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CLIMATE CHANGE DIGEST

Modelling the Global Climate System

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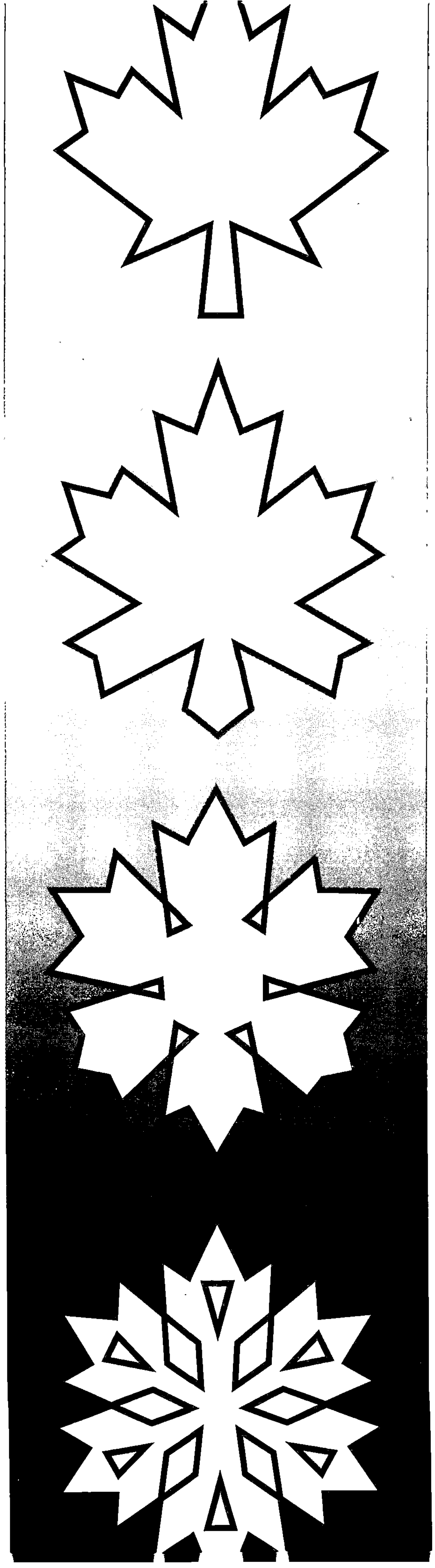
Special Edition

Canada



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MODELLING THE GLOBAL CLIMATE SYSTEM

BY

THE ATMOSPHERIC ENVIRONMENT SERVICE
ENVIRONMENT CANADA

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INTRODUCTORY COMMENTS AND ACKNOWLEDGEMENTS

Modelling the Global Climate System was prepared in response to questions often posed by policy makers and others on how climate models work and what their roles are in improving the understanding of the global warming issue. It is being published as the first of a number of "special" Climate Change Digest explanatory and overview reports, which will be issued as a complement to the regular CCD series on climate change impacts.

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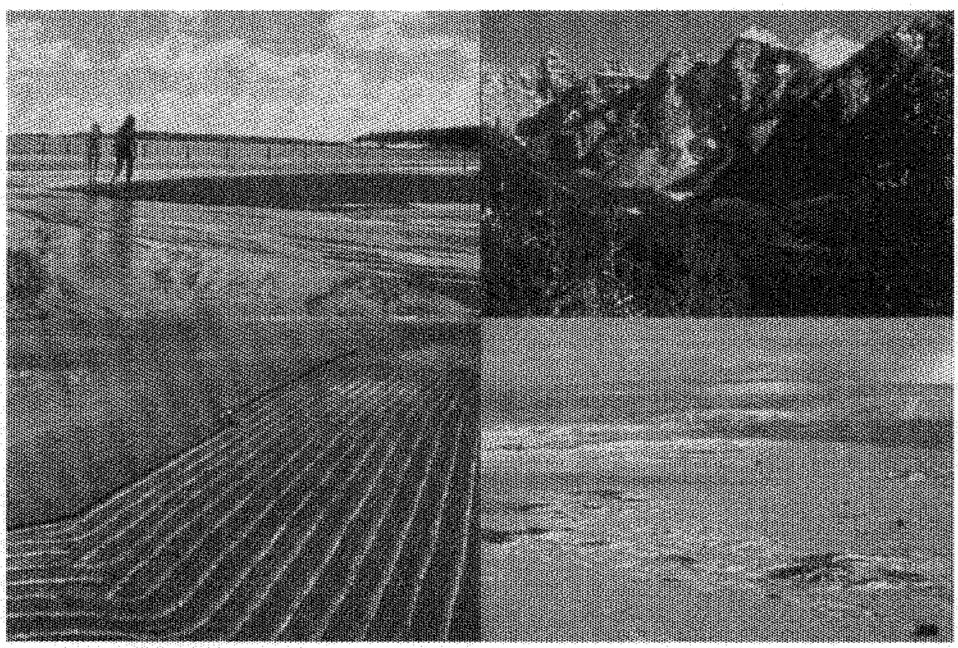


INTRODUCTION

Global warming is one of the most complex and perplexing environmental issues of the present age. For the last 200 years, the activities of a rapidly expanding and industrializing human population have added increasing quantities of heat-retaining greenhouse gases, such as carbon dioxide, to the atmosphere. Concentrations of these gases are now well beyond the highest known natural levels of at least the past 100,000 years, and they are believed to be forcing profound changes on the earth's climate system.

How we respond to the risks of such changes depends on how serious we think the problem will be and how rapidly we think it will develop. Clearly, our assessment should be based on sound scientific knowledge. Unfortunately, science cannot yet give all the answers we need with an adequate level of confidence.

Global warming has been studied intensively by scientists for several decades now. Most argue that there is a high probability of major global warming during the next century. But they also acknowledge that uncertainties in our understanding of the climate system and its complex behaviour make it difficult to project with confidence how much warming will occur, how quickly it will take place, or what its regional characteristics will be. Resolving or reducing these uncertainties has become a priority for current climate research efforts in Canada and elsewhere.

Climate touches almost every aspect of Canadian life. Because of this, global warming is likely to require significant adjustments in our society and economy. Understanding the nature and consequences of climate change has therefore become a priority for the Canadian scientific community.

One of the central features of this research has been the use of numerical climate models – and, in particular, powerful computer-based representations of the global climate system known as general circulation models (GCMs) – to estimate the effects of increasing greenhouse gas concentrations on the world's climate. These models have added greatly to our knowledge of climate change.

In Canada, so many aspects of our economy and everyday life, particularly in resources sectors such as agriculture, forestry, fisheries and energy, are highly sensitive to extreme weather events and other variations of our climate. Hence, understanding the way climate functions and responds to change is vitally important to us. Canadian scientists have taken a leading role in global efforts to better understand the climate system, and their work is providing valuable support for the development of domestic policies and strategies to reduce Canadian vulnerability to climate variability and change. At the same time, international recognition of Canadian expertise in climate research has given Canada an influential voice in shaping effective global research efforts and in the development of effective international responses to global warming. Numerical modelling has become a central component of the Canadian climate research effort.

