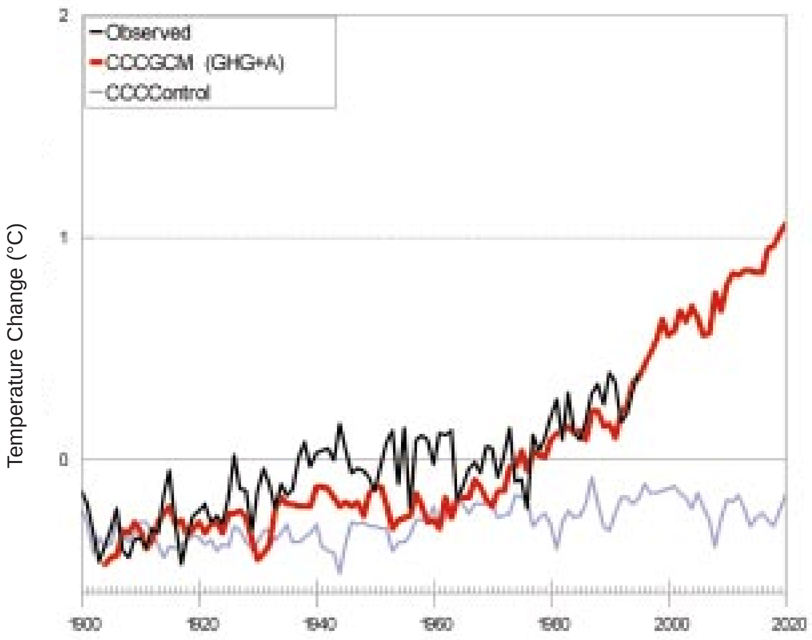
Source: Flato et al. (2000)

Differences between CGCM1 simulations and observations of surface temperature, shown here for the winter months of December, January, and February. In general the simulated temperature agrees quite well with observed conditions. There are, however, significant discrepancies over some land areas and over the Arctic Ocean.

- Mean global temperatures, sea level pressure patterns, and the atmospheric circulation are close to those observed in reality. Features similar to the Southern Oscillation (which plays a role in the El Niño phenomenon), the North Atlantic Oscillation (which is linked to periodic changes in European weather patterns), and other patterns of internal climate variability are also reproduced. In this respect, the model's performance is among the best of the coupled models tested under the inter-comparison programs. However, as Figure 1 shows, there are some notable discrepancies between the model's simulation of regional temperatures over land areas in winter and those observed. These are most pronounced in mountainous regions and over the Arctic Ocean. In addition, while CGCM1 captures the year-to-year variability of temperatures over land quite well, it underestimates such variability over some ocean areas, such as the tropical Pacific.
- Global precipitation patterns also appear to be reproduced realistically, although these are more difficult to evaluate than temperature and pressure.
- Ocean circulation, heat transport, and salinity patterns are generally within the range of observation-based estimates. Some discrepancies between simulated and observed patterns occur in polar regions.
- Ice extent is approximated reasonably well in the Antarctic but underestimated in both summer and winter in the Arctic. Global snow cover agrees well with observations, particularly in winter, although it is overestimated in some regions

Figure 2

Projected and Observed 20th Century Temperature Trends



Sources: Flato et al. (2000); NOAA

Trends and variations in average global surface temperatures as simulated in the CGCM1 control run (blue line) and one of the GHG + aerosol runs (red line), compared with observed climate trends (black line).

(e.g., the Mongolian Plateau) and underestimated in others (e.g., western Europe). Some of these discrepancies may be due to poor observational data rather than model deficiencies.

Simulations of Recent Climate History

CGCM1 has also been tested to see if it can realistically simulate changes in the world's climate over the past century. To do so, a series of experiments was run with the model. The first of these was a control run in which greenhouse gas concentrations and other external forces of change were held constant. The purpose of this experiment was to provide a reference or baseline against which the results of the other experiments could be compared. A second experiment (GHG) considered only increases in greenhouse gas concentrations, converted to an equivalent or "effective" concentration of carbon dioxide. Finally, a set of three experiments (GHG+A) looked at the effects of greenhouse gases and an additional factor, the direct effect of sulphate aerosols. These are tiny airborne particles that, like greenhouse gases, are largely byproducts of the burning of fossil fuels. Unlike greenhouse gases, however, they have a cooling effect on surface temperatures because they reflect incoming sunlight back to space. Sulphate aerosols differ from greenhouse gases as well in being relatively short-lived. They are thus concentrated downwind of the areas in which they form (mostly eastern North America and Eurasia), and their effects consequently tend to be more localized than those of greenhouse gases, which have much longer atmospheric lifetimes and are more evenly distributed around the world.

Each of the greenhouse gas plus aerosol experiments began with slightly different initial conditions in order to introduce an approximation of natural variability and noise within the climate system into the experiments. Changes in the concentration and distribution of sulphate aerosols were based on independent estimates compiled by aerosol experts using chemical models. Both the greenhouse gas and aerosol scenarios used in these experiments were similar to those used by other modelling groups.

The model did not take account of the indirect effects of sulphate aerosols on cloud properties, and hence climate, since these are still not adequately understood. For much the same reason, the effects of variations in the intensity of the sun, stratospheric ozone depletion, and changes in concentrations of non-sulphate aerosols were also excluded, although these have undoubtedly had some influence on climate over the past century (see box on *Possible Causes of Recent Climate Change*).

When the experiments were carried out, the simulation with greenhouse gases only overestimated the amount of temperature change, showing a global increase of 0.8°C since 1900, somewhat higher than that observed. The spatial pattern of the increase also did not show some of the areas of surface cooling evident in climate observations.

The three experiments that included both greenhouse gases and aerosols, however, reproduced the climatic changes of the past century with a respectable degree of realism. As shown in Figure 2, the modelled increase in the average global temperature of 0.6°C is consistent with the best estimates derived from climate records, although the model tended to underestimate average global temperatures in the middle of the twentieth century, perhaps because of natural variability or changes in climate forcings not accounted for by the model.

In addition, the major patterns of climate change as shown by the model experiments were qualitatively similar to those observed. The greatest warming in the central and northern areas of the Northern Hemisphere occurred in winter, while pockets of cooling formed over parts of the oceans and, in summer, over localized areas of the continents. The greatest warming in the Southern Hemisphere occurred over the mid-latitude oceans. The patterns of change differ in detail between the three experiments. These not only provide a realistic indication of the model's ability to simulate the variability of the natural climate but also show how such random fluctuations can make the effects of greenhouse gases and aerosols harder to detect.

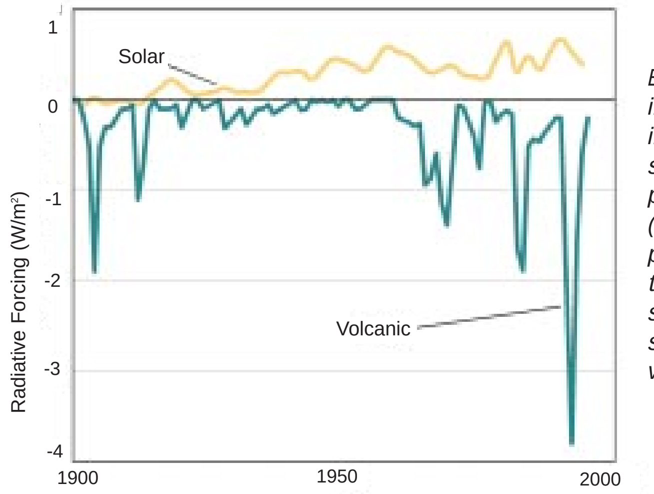
These results indicate that the internal processes of CGCM1 are operating realistically.

Recent Causes for Climate Change

During the past century, several processes external to the climate system are believed to have influenced trends in global climate. As illustrated in the figures below, these include:

- ***Changes in solar intensity.*** *The output of energy from the sun varies slightly from decade to decade, and there is also evidence that solar intensity has increased somewhat over the past 3 centuries. The causes for these decadal fluctuations and the longer-term trend are not well understood, and there is considerable uncertainty about the magnitude of these changes, but they may have some important effects on our climate. Best estimates suggest that these changes have increased the amount of energy flowing into the lower atmosphere by about 0.2 watts per square metre over the past century. Some experts suggest that the trend towards increased solar intensity may reverse during the next century.*

- ***Changes in concentrations of stratospheric aerosols.*** *Large quantities of aerosols (i.e., liquid and solid particles) can be injected directly into the stratosphere by explosive volcanic eruptions such as that of Mt. Pinatubo in 1991. These aerosols, which are predominantly composed of sulphates, are highly effective reflectors of incoming sunlight, and, during peak concentrations following such eruptions, can cause a net surface cooling of up to 0.5°C. This cooling effect is episodic, however, as the aerosols settle out of the atmosphere over a period of three to five years, and it can only be sustained if several large explosive eruptions occur in close succession. During the period between 1920 and 1960, concentrations of sulphate aerosols in the stratosphere due to such eruptions were below average, thus allowing more sunlight to reach the earth's surface. This may have contributed to some surface warming during the period, although the effect is believed to be small.*



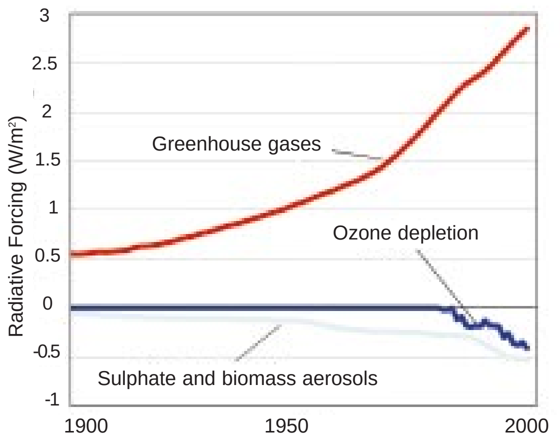
Estimated changes in net energy flow into the climate system, in watts per square metre (W/m^2), over the past century due to natural factors such as solar intensity and effects of volcanic eruptions.

