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A State of the Environment Report

Understanding Atmospheric Change

SOE Report No. 95-2

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Understanding Atmospheric Change

A Survey of the Background Science and Implications of Climate Change and Ozone Depletion

Second Edition 1995

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Atmospheric Environment Service
Environment Canada

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Preface

Sustainable development has become a key goal and functional underpinning of federal public policy in Canada. The fundamental objective of sustainable development is to achieve economic and social progress without impairing the quality of the environment and, hence, the welfare of future generations. The challenge lies in finding and adopting a path of economic development that sustains environmental quality. It is recognized that access to credible, balanced information is the foundation for building increased environmental awareness and improved decision making and ultimately sustaining the country's ecological, economic, and cultural heritage.

Like many other countries, Canada has implemented a State of the Environment (SOE) reporting program. Prepared for Canadians interested in their environment, SOE reporting products take many forms, including fact sheets, special reports, newsletters, environmental indicators and bulletins, and national overview reports.

These products are the result of an increasingly strong partnership involving federal, provincial, and territorial governments, private industry, academia, non-governmental organizations, and individual Canadians. Because the environment is affected by decisions and activities undertaken at all levels of society, it is imperative that all of these stakeholders have access to timely and credible environmental information and assessment.

The SOE Report series is designed to provide Canadians with careful, objective analysis and interpretation of data that will help identify significant ecological conditions and trends. Of equal importance are the explanations for these trends and the actions being undertaken to sustain and enhance the country's environment.

Those who would like more information about the original scientific studies on which the present report is based should contact:

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Summary

This State of the Environment Report addresses two major environmental issues associated with the Earth's atmosphere: global warming and the depletion of the atmosphere's ozone layer.

The report begins with an assessment of how the atmosphere naturally influences the Earth's climate and how that climate has behaved in the past. Of particular importance in this regard is the natural presence in the atmosphere of greenhouse gases such as water vapour, carbon dioxide, methane, and nitrous oxide. Studies of ancient climates show a close correlation between long-term temperature fluctuations and the concentration of these gases in the atmosphere. Since the industrial revolution, these concentrations have increased to historically unprecedented levels, raising concerns within the scientific community about the possibility of a rapid and dramatic change in global climate.

Mathematical models of climate processes suggest that a doubling of pre-industrial levels of carbon dioxide would cause the average temperature of the Earth's surface to rise anywhere from 1.5 to 4.5°C. Such a warming, accompanied by inevitable shifts in precipitation patterns, could lead to widespread disruptions of natural ecosystems and would require radical adaptation on the part of both wildlife and human societies.

The second major theme of the report deals with the potential depletion of the upper atmosphere's protective ozone layer. The release of long-lived chemicals such as chlorofluorocarbons into the atmosphere through industrial processes appears to be accelerating the rate of ozone decay. A net global reduction in ozone concentration of several percent has already been observed over the past few decades, with particularly large seasonal decreases of more than 50% evident over Antarctica in recent years. The resulting significant increase in penetration of harmful ultraviolet radiation from the sun to the Earth's surface, should ozone concentrations continue to diminish, would have major impacts on human health, vegetation, and materials.

The final chapter of the report considers the linkages between these two issues, other atmospheric pollution problems, and human behaviour, and examines what is being done and must be done to respond, both nationally and internationally.

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Introduction

To the best of our knowledge, Earth's atmosphere is unique in its ability to support life. It provides the oxygen, water vapour, and carbon dioxide needed to sustain the biological processes within the Earth's surface ecosystem. It contains a protective high-level ozone layer which acts as a screen against harmful ultraviolet radiation from the sun. Moreover, its constituents include gases that serve as an insulating blanket around the planet, keeping surface temperatures within the range necessary for the presence of liquid water and, hence, life as we know it. Each of these factors is essential to the presence of living things, and all have persisted for millions of years.

Scientists have long recognized the importance of the Earth's atmosphere. However, it was not until the late 1960s that we were presented with the first stunning images of Earth from space. These showed a remarkable oasis of blue and white within the broad expanses of a lifeless cosmos—an oasis protected by a thin, fragile mantle of gases. It was a gripping reminder that Earth may indeed be unique and irreplaceable. Neil Armstrong, who in July 1969 became the first human being ever to set foot on the moon, remarked that "when you look at the Earth from the lunar distance, its atmosphere is just unobservable. . . . We're going to have to face the fact that we have to learn how to conserve it and use it wisely."