THE CLIMATE SYSTEM

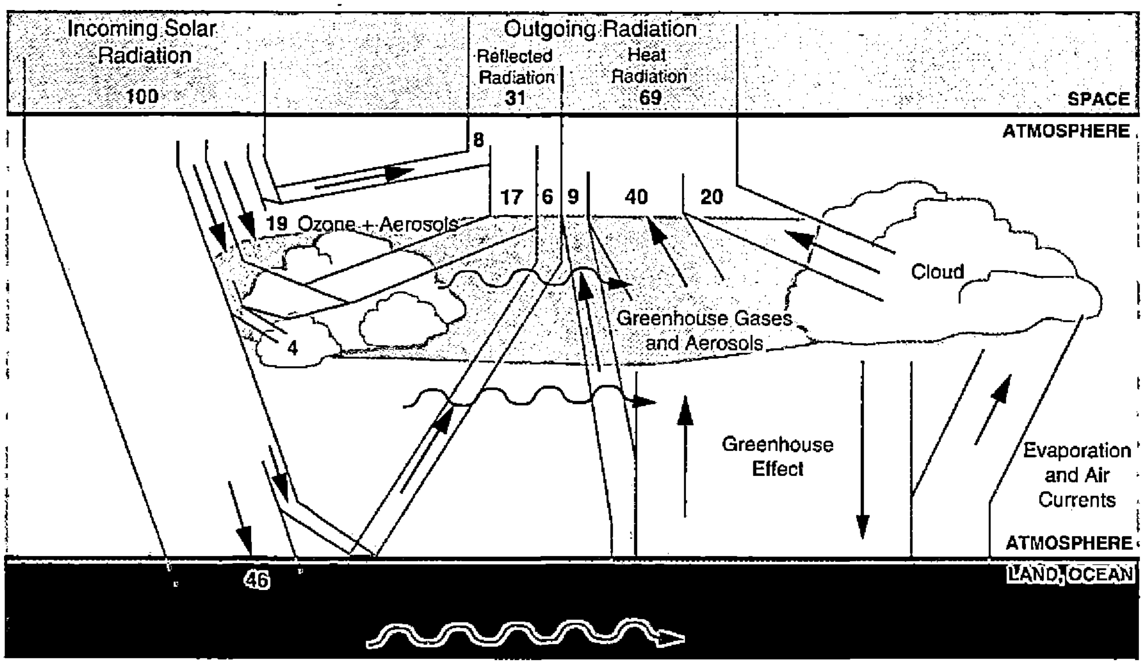
The climate system can be thought of as a heat engine composed of three sub-systems: a radiative energy flow system, a circulation system, and a water cycle.

Radiative energy flow is the source of energy that drives the engine. Fuelled by short wave radiation from the sun, it provides the energy that heats the earth's surface and atmosphere. Long wave heat energy radiated back to space from the earth's surface and atmosphere cools the system off again. In equatorial latitudes, the heating caused by incoming solar energy exceeds the cooling by the outgoing long wave energy, while, in polar regions, the cooling exceeds heating. The resulting temperature difference between the equator and the poles drives the climate's circulation system, which sets the winds and ocean currents in motion. Meanwhile, incoming solar radiation also evaporates water at the earth's surface to drive the water cycle. The evaporated water, as it rises in the atmosphere, transports latent heat energy with it. When it reaches higher levels in the atmosphere, the heat is released again as the water vapour condenses to form clouds and eventually precipitation. Atmospheric winds can help transport clouds and precipitation long distances from their source. Thus the water cycle and the circulation system let the climate engine accomplish its work of redistributing heat and moisture both vertically and horizontally around the globe.

While these are the basic mechanisms of the climate system, its actual operation is complicated by a host of other factors. In the atmosphere, fine particles and trace gases such as ozone, carbon dioxide, methane and sulphur dioxide – whose presence is measured in parts per million or less – alter the amount of energy entering and leaving the climate system. So do clouds and the reflective properties of different parts of the earth's surface. The flow of gases, particles and moisture into and out of the atmosphere, as well as the surface reflective properties, are in turn influenced by biological and physical processes within the oceans and land ecosystems. Sporadic events such as volcanoes also have an influence. As the atmosphere circulates in response to the temperature gradient between the equator and the poles, its motion is also affected by the earth's rotation, the force of gravity, the temperature of the underlying ocean and land, and the presence of topographical features such as mountains. Likewise, the ocean circulation is affected by other factors, such as precipitation patterns, surface winds, and water salinity.

One of the most important features of the climate system is that it responds to changing conditions in a manner that restores and/or maintains the balance between the rate at which energy enters the system (as short wave radiation from the sun) and the rate at which it leaves it (as long wave radiation released to space). As long as this radiative balance is preserved, the climate system remains stable and the average global temperature stays relatively constant from one year to another. However, if a change in one part of the system (such as increased concentrations of greenhouse gases) upsets this equilibrium, the resulting imbalance induces secondary changes and reactions in other parts until the system arrives at a new equilibrium. These secondary changes are known as feedback responses, and they can modify substantially the outcome of the initial change. Feedbacks that reinforce and amplify the initial change are known as positive feedbacks. Those that offset and diminish it are negative.

We can see how feedbacks operate by considering the example of water vapour. Because the evaporation rate of water and the capacity of air to retain water vapour both increase with temperature, a warmer



THE ENERGY BALANCE

The amount of energy that drives the climate system is determined by the energy entering the system as short-wave radiation from the sun. However, in a stable climate system this energy must be balanced, when averaged over time, with energy returning to space as long-wave radiation from the earth's surface and atmosphere.

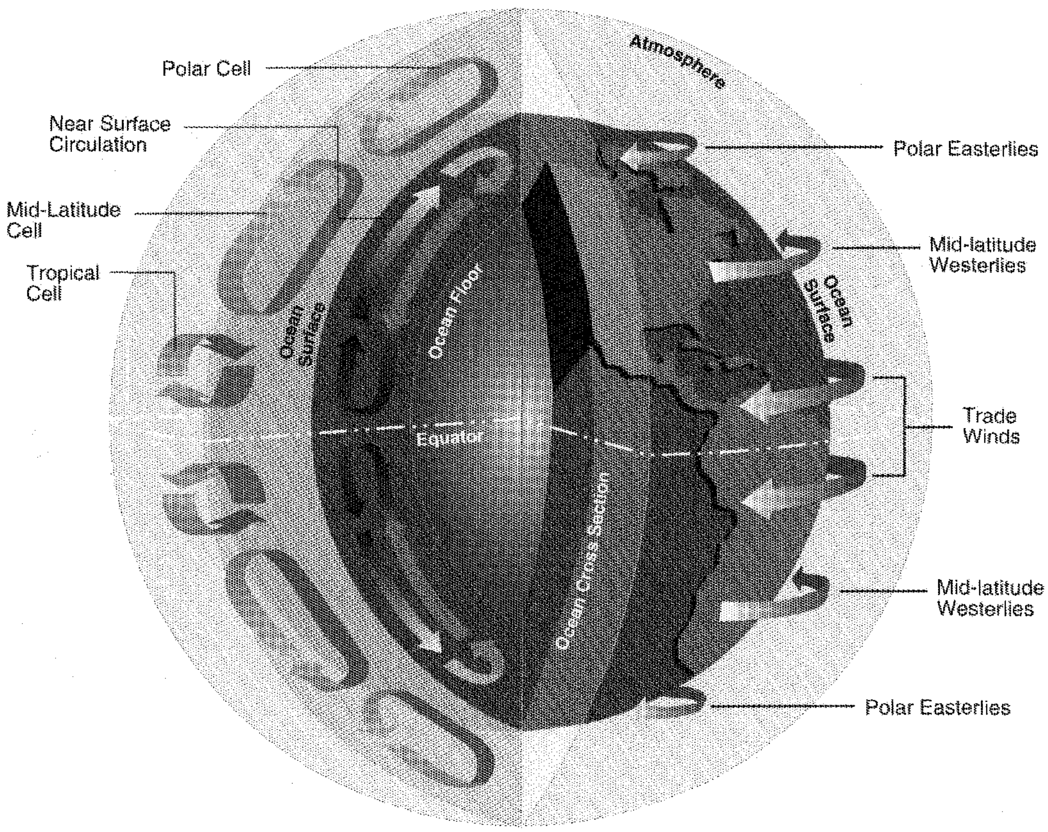
As solar radiation passes through the atmosphere, it encounters particles, atmospheric gases such as ozone, and clouds. Some of these absorb the incoming solar radiation before it reaches the earth's surface and thus warm parts of the atmosphere directly. Others scatter it or reflect it back to space. The earth's surface itself also reflects a portion of the incoming radiation. Ice and snow-covered regions are the most reflective, while darker areas such as forests and oceans are much less so.