Sources: Lean et al. (1995); Schimel et al. (1995)

- ***Increases in concentrations of greenhouse gases.*** *Atmospheric concentrations of long-lived, and hence well-mixed, greenhouse gases have increased substantially in all areas of the world. Carbon dioxide concentrations, for example, have increased by 30% over pre-industrial levels, methane by 145%, and nitrous oxide by 15%. Concentrations of other trace gases, some created entirely by human activities, have also increased. The increased forcing from these gases during the past century amounts to about 2.5 watts per square metre. Further increases in concentrations of these gases over the next century could add an additional 2 to 8 watts per square metre.*

- ***Increases in concentrations of tropospheric aerosols.*** *Concentrations of these aerosols, including sulphate aerosols, soot, mineral dust, and particles from burning biomass,have increased substantially over the past century as the result of human activities. Because they remain in the atmosphere for relatively short periods of time, their concentrations are highest near their sources, decrease rapidly with distance from the source, and decline quickly as sources are eliminated. Most of the increase in concentrations has occurred during the past 50 years, near and down-wind of industrialized* regions and hence primarily in the Northern Hemisphere. Their climatic effects are complex and as yet poorly understood. The direct effects of past increases in sulphate aerosols (believed to be the most dominant) through reflection of incoming sunlight are estimated to have reduced solar energy absorbed within the lower atmosphere and at the surface by somewhere between 0 and 1.5 watts per square metre. Indirect cooling effects due to changed cloud properties induced by these aerosols are as yet very difficult to estimate, but could be even larger. In future decades, this cooling influence is expected to initially increase as emissions in developing countries rise, although emissions would be slowed and perhaps reversed if emission controls were to be implemented in these countries.

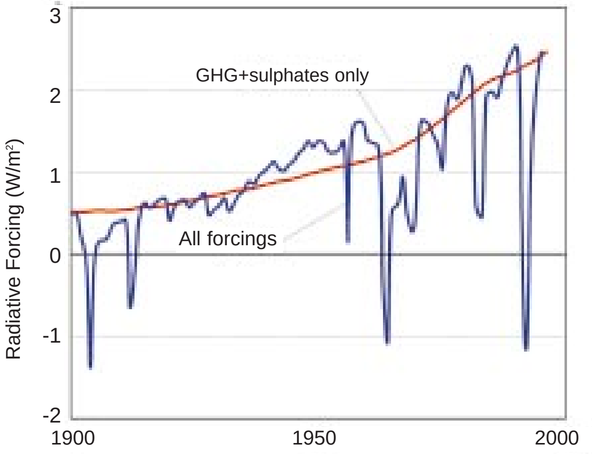
- ***Thinning of the ozone layer.*** The thinning of the stratospheric ozone layer during the past two decades has also reduced the net amount of heat energy retained by the climate system by an estimated 0.2 watts per square metre. Studies with atmospheric chemistry and climate models suggest that ozone depletion will continue to have some influence on climate for the next few decades. This influence will diminish gradually if the ozone layer recovers as expected in response to the phasing out of ozone-depleting substances under the Montreal Protocol.



Estimated changes in net energy flow into the climate system during the past century due to human influences, including well-mixed greenhouse gases (solid red), stratospheric ozone depletion (dark blue), and sulphate and biomass aerosols (light blue).

Sources: Shine et al. (1990); Schimel et al. (1995); Hansen et al. (1997)

Each of the above forces of change has a unique effect, in time and space, on the climate system. This is because each evolves in a different way, and each has a distinct effect on the flow of energy through the climate system. Changes in solar intensity and in concentrations of greenhouse gases, for example, have a global effect, whereas changes in aerosol and stratospheric ozone concentrations are more regionalized. While much remains to be known about their various influences on climate, the net effect of all these forces appears to be broadly similar in magnitude to the combined influence of greenhouse gases and the direct effect of sulphate aerosols.



Comparison of net radiative forcing due to past changes in greenhouse gas and aerosol concentrations (orange line) with that estimated if other forcing factors such as solar irradiation, ozone depletion and non-sulphate aerosols are added.

Sources: Shine et al. (1990); Lean et al. (1995); Schimel et al. (1995); Hansen et al. (1997)

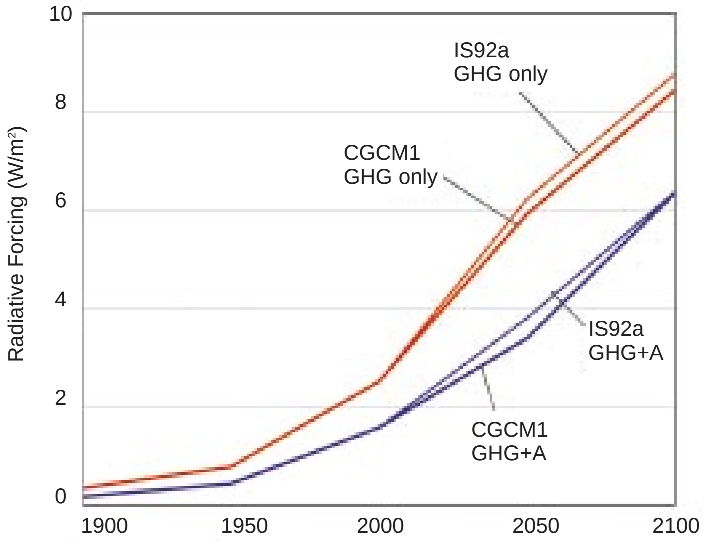
CGCM1 EXPERIMENTS FOR PROJECTING FUTURE CLIMATE CHANGE

Once the credibility of a model has been established through realistic simulations of past and present climates and intercomparisons with other models, it can be used with some confidence to explore future climate change. For their study of climate change in the twenty-first century, modellers at CCCma continued the control run, the GHG simulation and the three GHG+A climate change experiments beyond 1990 to the end of year 2100. The control run provided a basis for assessing model drift and natural variability and a reference against which the results of other experiments could be compared. By continuing the "historical" experiment (rather than beginning with a "cold" start), the simulations for climate change in the 21st century were given a running start (also referred to as a "warm" start) that ensured that climatic changes that had already begun in the 20th century and that were still evolving would be incorporated into the future climate change projections. It also ensured that the effects of the original differences in the starting conditions of the historical experiments would be continued into the 1990–2100 experiments and thus provide an indication of the degree of natural climate variability in the three responses to changes in greenhouse gases and aerosols.

From 1990 on, combined greenhouse gas concentrations used in the four climate change experiments were increased at a rate of 1% compounded per year. This leads to the equivalent of a doubling of 1980 concentrations of carbon dioxide (or a tripling of

Figure 3

Comparing Radiative Forcing Scenarios



Sources: IPCC (1992); IPCC (1995); Boer et al. (2000)

Comparison of the global mean radiative forcing, in watts per square metre, used for the four CGCM1 climate change experiments with that estimated for the IPCC IS92a forcing scenario used by some other modelling groups. The proximity of the lines indicates that these scenarios are very similar.

pre-industrial concentrations) by 2050. By 2100, the model's greenhouse gas concentrations are equivalent to three times the 1980 concentration of carbon dioxide and four times the pre-industrial value.

Although several other modelling groups also use the 1% compounded scenario for increases in greenhouse gases, some groups use an alternative scenario published by the Intergovernmental Panel on Climate Change in 1992. Known as IS92a, this scenario forecasts increases in greenhouse gas emissions over the next century on the basis of estimated changes in energy demand, population growth, and other factors. As shown in Figure 3, the increased energy made available to the climate system (or the "global mean forcing") is very similar for the two scenarios.

In the three "GHG+A" experiments, it was assumed that the direct effects of sulphate aerosols on the climate system for the 1990–2100 period would change little in the currently industrialized regions of the world. However, substantial increases were included for developing regions, particularly Mexico, the Middle East, Southeast Asia, and regions of South America and Africa. Aerosol concentrations in these regions peak by 2050 and then begin to decline slightly thereafter.

A number of other factors, such as changes in the intensity of the sun's radiation and the thinning of the ozone layer, may also affect the course of future climate change. Because of uncertainties about their impacts on climate, these factors were not included in the experiments. The contribution of these factors to future climate change is believed to be much less important than that of greenhouse gases or sulphate aerosols (see box on *Recent Causes of Climate Change*), but the omission of these factors from the experiments may have made the model's portrayal of decade-to-decade changes in climate somewhat less realistic.