If Armstrong's warning was timely then, it is even more relevant now. The scientific evidence is increasingly clear that the Earth's atmosphere is undergoing major changes. These changes have in some respects already exceeded the limits of the natural atmospheric fluctuations of at least the last 100 000 years, and they are projected to become significantly larger with time. They appear to be directly linked, not to some external changing force at work upon the planet but to a global-scale geophysical experiment unwittingly commenced from within by humankind, an uncontrolled experiment that could change the global ecosystem beyond anything the Earth has experienced for the last several hundred thousand years.

This experiment is a by-product of two factors—rapid technological development and an unprecedented expansion of human population—both of which began in the eighteenth century. Technological development, by utilizing new forms of energy and multiplying productive capacity, has greatly increased the human impact on the environment, not only through greater consumption of resources but also through the creation of vast quantities of environmentally harmful products and by-products. The growth of the global human population—from approximately 600 million at the beginning of the eighteenth century to more than 5 billion today—has compounded these effects, with the result that human activities are now on such a scale as to rival the forces of nature in their influence on the environment.

Associated with these phenomena are rapid changes in land use, increased industrialization, and a voracious appetite for energy. Some of the consequences of these developments—smog, water pollution, and impoverished and contaminated soils—are already painfully obvious on a local and regional scale and have been the object of strong anti-pollution legislation within many countries. On a global scale, however, the effects have been much more subtle, because the damage is being caused by the unnatural release into the atmosphere of gases that are mostly odourless and invisible—seemingly innocent substances, whose effects are not immediately apparent. Only recently have we recognized that the release of these gases is capable of changing the composition of the atmosphere. Because the atmosphere is Earth's most vital life support system, such changes will inevitably have a major impact on the biosphere.

The changes in atmospheric composition that are now taking place raise two fundamental concerns. One is the gradual depletion of the protective ozone layer in the upper atmosphere. The other is the warming of the Earth's surface and lower atmosphere. These concerns are the subject of this report, which is intended to summarize our current scientific understanding of the processes involved in these changes and of their implications for the global ecosystem, the world community, and Canada.

Chapters 1 to 4 of the report summarize our current scientific understanding of atmospheric warming and climate change and their potential global impact. The data in these chapters have been derived primarily from the reports of the Intergovernmental Panel on Climate Change, released in 1990 and updated in 1992 and 1994. The Panel's reports represent the most recent consensus of the international scientific community on global warming and climate change.

Chapter 5 examines the many possible impacts of a warmer climate on Canada. The depletion of the ozone layer is discussed in Chapter 6. In conclusion, Chapter 7 considers the linkages between all of these aspects of atmospheric change and examines what must be done to respond to them.

Chapter 1

Earth's natural climate

Through its constituent gases the atmosphere provides the basic conditions for life on Earth. But it is through climate that it shapes the patterns and sets the limits of terrestrial existence. Climate regulates the life cycle of plants and animals, affects their growth and vitality, and is a principal factor in determining how they distribute themselves around the globe. Almost all complex life forms are adapted to live within a specific and relatively narrow climatic niche.

Thanks to technology, human beings have managed to expand their niche to include nearly every part of the globe. Yet even human life remains closely constrained by climatic factors. Settlement patterns, shelters, clothing, agriculture, transportation, and even culture all reflect the deeply pervasive influence of climate.

Climate is commonly defined as average weather. Thus, the climate of a place is the average over a number of years of the day-to-day variations in temperature, precipitation, cloud cover, wind, and other atmospheric conditions that normally occur there. But climate is more than just the sum of these average values. It is also defined by the variability of individual climate elements such as temperature or precipitation and by the frequency with which various kinds of weather conditions occur. Indeed, any factor which is characteristic of a particular location's weather pattern is part of its climate.

Although the very notion of climate assumes a long-term consistency and stability in these patterns, climate is nevertheless a changeable phenomenon. The order of change may be small and relatively short—an abnormally cold winter here, a dry summer there. Or—like the great ice ages that have come and gone over thousands of years—it may be on a scale of geological immensity.