For every 100 units of solar radiation entering the atmosphere, slightly less than half is absorbed by the earth's surface, where it evaporates water and heats the continents, the oceans and the air immediately above them. This heat is eventually released back to space as long-wave radiation. Before it escapes the atmosphere, however, much of this radiation is absorbed by clouds and by greenhouse gases such as water vapour, carbon dioxide, methane, ozone, CFCs, and nitrous oxide. These subsequently reradiate the absorbed energy in all directions, some back towards the earth's surface. By slowing the return of energy to space, this process raises the temperature of the earth's surface.

Eventually, all of the energy that enters the climate system from the sun returns to space as long-wave radiation. When energy enters and leaves the system at the same rate, warming and cooling are in balance, and the earth's climate remains relatively stable. When the balance between incoming and outgoing energy is upset, the earth's climate changes as the system adjusts and seeks a new equilibrium.

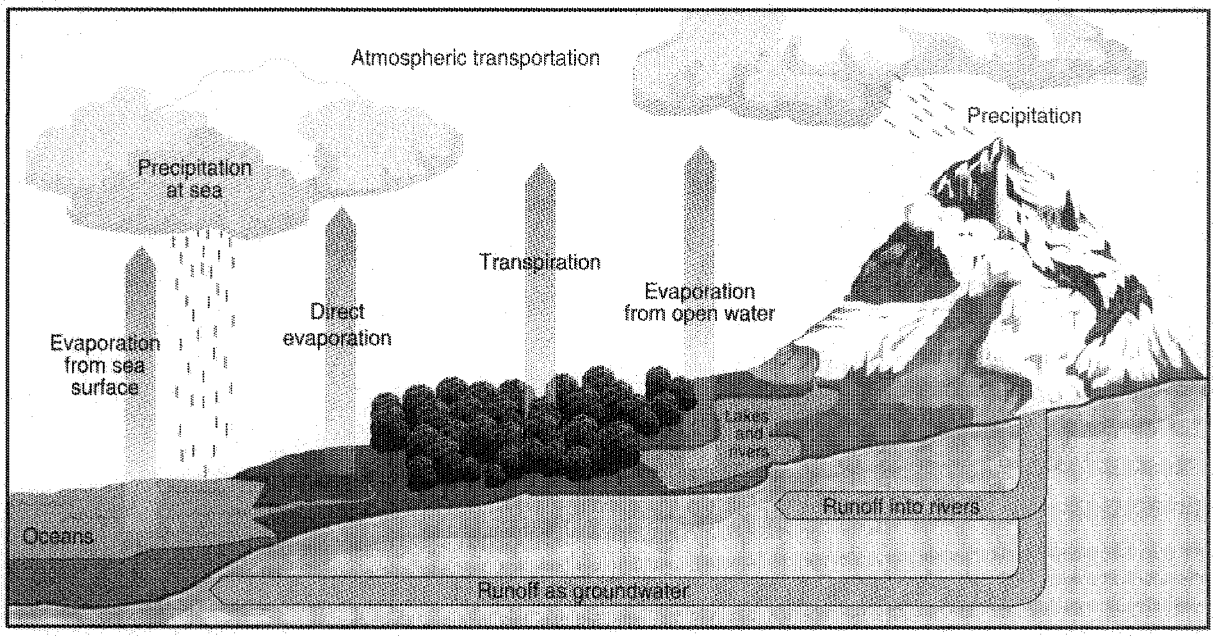
THE CIRCULATION SYSTEM

Because the intensity of solar radiation at the earth's surface diminishes as we move farther away from the equator, the tropics are much warmer than the poles. This temperature difference drives the atmospheric and oceanic circulation systems, which carry warm air and water poleward and bring cold air and water back towards the equator. These basic circulation patterns are modified substantially by the earth's rotation, gravitational forces, the presence of land masses, and other factors to produce the more complex (but still highly simplified) pattern shown here. The transport of heat and moisture by both the atmospheric and oceanic circulation systems exerts a profound influence on the character of regional climates.



atmosphere will hold more water vapour. Since water vapour is a greenhouse gas, the increased vapour content will amplify the initial temperature increase. In other words, it will produce a positive feedback. Similarly, the melting of large areas of snow and ice will reduce the planet's overall reflectivity and allow it to absorb more heat. On the other hand, changes in cloud extent, distribution and properties could give rise to both positive and negative feedbacks simultaneously. The net cloud feedback effect depends on how cloud amounts and properties respond to a warmer climate.

Because of these highly complex and dynamic linkages among the various elements of the climate system, seemingly small initial changes can trigger a complicated chain of events before the system establishes a new equilibrium and stability. The strength of climate models is that they allow us to deal with this complexity. By integrating our knowledge of fundamental climate processes, they give us some insights into how the system as a whole will respond to a particular set of initial changes.



THE WATER CYCLE

Water vapour enters the air as a result of evaporation from the oceans, freshwater sources, and soils and through transpiration from plants. The temperature and pressure of the air determine the amount of water vapour it can hold. As water vapour cools in the atmosphere, it forms clouds and eventually returns to earth as precipitation. Here it may return quickly to the rivers and oceans as surface runoff, or it may remain for varying lengths of time as soil moisture and groundwater or as ice and snow. The evaporation of surface water and its condensation in the atmosphere is also an important mechanism for the transport of heat from the earth's surface to higher levels within the atmosphere, where it can become a source of energy for storms.

WHY MODEL THE CLIMATE SYSTEM?

Studies into the earth's past climates can provide valuable information on the natural variability of the global climate system and on the response of ecosystems to climate change. However, they cannot answer the many questions about processes and feedbacks within the very intricate climate system, and between its sub-elements. On the other hand, planned experimentation with the earth's climate is virtually impossible, as well as foolhardy, because of the immense size of the system and the risks associated with such experiments. Although humans through their actions have already inadvertently started an unplanned global experiment with the climate, the results of that experiment will take decades and centuries to emerge. The knowledge gained would be too late for use in developing responsive policy action to limit and mitigate the effects of climate change.

Thus climate models have emerged internationally as the only practical and timely manner of investigating the behaviour of the complete climate system and studying its response to the forces that affect it.

The benefits of climate modelling activities in Canada are enormous. These include:

- major contributions, particularly from experiments with the Canadian GCM, to the international understanding of the risks of global warming. These contributions have given Canada considerable authority in influencing the development of sound global action strategies for mitigating these risks;
- the development of the modelling tools, including regional climate models, that are needed to assess the regional implications of climate change for Canadian ecosystems, and hence for the economic, social and cultural fabric of Canada. This enables Canadian scientists to address the impacts of global warming on our society in an effective and responsible manner;
- the availability of domestic scientific expertise to assess the international scientific understanding of global warming, and to advise Canadian policymakers in decisions relating to international climate treaties;
- improved understanding of the natural variability of climate, and of the relationship of extreme climate events, such as droughts, floods, hurricanes, tornadoes and winter snow storms, to climate change, whether due to global warming or other factors such as volcanic eruptions. During the past decade, in North America alone, such events have caused economic losses of more than $100 billion.
- the development of models for use in seasonal climate forecasts, which would be a major benefit to farmers, foresters, fishermen, and other managers of Canada's natural resources.