CLIMATE PROJECTION RESULTS

The results of the climate change experiments with the CGCM1 described in the preceding section reveal a great deal about the probable direction, magnitude, and large-scale pattern of climate change in the twenty-first century. They tell us not only about projected changes in average global temperature and precipitation but also about potential changes in ocean circulation patterns, sea level, sea ice, and climate extremes as well as possible trends in regional, seasonal, and even daily patterns of climate behaviour.

Before looking at these results in detail, however, we should remember that they are only part of an ongoing process of refining our knowledge of climate change. While they do provide valuable insights into future climates, they are by no means definitive. They must be interpreted in the light of what is known about the model's strengths and limitations, the results of similar experiments with other models, and our overall understanding of the climate system. They provide a way of checking and refining our current assessments and best estimates of climate change, such as those published by the Intergovernmental Panel on Climate Change, and they also contribute to the development of new estimates based on improved simulations. These, in turn, will be modified over time as the results of future experiments with still more sophisticated models become available.

Projected Global Trends to 2100

The following discussion of the CGCM1 projections of climate change over the next century is based on the results of the three GHG + aerosol runs (the more realistic of the scenarios used), unless otherwise noted. Because climate can fluctuate considerably from year to year as a result of internal climate system variability, the model projections are calculated as changes between the average conditions over a given 20-year period against those over another 20 year reference period. For convenience, these time periods are referred to in this report by their central year. Thus, projections for "2010" actually describe average conditions for the period from 2000 to 2020, and "2050" those for the period from 2040 to 2060. Likewise, the 1975 to 1995 reference period is denoted as "1985".

Temperature. All three GHG+A runs show very similar trends in average global surface temperatures. These increase by about 0.5ºC above 1985 levels by 2010, and by about 1ºC by 2025. By 2050, the difference increases to 1.7ºC above 1985 levels, rising to about 3ºC by 2075 and nearly 4.5ºC by 2100. Neglecting the cooling effects of aerosols gives even higher increases, with average global surface temperatures in the GHG only simulation rising 2.4ºC by 2050 and nearly 5.5ºC by the end of the century. The control run, in contrast, shows temperatures remaining within a range of a few tenths of a degree of pre-industrial values.

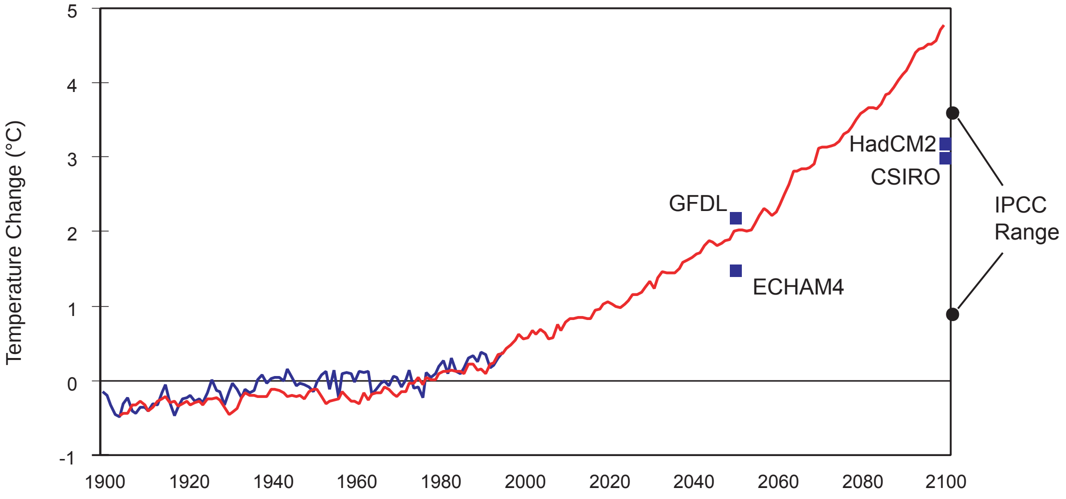
Looking beyond the global averages, one can expect temperatures to rise faster over land than over the oceans. In the three GHG+A experiments, temperatures over land masses rise, on average, by 2.5ºC by 2050, while ocean temperatures warm by 1.5ºC. By 2100, however, the spread between land and ocean temperatures increases, with land surfaces warming by 6ºC and oceans by 3.5ºC.

When the Intergovernmental Panel on Climate Change completed its second assessment of climate change for the United Nations in 1995, it estimated that the probable range of increase in the earth's average surface temperature over the next century would lie somewhere between 1ºC and 3.5ºC, if the effects of both greenhouse gases and sulphate aerosols were taken into account. As Figure 4 shows, CGCM1's three GHG + A simulations remain close to the upper limit of these estimates until about 2060, as do the results of similar experiments with four other advanced models. After that, however, the projections of the various models begin to diverge as a result of differences in model characteristics. CGCM1 shows more warming by 2100 than either the IPCC estimates or the two other models whose experiments extend that far, but the projections for all three models appear to be well above the mid-point of the IPCC range.

If these model projections are correct, then average global temperatures can be expected to approach and possibly exceed levels that have not been seen

Figure 4

Projected Changes in Global Surface Temperature

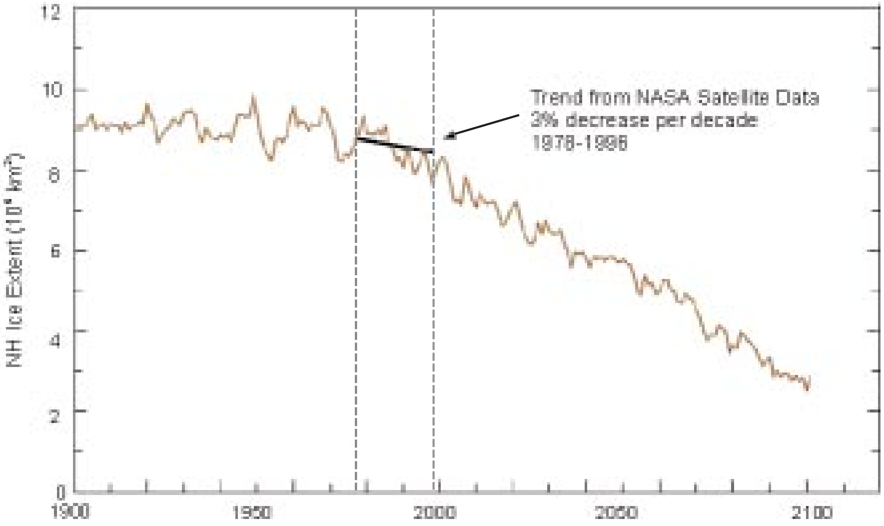


Source: Boer et al. (2000); IPCC Data Distribution Centre

The CGCM1 simulation (red line) projects a warming relative to the 1951–80 temperatures of more than 4°C by 2100. Results from other modelling experiments for the 2050 and 2100 time periods (blue squares), as well as observed trends and the range of expected warming in 2100 projected by IPCC in 1995 (black dots), are also shown for comparison.

Figure 5

Projected Changes in Arctic Sea Ice Cover



Source: G. Flato

CGCM1 projects that sea ice cover in the Arctic will decrease dramatically by 2100. Recent trends as measured by satellite are shown for comparison.

since the warm interglacial period that preceded our last great ice age, some 125,000 years ago. The rate at which this change will occur is also notable. The transition between the peak of the last ice age about 25,000 years ago and the start of our present interglacial about 10,000 years ago involved a global temperature increase of 4–8ºC spread across several millennia. While projections for temperature increases over the next century are of almost the same order, the period in which they occur will be dramatically shorter.

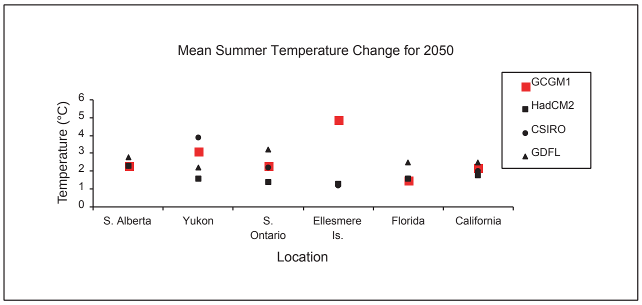
Precipitation. When temperatures rise, evaporation from surface waters also becomes greater and the water cycle becomes more active. As a result, average global precipitation can be expected to increase as well. The CGCM1 experiments project an increase of about 1% by 2050 for the GHG+A runs and more than 2% for the GHG only scenario. By 2100 these estimates rise to 4.5% and 7% respectively. These increases occur primarily over the oceans (where surface moisture is readily available) and over land masses in the higher latitudes of the Northern Hemisphere. Elsewhere, average precipitation over land changes little or decreases. Because of increased temperature and evaporation, almost all land areas experience a decrease in average soil moisture, particularly in summer. The type of precipitation over the Northern Hemisphere also changes as the climate warms. The snow season becomes significantly shorter, and the area covered by snow decreases by more than 30% in winter.