Our focus here will be on changes that can be expected to occur over the next few decades and centuries, since it is within this relatively short time span that the first major effects of global warming are likely to be felt. But to understand how these changes are coming about, we must also extend our timeframe and look at the long record of climate change in the past. From this we can obtain a better understanding of the natural variability of Earth's climate and the processes involved in its often spectacular oscillations. Before doing so, however, we need to examine the physical forces that govern the flow of energy through the atmosphere, for it is these that ultimately determine the principal characteristics of our planet's climate.

The natural global climate system

The global heat engine

In a very simple way, the Earth's climate system can be thought of as a giant heat engine, driven by incoming energy from the sun. As the solar energy passes through the engine, it warms the Earth and surrounding air, setting the atmospheric winds and the ocean currents into motion and driving the evaporation-precipitation processes of the water cycle. The result of these motions and processes is weather and, hence, climate.

All of the energy entering the climate system eventually leaves it, returning to space as infrared radiation. As long as this energy leaves at the same rate as it enters, our atmospheric heat engine will be in balance and the Earth's average temperature will remain constant. However, if the rate at which energy enters or leaves the system changes, the balance will be upset and global temperatures will change until the system adjusts itself and reaches a new equilibrium.

The flow of energy through the system is regulated by certain gases within the atmosphere. Surprisingly, however, the largest constituents of the atmosphere play little or no part in this process. Although 99% of the atmosphere is made up of nitrogen and oxygen (Table 1), these gases are

Table 1
Concentration of various gases in dry air (percentage of total volume)

Nitrogen	78.1	Helium	0.0005
Oxygen	20.9	Methane	0.00017
Argon	0.9	Hydrogen	0.00005
Carbon dioxide	0.035	Nitrous oxide	0.00003
Neon	0.0018	Ozone	variable

SOURCE: Liou 1980.

comparatively transparent to radiation and have little effect on the energy passing through them. It is the remaining 1% of the atmosphere that plays the major part in regulating the crucial energy flows that drive climate processes. This 1% is made up of a variety of aerosols and gases that reflect, absorb, and re-emit significant amounts of both incoming solar radiation and outgoing heat energy.

Incoming solar radiation

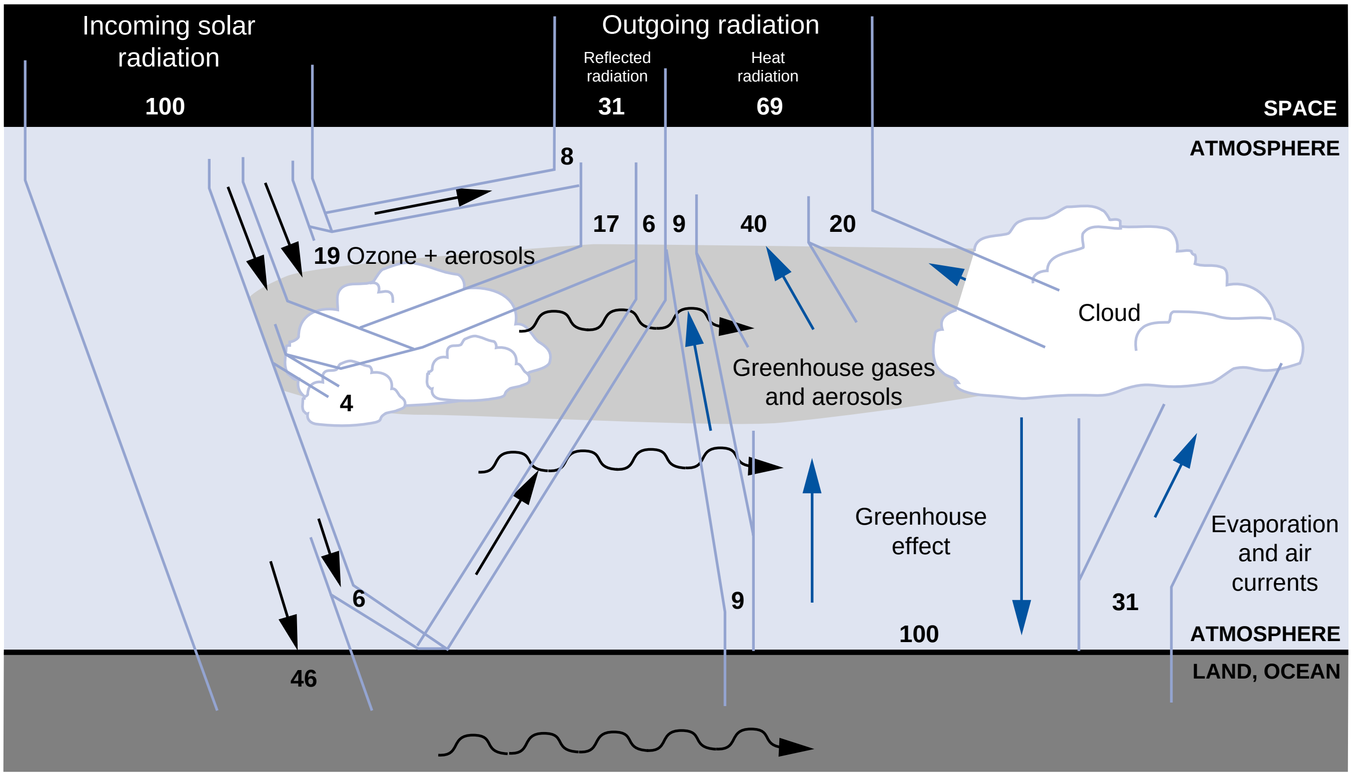
Figure 1 shows what happens to the sun's radiation as it passes through the atmosphere. Only about half of this radiation is actually absorbed by the Earth's surface. The other half is diverted or intercepted in a variety of ways by the following agents.