DEVELOPMENT OF CLIMATE MODELLING

The idea of constructing a mathematical model of the atmospheric component of the climate system was first published in the early 1920s, when the British meteorologist Lewis Richardson suggested the technique could be used for weather forecasting. At the time, however, it was a practical impossibility. According to Richardson's own estimate, 64,000 mathematicians would have been needed to perform the calculations for daily weather forecasts. But with further developments in dynamical meteorology and numerical methods, the emergence of the electronic computer in the 1950s and the almost exponential expansion of computing power in subsequent decades, his idea became a reality. By the late 1960s, meteorologists were routinely preparing weather forecasts with the aid of numerical modelling methods.

The underlying concept of numerical modelling is fairly simple and straightforward. Climatic processes are based on fundamental physical laws that can be expressed mathematically. If we write the equations that describe a certain climatic process, we, in effect, have created a model of it. Change certain values in the equations, and the model will tell us how that process will respond to a different set of conditions. By adding more equations to describe more processes, we can eventually create a model of the climate system as a whole.

Simple climate models that deal with only a small number of processes and/or one or two dimensions in space are often an economical tool for exploring hypotheses about climatic processes. However, to produce useful estimates of how greenhouse warming will affect temperatures and climate around the world, we need to understand the net response of the climate system as a whole in three dimensional space and in time. To do that, we must model it in as much detail as possible. The tool that has been developed to do this is the general circulation model (GCM). Derived from the very successful models used for weather forecasting, GCMs are powerful three-dimensional models that attempt to replicate the structure of the global climate system and the operation of its major processes and feedbacks. They differ from the weather models in that they operate on time scales of decades and centuries, rather than hours and days. Therefore they must include certain climate processes that are unimportant on the shorter time scales of weather forecasting. This can be offset by excluding some weather model processes that are less significant when considered over the longer climate time scales.

Although the first GCM was developed in the late 1950s, such models were not used extensively for climate studies until the late 1970s. Because GCM research requires access to very advanced computing technology and to high levels of scientific expertise, there are as yet only 10 or so major climate modelling groups in the world.

Canada's Atmospheric Environment Service recognized that numerical modelling would be an immensely valuable component of its national climate research activities, and formed its climate modelling group in the mid-1970s. The GCM developed by this group has become a powerful tool in identifying gaps in the understanding of the climate system, designing experiments to address these gaps, and integrating and applying the results to the study of global and Canadian climates. The results achieved have already significantly enhanced the understanding of the risks and implications of future climate change and of other atmospheric phenomena (such as the Antarctic ozone hole and volcanic aerosol clouds). The expertise that has emerged has become an equally valuable asset.

This expertise has provided the means of interpreting the implications for Canada of results of research conducted elsewhere within the global community, and has provided Canadian scientists with an influential role in developing the scope and direction of global climate research programs. Their work and expertise also provide valuable support to Canadian decision makers in the development of responsible domestic policies and strategies on global warming, and in the shaping of international response to the risks of global warming. Finally, the knowledge and expertise gained in developing and using the GCM provides the basis for development of regional climate models and seasonal climate forecasting models. These will be particularly important in the effective management of Canada's agricultural, forestry and other natural resources under a variable and changing climate.

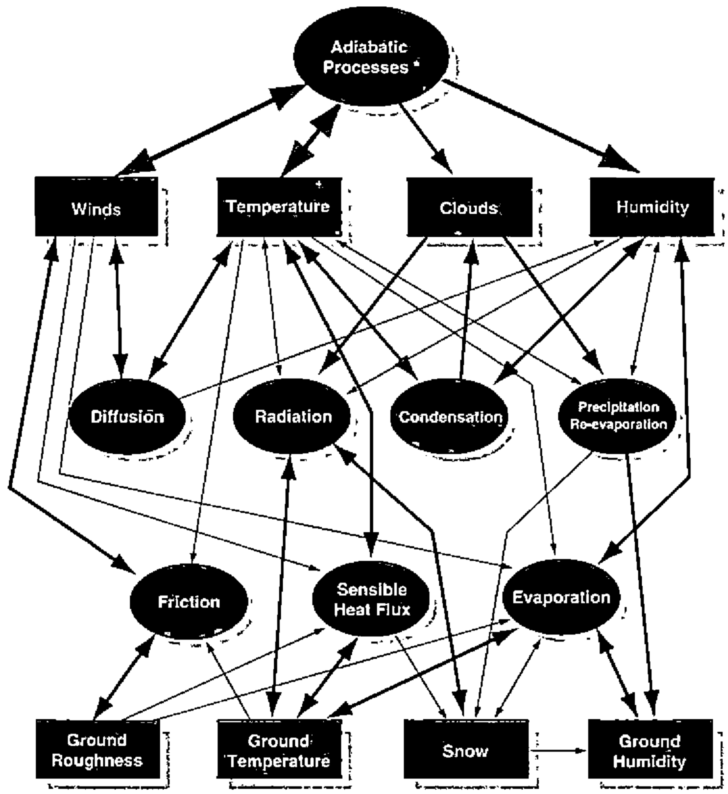
THE ANATOMY OF A GENERAL CIRCULATION MODEL

A GCM simulates the passage of energy through the climate system from the entry of solar radiation into the top of the atmosphere to its final departure to space as longwave radiation. It also simulates the effects of this energy on various elements of the climate system and calculates the outcome in terms of temperature, precipitation, soil moisture, and other important climatic variables.

The workings of the climate system are represented by sequences of mathematical equations. Essentially, these describe the earth's radiation budget, its translation into heat and motion, and the operation of the water cycle. Values are also specified for certain quantities such as the amount of solar radiation reaching the top of the atmosphere and the reflectivity of different types of surfaces. Additional equations or sub-models may be added to account for other factors that affect the basic climate processes.

GCMs must also accommodate the spatial diversity of a large three-dimensional world varying with time. They try to capture as much of this diversity as possible by making calculations for a large number of regularly spaced points, both on the earth's surface and in the atmosphere. The more points there are, the higher the resolution of the model and the finer the detail it can simulate. Today's highest resolution models may have 30 or more vertical layers, with each spatial point representing a few degrees of latitude and longitude horizontally, or an area of about one hundred thousand square kilometers.

Many climatic processes, such as cloud or thunderstorm development, precipitation, evaporation, and soil moisture, take place on scales considerably smaller than this. These are known as sub-grid-scale phenomena. The GCM model cannot handle these directly. Hence, they must either be given fixed values or be



SCHEMATIC STRUCTURE OF THE ATMOSPHERIC COMPONENT OF A GCM OVER LAND SURFACES

GCMs simulate climate by means of equations representing the physical processes of the climate system. The basic processes within the atmosphere, shown in the ovals, are those involving radiation, heat and motion, and the water cycle. The model must calculate how these processes interact with climate parameters, which are shown in the boxes. The thickness of the arrows indicates the strength of the interaction involved.

* Adiabatic processes involve heat exchanges internal to a parcel of air.

estimated through a process, known as parameterization, which links them physically and statistically to the larger scale variables (such as air pressure, temperature, and humidity) that the model can resolve. The average cloud characteristics for a given area, for example, can be parameterized in terms of the temperature and atmospheric moisture at that location. When a certain relative humidity is reached, the model forms clouds. The results can be tested against climate records to determine how well the parameterization works, and whether additional improvements are needed.

When the model is run, the energy flow through the simulated climate system is calculated in a series of time steps. Each step allows the system to change, transfer energy, momentum, and moisture, and respond to feedbacks until a stable pattern emerges. Calculations are made for every one of the model's spatial points both on the surface and at every vertical layer at each of these steps.

In spite of its sophistication, a GCM is still only an approximation of reality. Even the most powerful supercomputers available today cannot handle all the detail needed to give a complete description of the climate system. Nor do we fully understand all of the processes that affect climate. Therefore, the model must simplify or estimate some features of the system and simply ignore the less important ones. Consequently, the world as seen by a GCM bears a strong resemblance to a three-dimensional map made of Lego pieces. All of the major features are recognizable, but much of the fine detail is missing. The objective, as the models evolve, is to fill in more of the missing detail and make the models more realistic.