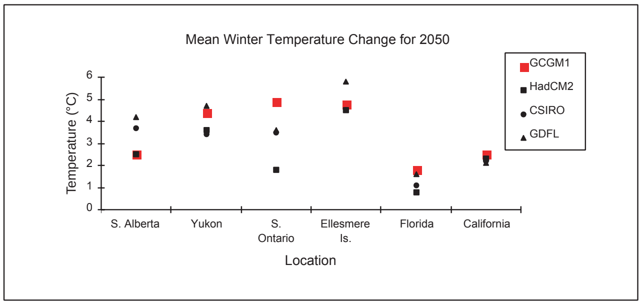
Sea Ice. CGCM1 projects major changes in sea ice coverage in the Northern Hemisphere, with annual mean coverage decreasing by about 40% by 2050 and virtually disappearing by 2100 (Figure 5). The resulting increase in the amount of open water and the duration of the open water season in the High Arctic has important implications for the regional climate, since open water allows more moisture to escape into the atmosphere above it and absorbs more incoming sunlight. This, in turn, increases regional precipitation, particularly in winter, and allows more heat to escape from the ocean into the atmosphere. Changes in ice conditions in the Southern Hemisphere, in contrast, are much less dramatic, mainly because of a more modest warming in waters surrounding Antarctica.

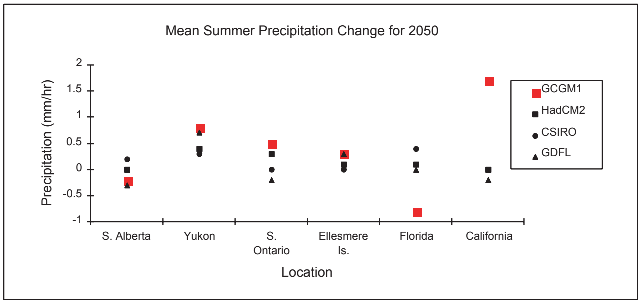
Comparisons with Projections from Other Climate Models

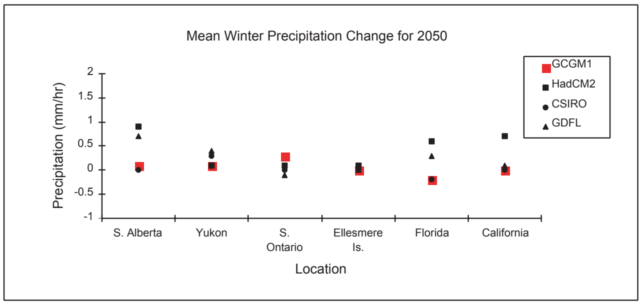
Several other climate models have been used to conduct experiments similar to the one described here. All show significant warming during the twenty-first century in response to increasing concentrations of greenhouse gases and changing concentrations of aerosols, with temperature increases for the century in the upper half of or above the 1–3.5°C range estimated by the Intergovernmental Panel on Climate Change in 1995. Using similar forcing scenarios, the UK Hadley Centre, the American GFDL, the German MPI, and the Australian CSIRO modelling groups project temperature increases of between 1.4° and 2.2°C for the 2040–2060 period, or an average of 1.8°C for all four models. In comparison, CGCM1's projection for the same period is about 2°C. Other coupled models, in general, show continental-scale characteristics similar to those of CGCM1 as well as a comparable pattern of enhanced land mass warming relative to the oceans.

At the regional and local levels, however, some important differences can emerge. Such differences underscore the lack of confidence in the details of model simulations at such scales. The following illustrations provide some comparisons between CGCM1's projections for temperature and precipitation changes between 2040 and 2060 and those of three other models for six relatively small areas within North America – Ellesmere Island, the northern Yukon, the central Prairies, southern Ontario, Florida, and southern California. All show considerable warming, but the range between results is also substantial for most locations. All of them also show modest changes in summer precipitation for the four Canadian sites, but CGCM1 shows more dramatic changes for the two American sites. Similarly, all show increased precipitation at the two Arctic sites but disagree on the direction of summer rainfall changes in southern Canada. All four models show winter precipitation changing little or increasing at all six locations. These results are a reminder that regional and local results must still be used with caution, particularly for precipitation. For that reason it is important to have results available from a number of advanced models when assessing the social and ecological implications of climate change.


Mean Summer Temperature Change for 2050


Mean Winter Temperature Change for 2050


Mean Summer Precipitation Change for 2050


Mean Winter Precipitation Change for 2050

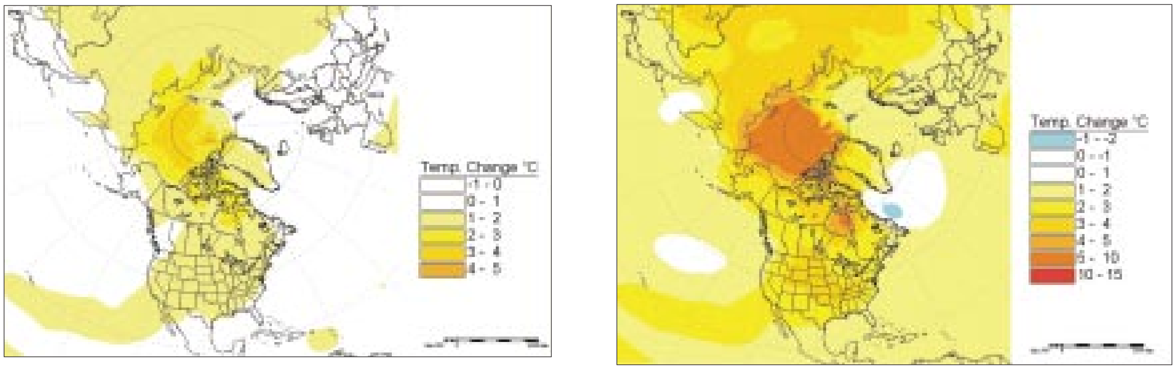
Ocean Circulation. In the North Atlantic and off the coast of Antarctica, the surface sea water becomes very cold and salty, and its density causes it to sink rapidly from the ocean surface to the ocean floor at certain locations. This process, known as deep water formation, plays an important role in the planet's climate because it produces an overturning "thermohaline" circulation that causes the sinking cold water to flow southward in the deep ocean and warmer surface water containing vast quantities of heat to flow towards these higher latitude regions to replace the sinking water. Much of the heat from this water is transferred to the atmosphere.

Simulations with CGCM1, as well as with other models, predict a slowing down of this overturning circulation during the 21st century. This is because the models project that a higher flow of fresh water into the North Atlantic from increased high latitude precipitation will reduce the salinity of the surface water and cause an estimated 50% decrease in the rate of deep water formation by 2100. That, in turn, would cause a major decrease in the movement of warm tropical waters into the North Atlantic, thus offsetting some of the expected atmospheric warming in this region. Small areas within the northwestern Atlantic, as well as in the Southern Ocean, are actually projected to become slightly cooler than they are now.

Trends in North America and Adjacent Regions

While global averages and patterns give a useful indication of the expected magnitude and general characteristics of climate change, it is at the local and regional levels that climate change will be experienced and responded to. Regional changes, though, could be quite different from the global averages. Consequently, there is considerable interest in what the models have to say about climate change at the regional level. Regional climate projections, however, are generally less reliable than global projections and should be treated with greater caution. Model intercomparisons are especially important at this level as a way of estimating the degree of uncertainty in the results.

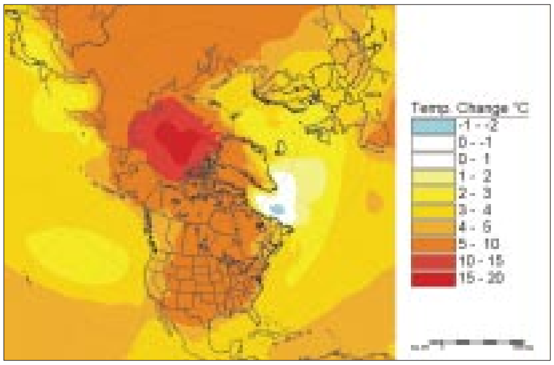
Figure 6
Projected Changes in Annual Temperature



a) 2010–2030

b) 2040–2060

c) 2080–2100



Source: CCCma

CGCM1 projections of Northern Hemispheric annual temperature change relative to mean values for 1975–1995 for (a) 2010–2030, (b) 2040–2060, and (c) 2080–2100.

Temperature. Because land masses warm faster than oceans, warming over the North American continent can be expected to be greater than the global average. For most of the central and southern parts of continental North America, for example, the model shows average temperatures rising by 1–2ºC by 2020 and increasing to 2–4ºC by 2050 and 5–10ºC by 2090 (Figure 6). The amount of warming is broadly similar in both winter and summer. Coastal areas and the low latitudes of central America warm more slowly, but also reach temperature increases of 3–5ºC by 2090. The greatest warming, however, occurs over the High Arctic, where average annual temperatures increase by as much as 3–4ºC by 2020, 5–10ºC by 2050, and more than 15ºC in some sectors by 2090.