Trace gases—Most of the minor gases in the air do not significantly affect the transmission of sunlight. Ozone is the major exception. By absorbing ultraviolet rays from incoming solar energy, the ozone layer not only protects the Earth's ecosystem from the harmful effects of this radiation but also retains a portion of the sun's energy in the upper atmosphere.

Aerosols—These are very fine particles and droplets that are small enough to remain suspended in the atmosphere for considerable periods of time. They include tiny droplets of sulphuric acid from volcanic eruptions, soot and sulphates from surface fires and industrial processes, salt from sea spray, and dust. These both reflect and absorb incoming solar radiation, the amount depending on the quantity of the aerosols and their reflectivity. It is estimated that about 8% of incoming solar radiation is reflected or scattered back to space by aerosols. Together with ozone, however, they also absorb and thus retain within the atmosphere an additional 19% of the incoming energy.

Clouds—Water droplets within clouds have an important effect on incoming solar energy. This is partly because there are

Figure 1
Energy flow in the global climate system



SOURCE: Adapted from MacCracken and Luther, 1985.

The diagram traces the flow of 100 units of solar energy through a balanced climate system. The greenhouse effect delays the departure of a significant portion of this energy from the system, and thus the heating of the Earth's surface is intensified. Because of this the Earth's surface releases much more energy (140 units) than it absorbs directly from the sun (46 units). Since the system shown here is in balance, all units of incoming energy are eventually returned to space.

so many clouds in the lower atmosphere and partly because they are highly reflective. They account for the reflection of an additional 17% of the incoming radiation, while absorbing about 4% of it.

The Earth's surface—The Earth's surface consists of open oceans, terrestrial ecosystems such as forests and deserts, and expanses of ice and snow. It reflects about 6% of the sunlight entering the atmosphere.

Of the total amount of solar radiation entering the atmosphere, 31% is reflected back to space by aerosols, clouds, and the Earth's surface, and hence lost to the climate system. Of the 69% that remains to fuel the system, 23% is absorbed within the atmosphere and 46% heats the Earth's continents and oceans.

Outgoing heat radiation

The Earth's surface and lower atmosphere, heated by the sun's rays, release this heat again by giving off infrared radiation. As it travels towards space, this radiation encounters two major atmospheric obstacles—clouds and absorbing gases.

Clouds—Besides reflecting incoming solar radiation, clouds also absorb large quantities of outgoing heat radiation. The energy absorbed by the clouds is reradiated, much of it back to the surface. That is why air near the Earth's surface is usually much warmer on a cloudy night than on a clear one. The amount of radiation absorbed and returned depends on the amount, thickness, height, and type of cloud involved.