First generation GCMs used during the 1980s were quite limited in the amount of detail they could represent. Their resolution was coarse – from about 800 to more than 1000 km horizontally – and many of their features were highly simplified. Despite the important effect of highly variable soil and vegetation types on reflectivity, heat capacity and the water cycle, these models generally treated all land surfaces in the same way for soil moisture calculations and offered only a few variations for reflectivity.

MODEL RESOLUTION

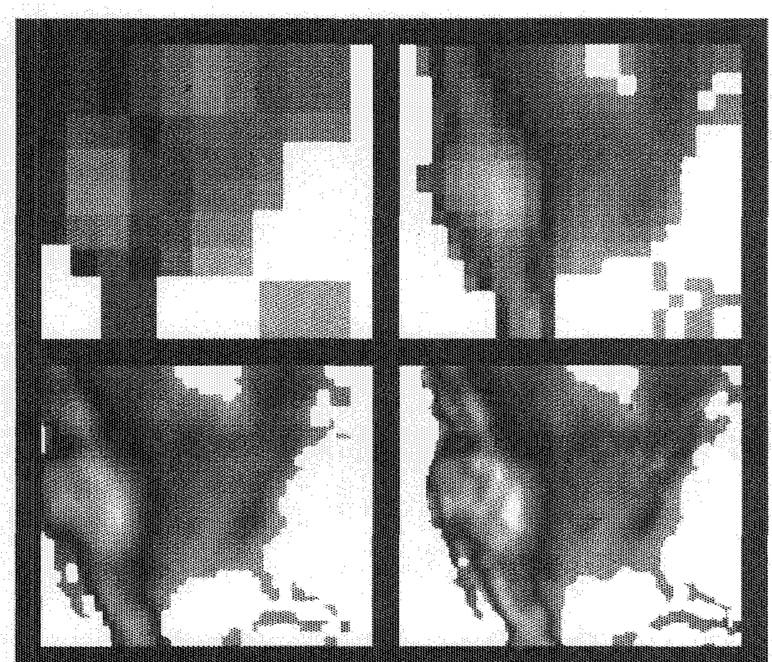


Image Credit: T. Bettge, NCAR

The extent to which physical features must be simplified depends on the model's resolution. The upper left picture illustrates the terrain of North America as seen by a coarse resolution first-generation model. The upper right picture shows the same terrain as seen by a high resolution second-generation model. Further improvements in resolution as shown in the bottom pictures should produce more useful and reliable climate simulations. However, these improvements would require substantial increases in supercomputer power and are as yet not practical on a global scale.

Similarly, the oceans in first-generation models were represented by a simple "swamp" ocean that evaporated water and absorbed energy but did not circulate heat. Such an ocean was useful for approximating changes in the equilibrium state of global energy balance but of negligible value for determining changes in regional climates, or in assessing ocean heat uptake. Some important parameterizations were also relatively crude. Most first-generation models had equations for forming clouds in response to changes in temperature and humidity, but the clouds' optical properties – the way they transmit and reflect light – had to be prescribed and could not respond to changes in the model climate.

A second generation of GCMs emerged in the late 1980s, with higher resolution, more detailed representation of features and processes, and more sophisticated parameterizations. One of these is the Atmospheric Environment Service's GCM2, which incorporates virtually all of the features considered state-of-the-art for a second-generation model. It has a relatively high horizontal resolution (about 600 km) and simulates horizontal heat transport in oceans, thus providing a better representation of the oceanic heat distribution and its effects on regional climates. Sea ice is also simulated more realistically, both in terms of its optical characteristics and its formation and melting. The treatment of clouds is highly sophisticated, incorporating a process for determining cloud optical properties and varying them in response to other climatic changes. The model also reproduces the cycle of night and day and its effects on temperature, pressure, and other climatic elements.

To account for the influence that different types of soil and vegetative cover have on the earth's radiation balance, the Canadian model includes more than 20 different reflectivity variations for land surfaces. In snow-covered regions, the model also accounts for the effects of vegetation and the age of snow on surface reflectivity. In addition, the detailed representation of soil and vegetation types gives a much more realistic modelling of soil moisture capacity.

To achieve this level of detail, the Canadian model uses more than 200,000 lines of computer code and makes calculations for tens of thousands of spatial points on the earth's surface and in the atmosphere. Even with today's most powerful supercomputers, capable of performing two billion operations or more a second, a typical climate change experiment can consume more than 1000 hours of computer time.

WHAT DO THE MODELS TELL US?

The most common application of GCMs is to determine the sensitivity of the climate system to a change in one of its key elements. Strictly speaking, the result is not a prediction of climate change, though it does have some predictive value. Instead, it is an answer to a "what if" question – in the case of global warming, what would be the response of the climate system if the concentration of greenhouse gases in the atmosphere increased significantly?

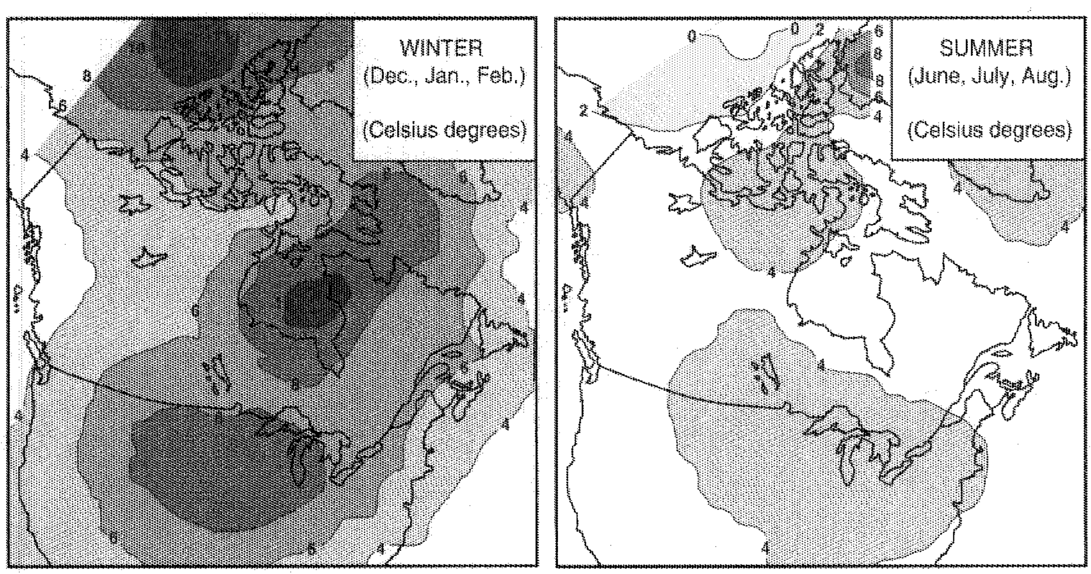
The classic experiment for testing the climate's sensitivity to higher greenhouse gas concentrations is known as a 2 x CO_2 or doubled carbon dioxide equilibrium response experiment. It is, in effect, two experiments in one. It begins with a present climate simulation. The average global carbon dioxide concentration is set at the present value (1 x CO_2) and the model is run until it produces a stable climate. The model is then reprogrammed, with the carbon dioxide concentration set to twice its present level (2 x CO_2), and run again until it reaches a new equilibrium. The difference between the two sets of results is the model's projection of the climate's equilibrium sensitivity to a doubling of carbon dioxide.

This is the benchmark experiment for global warming simulations and provides a useful basis for comparing the performance of different models and evaluating the effect of different parameterization and feedback schemes. Over the past decade, more than a dozen modelling groups have run this simulation.