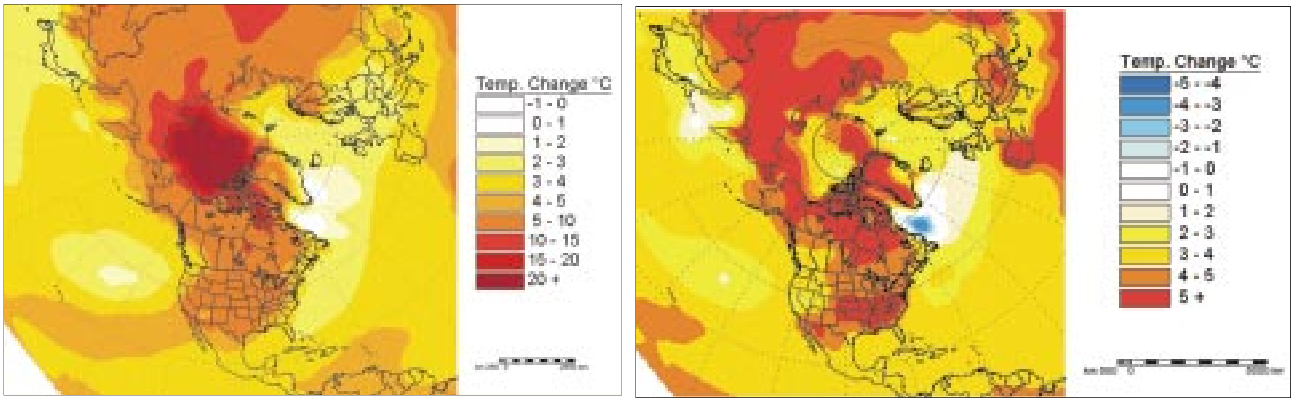
Winter changes in the Arctic are even more dramatic, with average temperatures rising considerably more than 20ºC above the current average by 2090 (Figure 7). Of course, since present winter temperatures in the Arctic can extend well below –40ºC, Arctic winters would still be cold, but the model's results imply that they would be much less extreme. Summer temperatures on the other hand do not warm as much because of the moderating effect of the cold waters of the Arctic Ocean.

Two factors are particularly important in shaping temperature change in the Arctic. First, the retreat of snow cover on land and ice cover on the oceans changes the Arctic surface from one that is highly reflective of incoming solar energy to one that is more absorbent. The greater amount of solar energy absorbed at the surface adds to the warming that has already taken place. This effect is particularly important in spring and fall throughout the Arctic and in summer as well in the most northerly regions. The second factor is that, as the climate warms, the ice on Arctic waters forms later in the fall, disappears earlier in the spring, and becomes thinner in winter. Consequently, its role as an insulating barrier between the cold winter air above and the warmer ocean waters below decreases. This allows much more of the ocean's heat to escape into the Arctic air during the cold seasons and warms the air considerably. The reverse, of course, is true in summer, when the ocean warms much more slowly than the air and thus reduces the rate of atmospheric warming.

Temperature trends over the northern Asian land mass are broadly similar to those over North America, with warming over the continental interior reaching

Figure 7

Projected Changes in Seasonal Temperature



a) winter

b) summer

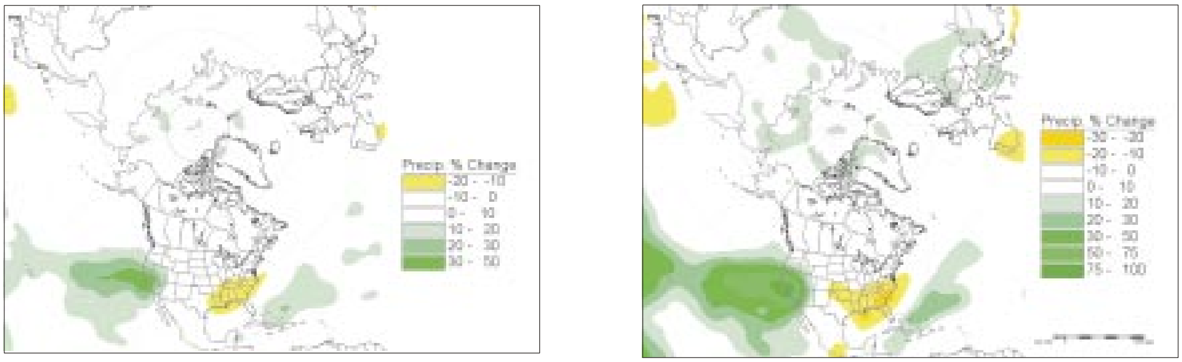
Source: CCCma

CGCM1 projections of Northern Hemispheric seasonal temperature change for 2080–2100 relative to 1975–1995 for (a) winter and (b) summer.

5–10ºC by 2090. Here, however, the pattern of greatly enhanced winter warming that was seen over the polar regions of North America extends further south into the mid-latitudes. Europe, on the other hand, warms less than either northern Asia or North America. A weaker snow reflectivity feedback could be a factor, since Europe currently also has less snow extent in winter. However, another significant influence may be the slowing down of the northward heat transport in the North Atlantic. Currently, warm tropical ocean waters brought northeastwards by this system release enough heat to the air to keep temperatures over much of Europe some 10ºC warmer than land areas at similar latitudes in other parts of the Northern Hemisphere. With the 50% reduction in the rate of deep water formation projected by the model, the movement of warm water into the North Atlantic will also be slowed and the warming effect on northern Europe will be diminished, thus offsetting some of the effects of global warming. Because of these factors, CGCM1 projects that average temperatures in northern and central Europe will warm by only a few degrees by 2050 and by about 3–5ºC by 2090. Warming in southern Europe, where the effects of the Atlantic circulation are minimal, will be similar to that in North America.

In contrast to the amplified polar warming shown by the model for Northern Hemisphere land masses and the Arctic Ocean, the North Pacific and North Atlantic Oceans warm more in the tropics and less in the middle to high latitudes. This appears to be linked to weaker ocean heat transport from the tropics to the higher latitudes as the ocean circulation system slows. Consequently, air temperatures over the tropical regions of both oceans, though warming more slowly than those over land areas, increase by 1–3ºC by 2050 and by 3–5ºC by 2090. In the mid-latitudes, on the other hand, warming in the North Pacific and much of the North Atlantic is limited to 2–4ºC by 2090, with areas in the Labrador Sea and south of Greenland showing no significant change and a small region east of Labrador actually showing slight cooling, particularly in summer.

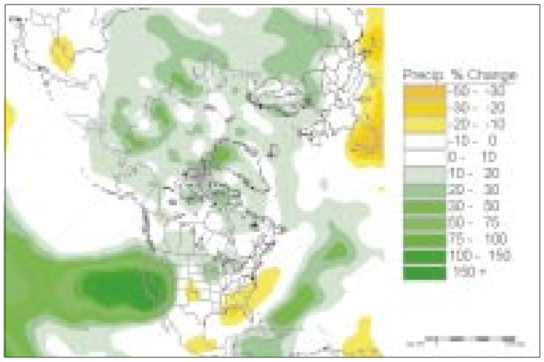
Figure 8
Projected Changes in Annual Precipitation



a) 2010–2030

b) 2040–2060

c) 2080–2100

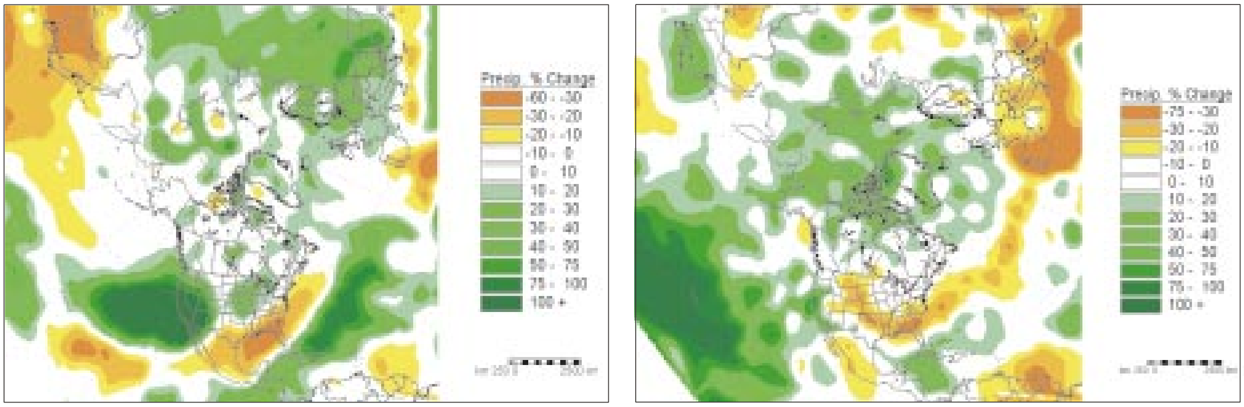


Source: CCCma

CGCM1 projections for changes in precipitation relative to 1975–1995 averages for (a) 2010–2030, (b) 2040–2060, and (c) 2080–2100.

Figure 9

Projected Changes in Seasonal Precipitation



a) winter *b) summer*

Source: CCCma

CGCM1 projections for changes in seasonal precipitation by 2080–2100 relative to the averages for 1975–1995 for (a) winter and (b) summer.