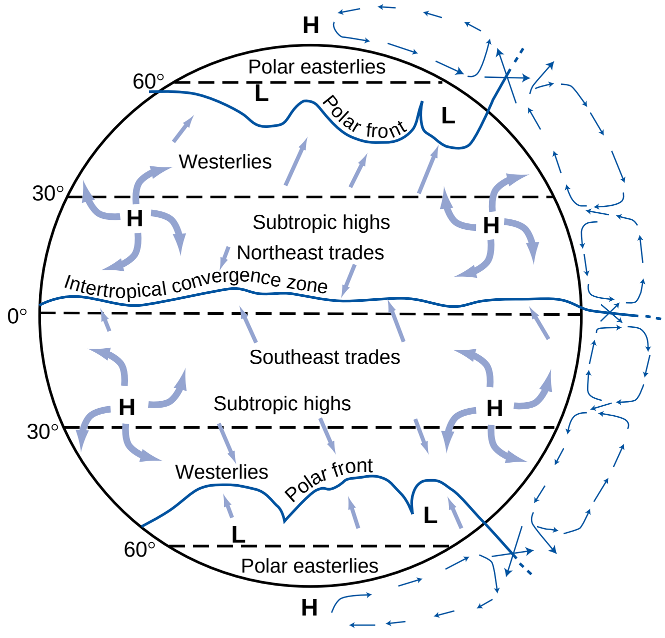
Absorbing gases—A number of the naturally occurring minor gases within the atmosphere, although relatively transparent to sunlight, absorb most of the infrared heat energy transmitted by the Earth towards space. The absorbed energy is then reradiated in all directions, some back to the surface and some upwards where other molecules are ready to absorb the energy again. Eventually the absorbing molecules in the upper part of the atmosphere emit the energy directly to space. Hence, these gases make the atmosphere opaque to outgoing radiation, much as opaque glass will affect the transmission of visible light. Together with clouds, these gases provide an insulating blanket around the Earth, keeping it warm. Because greenhouses retain heat in much the same way, this phenomenon has been called the "greenhouse effect," and the absorbing gases that cause it, "greenhouse gases." Important naturally occurring greenhouse gases include water vapour, carbon dioxide, methane, ozone, and nitrous oxide.

The magnitude of the natural greenhouse effect can be estimated fairly easily. Theoretically, the solar energy reaching our planet is sufficient to give it an average surface temperature of –18°C but no more. Yet we know from actual measurements that the Earth's average surface temperature is more like 15°C, some 33° higher. The additional warming is a result of the greenhouse effect. It is enough to make the difference between a body like the Earth that can support life and one like the moon that cannot.