When the 2 x CO_2 experiment was run on GCM2, it showed an average global surface warming of 3.5°C, with the greatest warming occurring at the poles in winter. However, temperatures in the stratosphere (the part of the atmosphere about 10-50 km above the earth) became cooler. The world became less cloudy (by 2.2%) while precipitation and evaporation

GCM2 2 x CO_2 TEMPERATURE PROJECTIONS FOR CANADA FOR WINTER AND SUMMER SEASONS

Climate changes will not be distributed uniformly. For a doubling of carbon dioxide concentrations, GCM2 projects an increase of 3.5°C in the earth's average annual temperature but shows more substantial warming over much of Canada, particularly in winter.



increased globally by 3.8%. But with more of the additional rain falling over the oceans rather than the land, soil moisture decreased by 6.6%, indicating a probable rise in the frequency of drought in many parts of the world, including Canada. Sea ice also became thinner and retreated poleward, resulting in a loss of about 66% of the sea ice mass.

Over Canada the changes were more intense. The model showed southern regions nearly 5°C warmer throughout the year and northern regions as much as 8 - 12°C warmer in the winter. Although seasonal increases in water supply were indicated for the west coast, the Yukon, and much of the Arctic, there was a decrease of more than 20% in soil moisture for the rich farmlands of the south-central region.

Should the above changes materialize over the coming decades as projected, they could have a number of very considerable impacts for Canada. Farmers would be affected more often by drought. Stocks of cod and salmon could be further diminished by changes in ocean temperature and circulation. Foresters would have to cope with more forest fires and new insect pests. At the same time, rising sea levels would increase the risk of flooding in many coastal areas, while stratospheric cooling would provide more favourable conditions for the formation of Arctic ozone holes.

Some changes could be beneficial – ice-free navigation in the Arctic, for example, or lower heating costs and longer growing seasons. However, offsetting the negative impacts and even profiting from the positive ones will require a major effort of adaptation, and much of the work of adaptation will have to begin before we have definite proof of climate change. If we are to make the potentially expensive commitments that this will require, we must be confident that the models' projections are correct. But can we put that kind of confidence in a computer simulation?

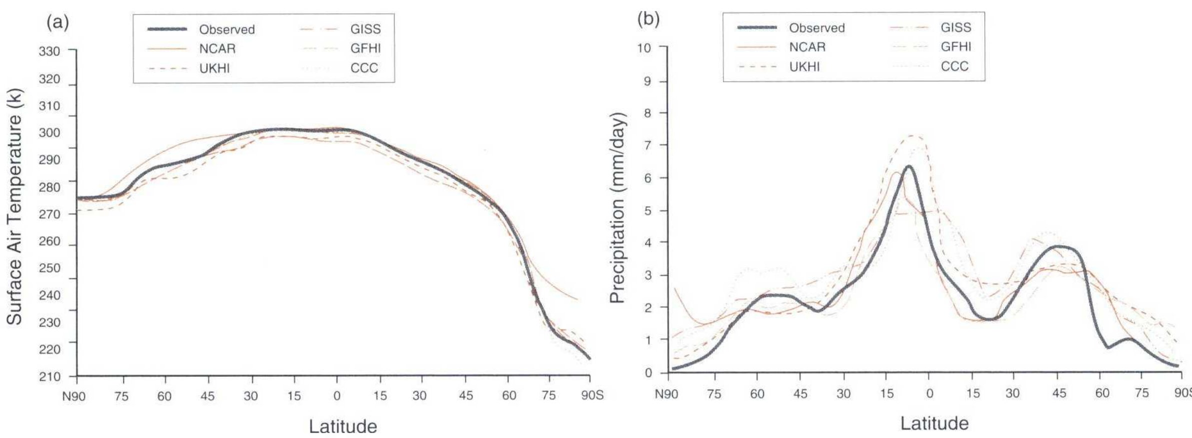
THE QUESTION OF CONFIDENCE

One test of a climate model is its ability to accurately simulate our present climate. In fact, such a test is an essential part of every climate sensitivity experiment. Hence a model's 1 x CO_2 experiment not only serves as a reference for comparing the results of other experiments, such as a 2 x CO_2 experiment, but also as a control for verifying and fine-tuning the model's performance. If the model produces a good approximation of the observed values and distribution of temperature, pressure, precipitation, and other climatic elements, then we can have some confidence in its results when used for climate change experiments. If, at the same time, the model can faithfully replicate the large and rapid climatic shifts that mark the changing of the seasons, then we can have further confidence that it is capable of simulating climate change as well.

In general, GCMs reproduce the large-scale features of the present global climate – such as the north-south distribution of pressure, temperature, wind, and precipitation – with considerable fidelity. On a regional or sub-continental scale, however, they are less reliable. This is especially true for precipitation and precipitation-dependent measures such as soil moisture

ACCURACY OF MODEL SIMULATIONS

GCMs simulate many of the large-scale features of the present climate with considerable accuracy. Various GCM simulations of the north-south distribution of temperature, shown for summer seasons in diagram (a) below, are remarkably similar to the observed values. The models are less reliable, however, in simulating other climate characteristics, as can be seen from a comparison of observed and modelled values for zonally averaged summer precipitation in diagram (b).



and snow accumulation. In some models, precipitation zones may be shifted by 1000 km or more from the observed locations. Models, on average, simulate seasonal variations of surface air temperatures quite well, while those of precipitation are also within about 20% to 50% of observed variations. Second-generation models such as GCM2, with high resolution and other advanced features, produce the best results, but even these still show noticeable regional inaccuracies.

When we compare the major modelling groups' projections for a doubled-CO_2 climate, a similar pattern of strengths and weaknesses is apparent. All of their models agree on the general nature and direction of change – increased surface warming with greater warming towards the poles, stratospheric cooling, increased precipitation and evaporation, and less sea ice. Most also agree on diminishing soil moisture in northern mid-latitude continents in summer. They disagree significantly, however, about the details. Their projections of average global temperature change vary between 1.7°C and 5.2°C, while projections for average global increases in precipitation (and evaporation) range between 3% and 15%. Disagreement on the geographical distribution of these and other changes is also substantial, particularly in an east-west direction.

These results give us reason to believe that the large-scale pattern of change predicted by the models is substantially correct. The world is indeed almost certain to become warmer. What we don't know with sufficient confidence, however, is how great the warming will be or how it will affect temperature, precipitation, evaporation, soil moisture and other important climatic features on a regional scale. Nor do we have enough certainty about when these changes will take place.

REDUCING UNCERTAINTIES

Canadian modellers are now at work on a third-generation GCM. It will build on the successful foundation provided by GCM2, incorporating improvements to many of its present features while adding some important new capabilities.

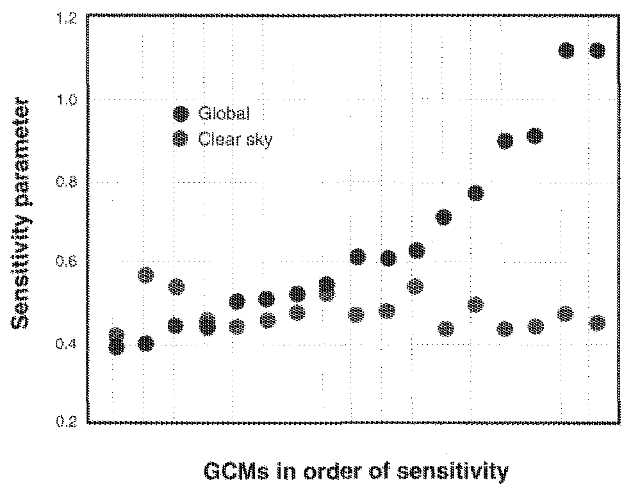
Part of the work is focused on refining existing parameterizations, particularly the treatment of clouds. Cloud processes are extremely difficult to model, and differences in their treatment are an important cause of disagreement among the present generation of models.

effects on the earth's radiation budget and atmospheric circulation. In addition, regional sub-models are being developed to provide a more detailed simulation of local climates. Fed with data from the GCM, these will model regional processes at a much higher resolution.