Precipitation and Hydrological Changes. Although the CGCM1 model indicates an increase in average global precipitation over the next century, there is considerable variation from region to region. In the tropical Pacific, the model shows an El Niño-like trend, with decreased precipitation in the western Pacific but substantial increases in the east extending over much of the western United States. These simulations suggest that annual rainfall averages over most of California, for example, could increase by 30–50% over present levels by 2020, by up to 100% by 2050, and by more than 150% by 2090 (Figure 8). These changes are more pronounced in winter than in summer (Figure 9). In contrast, much of central and southern North America could see significant decreases in annual precipitation by 2090, particularly in the southeast, where decreases of up to 30% are projected. These decreases are greater in winter than in summer. Southern Europe could also experience decreases in excess of 30%.

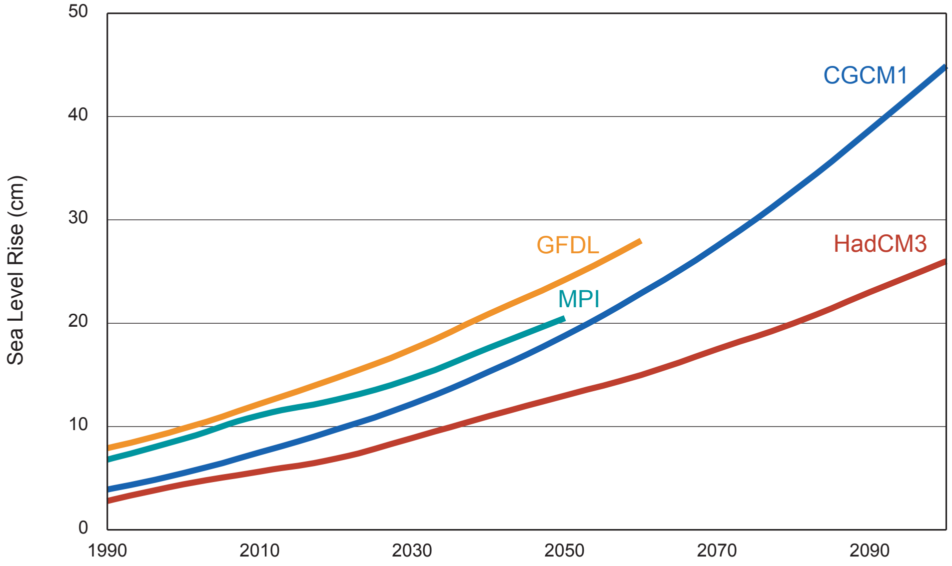
Projected changes over the middle to high latitudes of the Northern Hemisphere are more moderate, in general remaining within 10% of present levels until after 2050. By 2090, precipitation over most of Canada and northern Eurasia increases by 10–20%, although in some regions, like northern Greenland and northern Siberia (which currently receive very little precipitation), it increases by up to 50%. Most of these increases occur during winter. Such trends are consistent with both an increased flow of moisture northward from the tropics and a transition to a more maritime climate as sea ice cover over water bodies decreases.

Combined with warmer temperatures, these changes in precipitation could have important implications for soil moisture. The model indicates, for example, that most of North America would experience a notable decrease in available soil moisture, with the exception of the west coast, which would experience much wetter conditions. The reduction in soil moisture would be greater in summer. By the 2090s, regions such as Canada's southern prairies would experience serious summer deficiencies in soil moisture.

These changes illustrate the sensitivity of regional temperatures and water resources to global change, but like all regional projections they are subject to considerable uncertainty and should be used with caution. Assessments of potential regional impacts of climate change should never use such results in isolation but should take account of the results of other models as well.

Figure 10

Projected Global Sea Level Rise



Sources: CCCma; IPCC Data Distribution Centre

Sea level rise due to thermal expansion of sea water as projected by CGCM1 and three other model experiments. Rates of change for three of the models are very similar, while the fourth is lower.

Sea Level Rise. As the world's atmosphere and oceans become warmer, sea levels are expected to rise. This is mainly the result of the thermal expansion of ocean waters, although the melting of glaciers and changes in the volume of the polar ice sheets play significant but secondary roles. The results (Figure 10) show a rise in average global sea level due to thermal expansion of approximately 5 cm during the twentieth century and an additional rise of 40 cm by the last two decades of the twenty-first century. This is larger than the IPCC's 1995 projection for thermal expansion of 26 cm by 2100, but the magnitude and rates of related sea level rise are broadly similar to those predicted by some other recent model experiments.

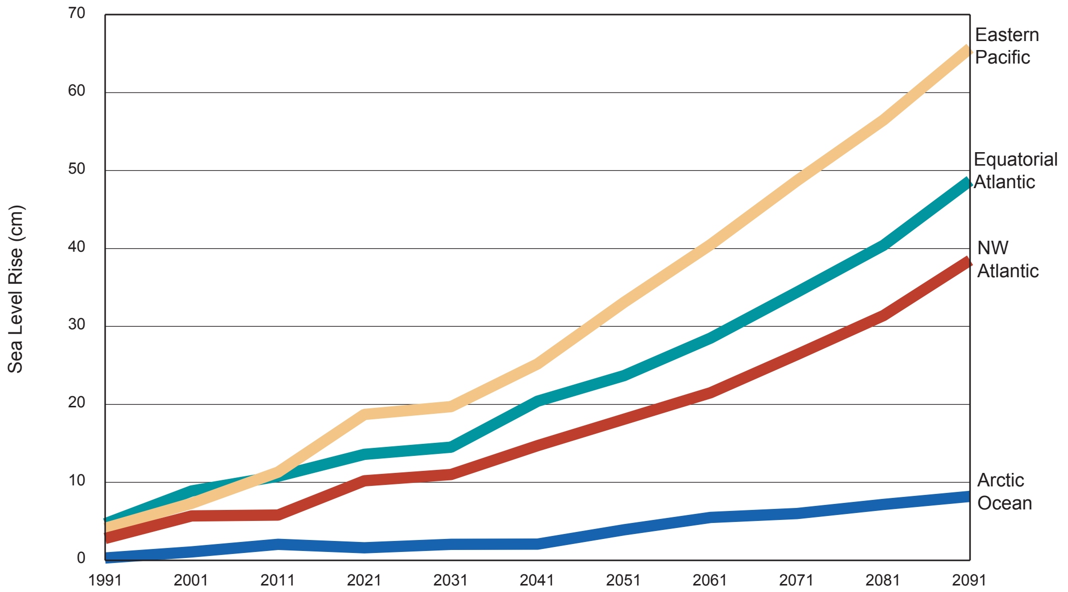
CGCM1's projections of sea level rise also show some substantial regional differences (Figure 11). In the Arctic Ocean, for example, thermal expansion results in a rise of only about 10 cm by the 2090s. In comparison, the eastern Pacific off British Columbia expands by 65 cm, the equatorial Atlantic by almost 50 cm, and the northwestern Atlantic east of the Maritimes by almost 40 cm. These results reflect regional differences in ocean temperature changes as well as other factors.

Extreme Events

Extreme climatic events are those that are rare both in their intensity and in the frequency of their occurrence. Because ecosystems and the physical infrastructure of human societies are "tuned" to normal climate conditions, they are generally poorly equipped to cope with such events. As a result, changes in the occurrence of extreme events can often have far greater detrimental impacts on ecosystems and human societies than a change in average climate conditions.

To some extent, deciding what is and what is not an extreme event is a subjective exercise. Consequently, climatologists use a variety of statistical criteria to identify such events. One of the more common is the concept of a return period. For example, an extreme event might be described as one that

Figure 11
Regional Changes in Sea Level



Sources: CCCma

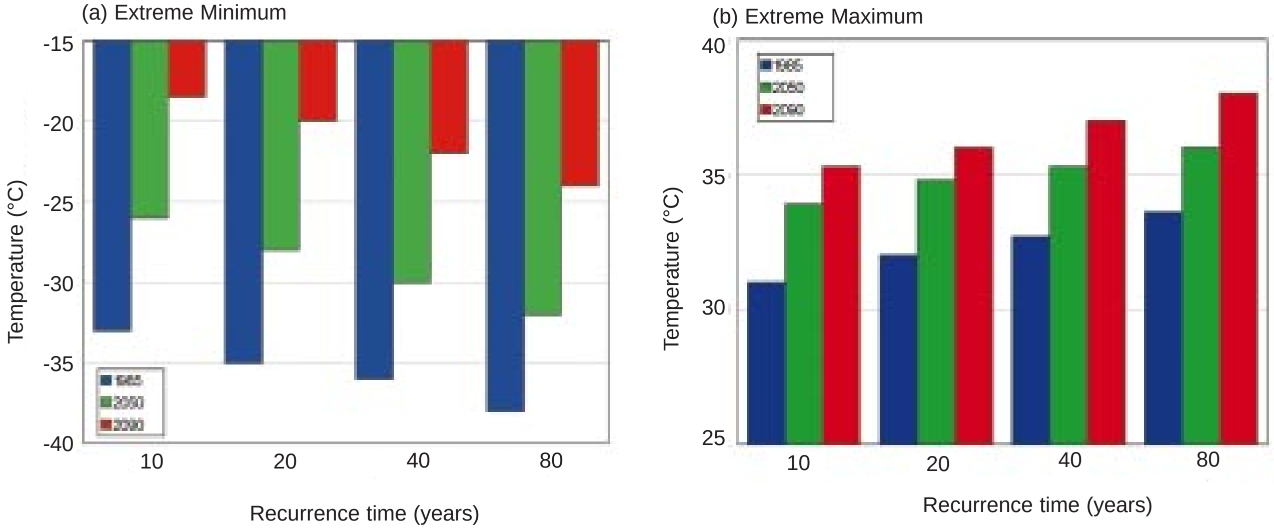
Because of different rates of ocean warming and local changes in atmospheric pressure patterns, the rates of change in sea levels due to thermal expansion vary significantly from region to region.

has a statistical probability of happening no more than once every 20 years. Such an event would then be said to have a return period of 20 years.