The most significant feature of the third-generation model, however, will be the inclusion of a three-dimensional, fully circulating, interacting ocean. While the simple slab ocean used in GCM2 can absorb and trans-

EFFECTS OF CLOUDS ON MODEL RESULTS

Differences in the parameterization of clouds are a major cause of disagreement among models. Modellers often use a "sensitivity parameter" to measure how feedbacks within the model increase or reduce an initial change in temperature. When global cloud feedbacks simulated by 17 different GCMs were isolated and removed, the resulting clear sky values of this parameter (blue dots) were in close agreement. When the cloud feedback was added again (brown dots), these values differed considerably.



Work is also under way on improvements to the methods used in GCM2 to represent soil and vegetation characteristics.

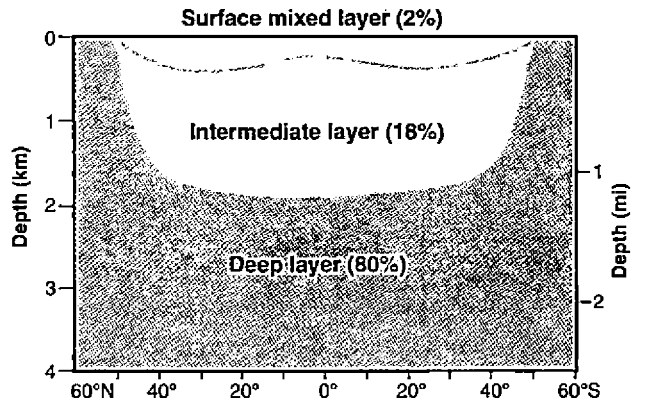
Other improvements will include a much more detailed treatment of processes in the middle atmosphere (up to 85 km above the earth's surface), particularly chemical interactions involving trace gases such as sulphur dioxide, ozone and carbon dioxide and their

port heat, it cannot represent the important transfer of heat between the ocean's surface layer and the ocean depths. As a result, the model cannot simulate the time lag in the ocean's response to surface temperature change. Nor can it simulate important long-term responses of ocean circulation and other ocean processes that may function as critical feedbacks of the climate system.

The new model will allow for the absorption and storage of heat by the deep ocean over periods ranging from a few decades to centuries. This feature will make it possible to conduct a much more realistic type of experiment in which the climate changes continuously in response to gradually increasing levels of greenhouse gases rather than to a sudden leap in concentration as in equilibrium response simulations. This experiment is known as a transient response experiment, and its chief benefit is that it permits the simulation of climate change as we are likely to experience it. These experiments should provide not only a more useful indication of how the climate will evolve but should also help to identify those signals that will confirm that climate change is indeed taking place. The model will also be able to simulate other important processes and feedbacks, such as the exchange of carbon dioxide between the atmosphere and the oceans. These are either neglected or crudely represented in current GCMs. Further insights can be expected as well into the impact of global warming on ocean circulation patterns and the potentially profound effect this could have on future climates.

All of this extra detail – in particular, the addition of the ocean model – will greatly increase the demand on computer power and speed. To handle the extra load, AES has acquired a powerful supercomputer with a normal operating speed of 2-4 billion operations a second and a peak speed of 24 billion operations a second. This extra power should make it possible to both handle this additional load and to double the model's resolution.

SIMPLIFIED VERTICAL STRUCTURE OF THE OCEANS

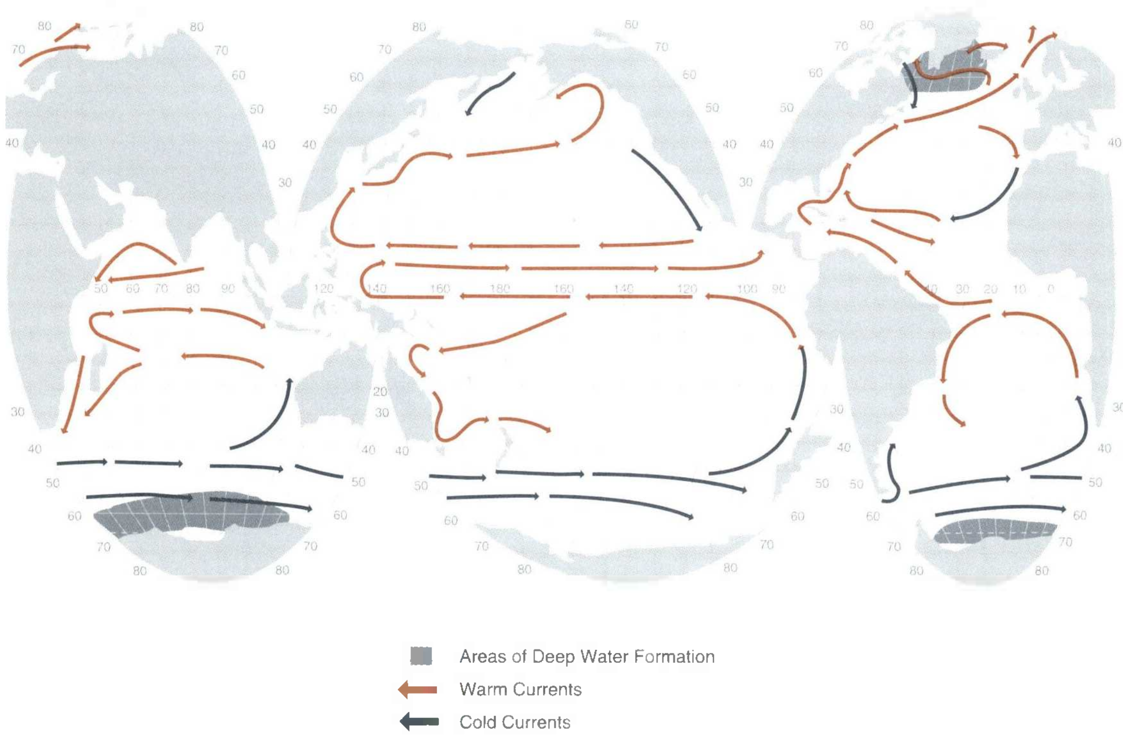


The vertical structure of the oceans is important because it influences the storage and transfer of heat and carbon dioxide and may also have a significant effect on the surface circulation. Because of density differences caused by variations in water temperature and salinity, the ocean is highly stratified. This structure, however, can be simplified into three layers – a shallow layer generally less than 100 metres deep at the surface, an intermediate layer marked by rapidly increasing density and extending downwards for several hundred metres, and a deep layer of very dense, cold, salty water. The surface layer exchanges heat and gases easily with the atmosphere. However, the deep layer, which includes about 80% of the ocean's volume, is largely isolated from the surface, except for small areas near the poles where surface waters become dense enough to sink to the ocean bottom and areas near the equator where deep waters rise to the surface. As a result, the deep ocean exchanges heat and gases with the atmosphere very slowly, and carbon dioxide dissolved in its waters may remain there for a millennium or more before returning to the atmosphere.

THE OCEANS AND CLIMATE

The oceans are one of the most important elements of the climate system. Absorbing considerably more than half of the solar radiation reaching the earth's surface, they exert a substantial influence on the planet's energy balance. They transfer heat from one part of the globe to another, they modify the temperature of overlying air masses, and because water has a much greater heat capacity than air, they act as a thermal reservoir and a moderator of temperature change. In addition, oceans are the major source of moisture for the continents, and they play a significant role in the global carbon cycle, absorbing carbon dioxide directly from the air and indirectly through the action of marine plants and animals and eventually returning it to the atmosphere.

Surface currents help to shape regional climates in many parts of the world. Driven largely by the wind, the movement of these currents is heavily influenced by the atmospheric circulation, but it is also channelled by the position of the continents and affected by forces such as gravity and the earth's rotation. Coastal winds and the divergence of ocean currents may also cause the upwelling of cooler sub-surface waters in certain areas, and these too significantly affect climatic patterns. The breakdown of the upwelling process off the coast of Peru, for example, is part of the periodic El Niño phenomenon, whose climatic impact can extend over much of the globe.



Creating a model of this complexity is an enormous task, however. Refining parameterizations, for example, is often more than a matter of massaging the mathematics. Much of it also requires improvements to our understanding of the processes themselves. Developing the ocean component alone and coupling it to its atmospheric counterpart is as demanding an undertaking as the creation of an atmospheric GCM itself. It is one that requires new expertise in oceanography and other areas, increased systematic monitoring of the behaviour and properties of oceans, as well as additional physical resources and funding. Other refinements, too, will require additional knowledge and skills – not only those of the cloud physicist and atmospheric chemist but also those of the biologist, the soil scientist, and specialists in many other areas.

To mobilize the necessary expertise, Environment Canada is developing a Climate Research Network in collaboration with partners in the universities, the private sector, and other federal and provincial government departments. The network will consist of a series of collaborative research groups located across the country, with each group focusing on a particular area of scientific uncertainty. It will have access to supercomputer facilities for GCM and other modelling applications, and a high-speed data link will allow researchers from every region to work together.

INTERNATIONAL COOPERATION

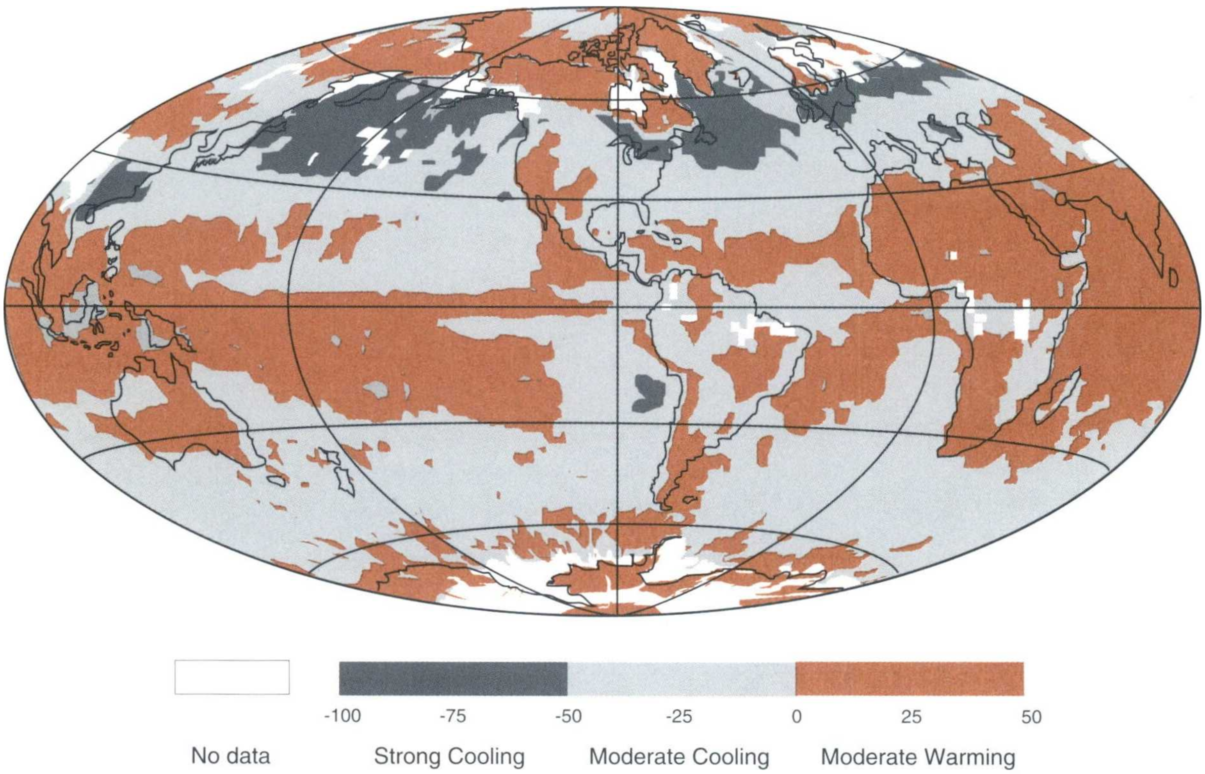
Even a modelling program that draws on the resources of the entire Canadian scientific community, however, cannot be self-sufficient. Cooperation with other researchers around the world is a necessity. Climate is a global phenomenon, and the data we need to improve the definition of surface characteristics, to refine cloud parameterizations, or to verify sea surface temperatures, ice boundaries, and other simulated conditions must be collected globally.

Much of this information is now being gathered by a variety of international programs under the World Meteorological Organization's World Climate Research Programme. These include the Earth Radiation Budget Experiment (ERBE), the International Satellite Cloud Climatology Project (ISCCP), the Global Energy and Water Cycle Experiment (GEWEX), the World Ocean Circulation Experiment (WOCE), and several others.

International cooperation among modelling groups is also a necessity. The work of developing and refining models is too complex to be done satisfactorily in isolation, and it is important for modelling groups to be able to exchange ideas and compare results. The use of different approaches by different groups is necessary to resolve uncertainties and improve the models.

NET EFFECT OF CLOUDS

This image, based on satellite observations, shows the extremely complicated effects of clouds on the earth's radiation balance. Improvements in our understanding of these and other climate processes will enhance our ability to develop better climate models. Much of this work is being carried out through international programs such as the Earth Radiation Budget Experiment and the International Satellite Cloud Climatology Project.



CLIMATE MODELLING: PRESENT AND FUTURE

In little more than a decade, climate modelling has assumed immense importance, largely because of the threat of global warming. In spite of the uncertainties associated with GCM projections, they have nevertheless confirmed the very real nature of this threat and helped to identify its most likely impacts. They have also added greatly to our understanding of how the climate system works by clarifying many of the complex interactions within the system, testing hypotheses, and revealing inadequacies and inconsistencies in our present knowledge base. Apart from their value in developing our understanding of global warming, models of various kinds are also making valuable contributions to the study of acid rain, stratospheric ozone depletion, and important climatic phenomena such as El Niños.

With current and future refinements in modelling techniques, the usefulness of GCMs and other models as research tools can only increase. As GCM capabilities are enhanced, especially for regional simulations, they will find other important applications as well.

With current and future refinements in modelling techniques, the usefulness of GCMs and other models as research tools can only increase. As GCM capabilities are enhanced, especially for regional simulations, they will find other important applications as well. Reliable climate forecasts that identify the principal climatic trends of the coming season are a realistic possibility. They could also warn of major anomalies, such as those associated with El Niños or volcanic eruptions, and could have considerable value for many sectors of society.

But the pressing demand for the moment remains the analysis of global warming and its climatic consequences. As greenhouse gas concentrations continue to increase, the next 10 or so years will probably be crucial for developing effective anticipatory responses. After that, we are likely to be in an increasingly reactive mode. The political and social will to take meaningful action and the effectiveness of the responses chosen will depend to a considerable degree on the reliability of GCM projections and on the amount of detailed information they can supply. The further development of GCM expertise must therefore remain one of the most urgent priorities in dealing with the challenge of global warming.