At the present time, models such as CGCM1 can only give us partial answers to the questions that we have about extreme events. The best information that they can provide relates to changes in extremes that occur on a large spatial scale, like those for temperature or wind speeds, and they can also provide useful information about the direction of change in extremes of other climate variables. Because of their low resolution, however, current models are poorly suited to providing more detailed information, particularly at the regional level where many extreme events take place. Furthermore, because extremes occur infrequently, very long simulation periods are needed before enough of these events are available for reliable statistical analysis. Similarly, very long records of observations of real events are needed to provide the reference base against which the model's results can be compared. As a result, validating the model's performance in simulating extremes can be very difficult. A few studies have tried to resolve this dilemma by embedding a very high-resolution sub-model of a specific geographical area within the global climate model. However, most studies with the present generation of global models still focus largely on the larger-scale aspects of changes in climate extremes. The CGCM1 studies described here followed this latter approach and concentrated primarily on large-scale changes in surface pressure, temperature, precipitation, and wind extremes. Some regional details have also been included in these studies, but confidence in these is much lower than for the larger-scale results. The following are some general results that have emerged from these studies.

Figure 12

Projected Changes in Extreme Temperatures



Source: Kharin and Zwiers (2000)

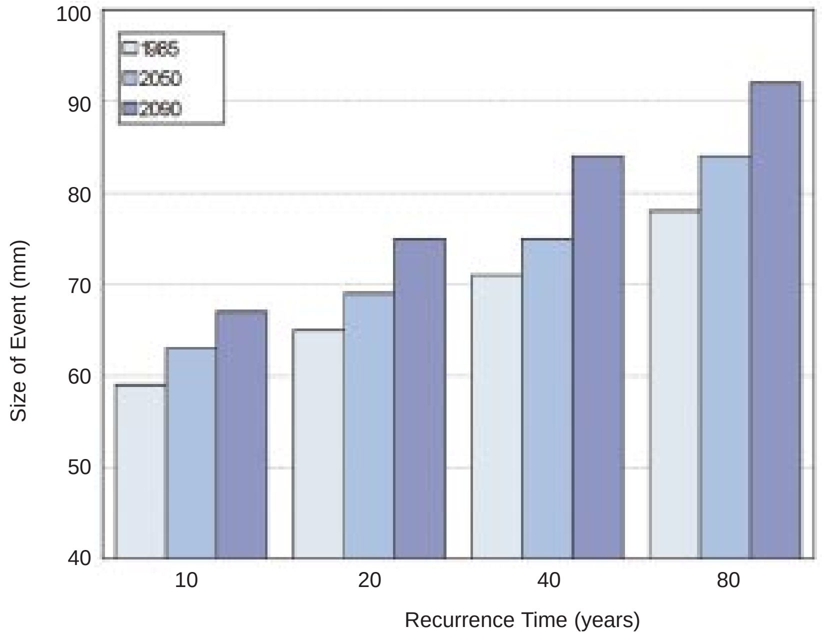
CGCM1 projections of changes in the magnitude of average Canadian (a) extreme daily minimum and (b) extreme daily maximum temperatures that can be expected to recur once every 10, 20, 40, or 80 years.

Daily Temperature Extremes. As the Intergovernmental Panel on Climate Change noted in its *Second Assessment Report* in 1995, small changes in average climate conditions can generate significant changes in extremes. However, changes in extreme temperatures can be very much influenced by changes in other climate factors as well. The disappearance of snow cover, for example, greatly enhances daytime surface warming and hence midday maximum temperatures. Drier soils can also add to the intensity of daytime temperatures by reducing cooling from surface evaporation. Conversely, while an increase in average temperature will tend to reduce the occurrence of extremely cold temperatures, in some regions the disappearance of sea ice or snow cover will significantly amplify this moderating effect by allowing much more heat to be transferred from the ocean and soil to the atmosphere, especially at night.

As Figure 12 shows, cold extremes across Canada (as represented by daily minimum temperatures) are expected to become less severe with time. By the 2050s, for example, the model projects cold extremes that now occur once every 10 years will likely occur less than once every 80 years. In some regions, these changes will be even more dramatic. In the Arctic, where average annual temperatures are projected to warm by 10–20ºC during the last half of the century, extreme minimum temperatures over open waters are expected to moderate considerably. The extreme minimum temperature with a return period of 20 years, for example, will be 25ºC warmer over open ocean areas by the 2050s than it is now and 40ºC warmer by the 2090s.

While extreme minimum temperatures will generally become more moderate in a warmer climate, extreme maximum temperatures can also be expected to become hotter. This increase can be seen in CGCM1's projections for extreme daily maximum temperatures averaged across Canada. These show that an extreme maximum temperature that has an 80-year return period today is likely to occur about once every 10 years

Figure 13
Projected Changes in Extreme Precipitation



Source: Kharin and Zwiers (2000)

Magnitude of average Canadian extreme 24-hour rainfall events for various return periods as projected by CGCM1.

by 2050. By the 2090s, the magnitudes of these extreme high temperature events are expected to increase, on average, by 4–5ºC.

A variety of physical processes, however, produce some interesting regional variations in the high temperature extremes projected by CGCM1. In the Arctic and sub-Arctic, for example, the one-in-twenty-year maximum temperature extreme changes little by 2050 and only moderately by 2090, since ocean waters in these regions warm very little. In the northwestern Atlantic, as well as in other regions where the model shows oceans cooling in summer, the one-in-twenty-year extreme actually decreases. Something similar also occurs over India, where the threshold for extreme daily maximum temperatures initially decreases and then returns to current levels, in this case because of an increase in monsoonal precipitation. In sharp contrast are the changes projected for such areas as the southeastern United States and the central plains of North America, where decreases in soil moisture result in less evaporation and hence greater heating of the surface air mass. In these regions, the daily maximum temperature extremes projected by CGCM1 increase by up to 12ºC by 2050, as compared to average daily temperature changes of 3–4ºC over the same period.

Precipitation Extremes. Analyses of the return periods of extreme precipitation events in the CGCM1 simulations suggest that rainfall will, on average, become more intense in almost all regions of the world, although the magnitude of such changes is still rather uncertain. Some of the greatest increases are expected in equatorial regions, particularly over the tropical Pacific. In this region, CGCM1 projects precipitation rates for one-in-twenty year extremes to rise by some 50 mm/day by the 2050s and by more than 70mm/day by the end of the century. An important factor in these changes is an increase in the evaporation of water from the oceans as they warm. Over continental North America, average precipitation rates for the one-in-twenty year extremes are projected to change by up to 10 mm/day by the 2050s. Such changes already suggest that damaging precipitation events can double in frequency. By the 2090s, however, increases of up to 40 mm/day in the one-in-twenty year extremes are simulated in the Gulf of Mexico region and the southeastern United States, and increases of 10–20 mm/day are projected in eastern Canada. When averaged over all of Canada, today's one-in-forty year extremes could become a decadal occurrence by the 2090s (Figure 13).

Results from these simulations also suggest that the extreme lengths of wet periods (days with more than 1 mm of rain) may decrease over many tropical and subtropical continental regions as the climate warms. The projected impact on extreme lengths of dry periods (consecutive days with less than 1 mm of rain) appears to be more variable. These are projected to increase in the Mediterranean, southern Africa, and southeast Asia, but they decrease over most of central Africa and change little over South America. Little change is indicated for Canada. However, the magnitudes of all such changes in wet and dry periods are even more uncertain than those for precipitation extremes.

Intense Low Pressure Events. Large storms can be identified in model climates as areas of low pressure, and the severity of a particular storm can be gauged by the intensity of the low pressure at its centre. Equilibrium change experiments with earlier atmospheric models showed a general decrease in storm conditions in response to a doubling of carbon dioxide in the atmosphere. However, very intense extra-tropical storms (which were defined as those with a central pressure of less than 97 kPa) were seen to increase significantly. A study of storm behaviour was also carried out using CGCM1's transient change simulations. It reveals a similar pattern: a slight decrease in the total number of extra-tropical storm events around the world by the 2090s but an increase of more than 30% in the number of very intense storms. The model shows the greatest change taking place in the occurrence of intense storms in the Southern Hemisphere.

FUTURE DIRECTIONS

Climate modelling is a continuing process in which models are constantly refined so that climate mechanisms can be simulated more realistically and greater confidence can be had in the results. At the Canadian Centre for Climate Modelling and Analysis this process has led to the development of a second and a third generation of coupled climate models.

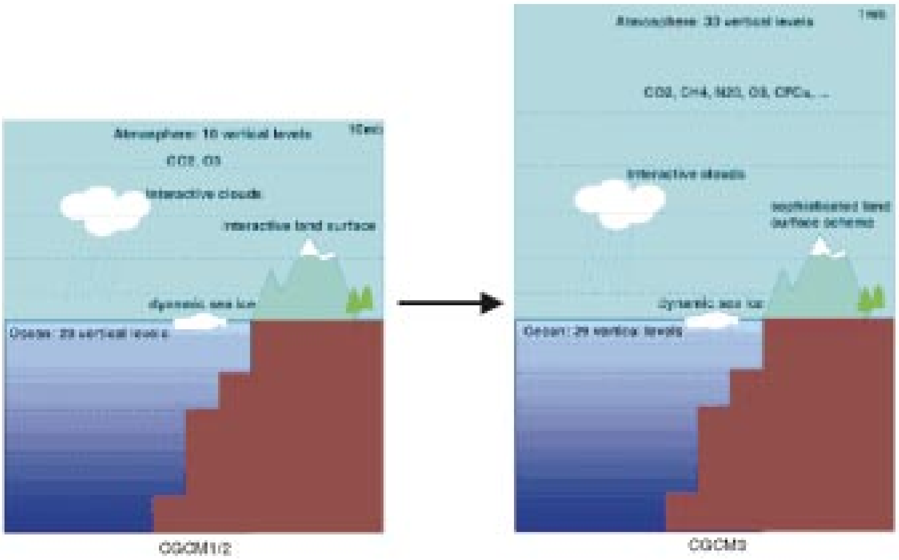
The second-generation model, known as CGCM2, uses the same atmospheric component as CGCM1, but its ocean component has been improved with the addition of a more realistic mixing scheme. The new model also has a more sophisticated sea ice component that simulates the transport of sea ice and the effects of ice deformation, both of which influence energy flow between atmosphere and ocean. The transport of ice also determines where sea ice eventually melts. CGCM2 has been used to conduct a similar suite of experiments to those described above. The results are now being analyzed and prepared for publication.

As of early 2000, the third-generation model, incorporating both a third-generation atmospheric model and a new ocean model, was in the advanced stages of development (Figure 14). The atmospheric model, GCM3, is an advanced version of GCM2. Like its predecessor, it has a physical resolution of about 3.7º of latitude and longitude, but processes controlling sea water movement are simulated at a higher resolution of approximately 2.8º of latitude (about 275 km) by 2.8º of longitude. The model is also thicker vertically. Whereas GCM2 covers 30 km of atmosphere in 10 layers, GCM3's atmosphere extends some 50 km above the earth's surface and is divided into 32 layers. Other features of the atmospheric component include:

- a new method for describing land surface processes. Known as CLASS, this new land surface scheme is considerably more detailed than the single soil-layer scheme used in GCM2. It includes three soil layers, a snow layer where applicable, and can even represent the effects of a vegetative canopy. Surface properties such as roughness and reflectivity are linked to the types of soil and vegetation and to soil

Figure 14

Improving the Structure of the CGCM



Source: G. Flato

Schematic comparing some of the differences between the structures of CGCM1 and 2 with that for CGCM3.

moisture conditions present within a given grid square of the model;

- better representation of the turbulent transfer of heat and moisture, and of atmospheric motion within the planetary boundary layer (the layer of the atmosphere closest to the surface);
- improved simulation of convective behaviour in the atmosphere (such as that associated with cumulus clouds);
- a more detailed description of solar heating;
- better representation of surface topography;
- improved simulation of surface winds and pressure distribution.

The new ocean model, known as NCOM1.3, was developed at the National Center for Atmospheric Research in Boulder, Colorado, and is based on the MOM model used in CGCM1 and CGCM2. The new model includes improvements in the representation of ocean physical processes and has been coded to take advantage of more modern computer architecture. The sea ice component is similar to that used in CGCM2 but has been improved so that the model can now determine how much of each grid cell is covered by ice and how much is open water.

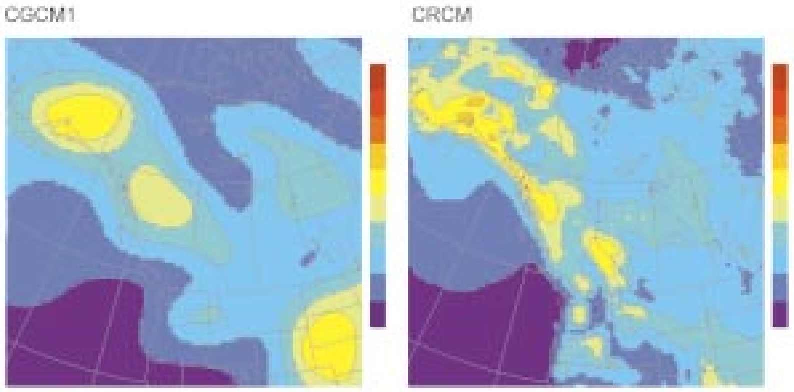
Regional Climate Models

Improving the simulation of regional climates continues to be one of the biggest challenges facing climate modellers. The main obstacle is the relatively coarse resolution of existing global climate models, since many of the processes that affect regional climates occur on a scale that is smaller than the smallest spatial unit or grid cell that present-day models can represent. The models use a variety of methods to approximate the average effect of these processes, but local variations are consequently overlooked. Much higher resolution global models would provide a solution to this problem but would also require considerably more computer capacity. Doubling the resolution in three dimensions and reducing the time step for calculations, for example, increases computational requirements by a factor of more than sixteen.

Regional climate models (RCMs) are a solution to this dilemma. These are high resolution models that can simulate climate features and physical processes in much greater detail for a limited area of the globe while drawing information about conditions at their boundaries from the larger global models. A Canadian RCM has recently been developed through the collaboration of a modelling team at the Université du Québec à Montréal and the CCCma team in Victoria. The regional model represents physical processes in much the same way as GCM2 and incorporates all of that model's advanced features. The Canadian RCM (CRCM) can be used for any region of the world and can be nested in the global model and run in tandem with it. Such nesting is a one-way process, with information flowing from the global model to the regional model but not in the opposite direction.

The performance of the CRCM has recently been tested in a series of simulations of the current climate and a doubled carbon dioxide climate for western Canada. Using a spatial resolution of 45 km (almost 10 times greater than that of GCM2, within which it was nested), the model showed increased spatial variability and detail in near-surface climate conditions, as one would expect from the greater topographical detail represented. However, there was little change in spatial variability in the free atmosphere well above the surface.

As of early 2000, three "time slice" experiments for the present and for two periods in the twenty-first century had been completed for western Canada, and a corresponding set of experiments for eastern Canada was scheduled to begin. These experiments used outputs from one of the transient climate change experiments described earlier in these pages.



Source: G. Flato

Comparison of detail in precipitation patterns over western Canada as simulated by CGCM1 and the CRCM.

CONCLUDING REMARKS

What is the value of climate model research? What does it contribute to our understanding of climate change? And how much confidence should we place in the results?

The ability of the CGCM1 experiments to successfully reproduce the general characteristics of the global climate since 1900 is a good indication that its simulation of climatic processes is largely correct, and we can therefore be fairly confident that its estimate of how the global climate is likely to change over the next century is realistic. The results of experiments into future climate change with CGCM1 and other advanced models confirm what earlier models have already indicated: that the probability of extensive climate change is both real and imminent. They suggest that the rate and magnitude of warming over the next century could certainly be within the upper range of previous expectations, if not higher. If this is so, both natural ecosystems and human societies will have difficulty adapting to a rate of climatic change that is virtually without precedent. Hence the related risks are significant.

That being said, however, it should be borne in mind that the model's results are approximations and not a precise forecast of future conditions. The accuracy of the model's projections depend, in part, on the accuracy of its assumptions about future changes in greenhouse gases and aerosols as well as the precision with which it simulates climatic processes such as water vapour and cloud response or changes in ocean circulation. If concentrations of greenhouse gases and aerosols change at rates that are significantly different from the estimates used in the model, then the model's projections will become increasingly unrealistic. Changes in natural forces that are not considered by the model could also have a noticeable effect on the actual course of climate change. An upsurge in volcanic activity, for example, or a decrease in the intensity of solar radiation could slow the rate at which the planet's temperature rises. However, these forces are unlikely to do more than partially offset the steadily rising effect of increasing concentrations of greenhouse gases. Conversely, the future role of aerosols in masking the full effects of rising greenhouse gas concentrations may have been overestimated, or the ocean's response to changing temperatures may be more abrupt than the models project. In these cases, the rate of change may be significantly more rapid and dangerous than projected by the CGCM1 experiments.

As policy makers begin to deal with the enormous challenge of reducing greenhouse gas emissions through the Kyoto Protocol, negotiating subsequent international agreements, and developing policies for reducing the harmful impacts of climate change, improved global and regional climate models will be needed to provide increasingly reliable insights into the consequences of unmitigated climate change and into the effects that different options for reducing greenhouse gas emissions will have on reducing the risks of change. They also need to provide plausible scenarios of future climate which can be used to test the sensitivity of ecosystems and social infrastructures and to support the challenging task of developing appropriate adaptive strategies to reduce the related risks. The future efforts of the CCCma and other modelling groups promise to contribute significantly to improving such scientific information.

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