Climatic balance

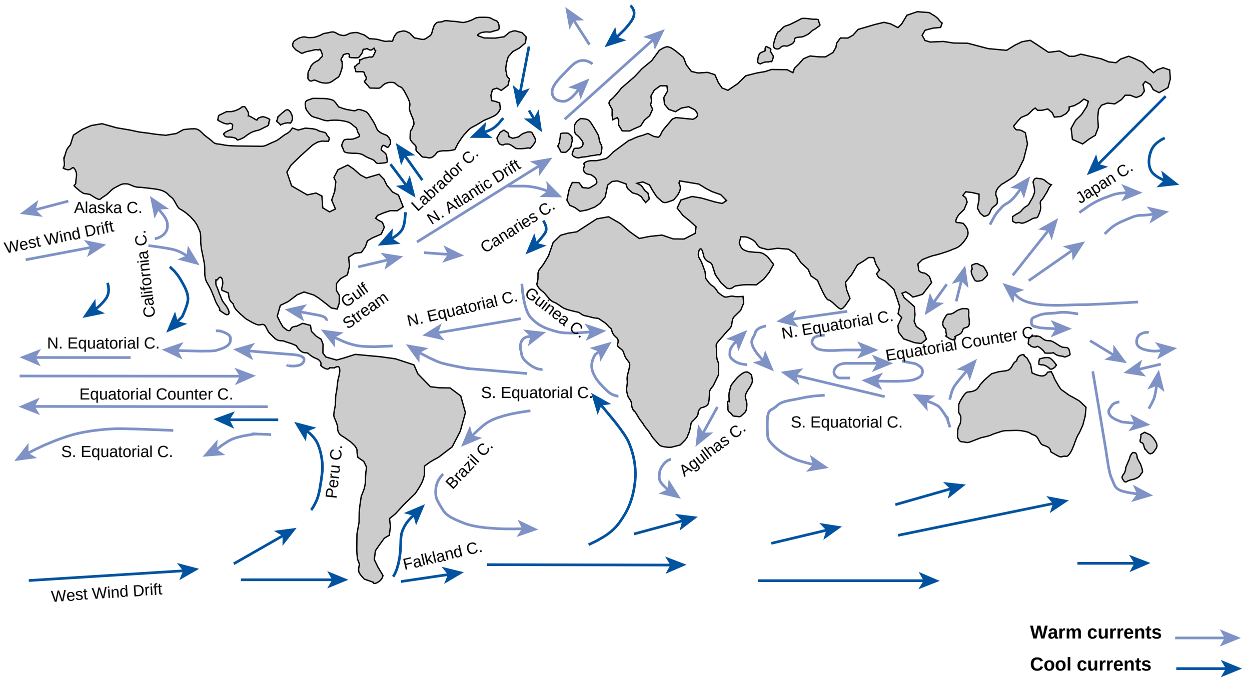
Climate is ultimately a consequence of the way the atmosphere redistributes the heat energy that the Earth has absorbed from the sun. Because the intensity of solar radiation changes with latitude, all parts of the planet are not heated equally. The heating effect is greatest in the tropics, where more energy is received from the sun than is radiated back to space. Temperatures here are consequently much warmer than the global average and remain consistently within a few degrees of 30°C. At the opposite extreme, the Earth's polar regions experience a net loss of energy to space and temperatures can vary from highs of nearly 20°C in northern polar summers to lows well below –60°C in southern polar winters.

Figure 2
General circulation of the atmosphere



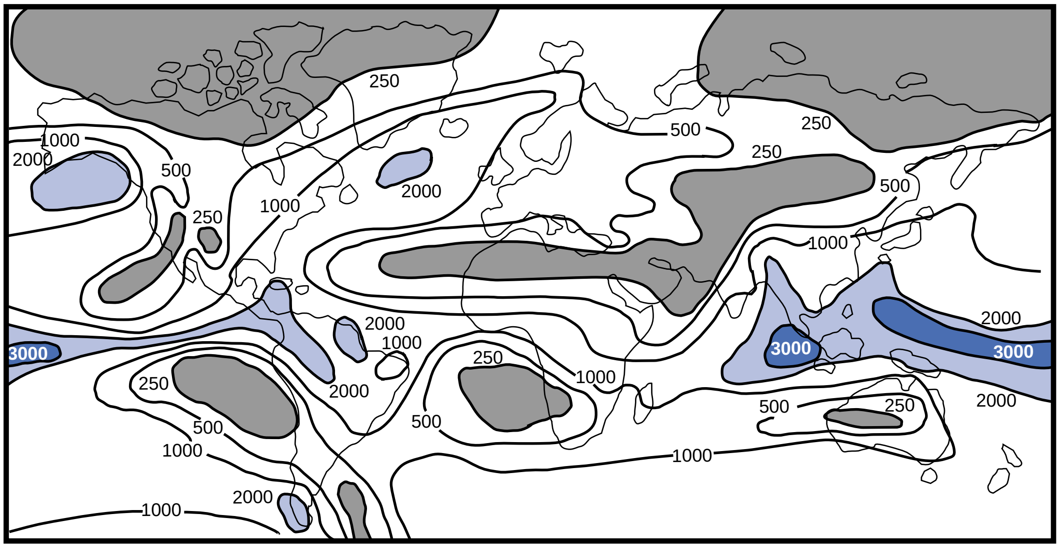
SOURCE: Adapted from Critchfield 1983.

Figure 3
Ocean circulation patterns



SOURCE: Adapted from Griffiths and Driscoll 1982.

Figure 4
Annual global distribution of precipitation (in millimetres)



SOURCE: Adapted from Lockwood 1974.

Shaded areas mark precipitation extremes, with grey indicating less than 250 mm a year, light blue more than 2000 mm a year, and dark blue more than 3000 mm a year.

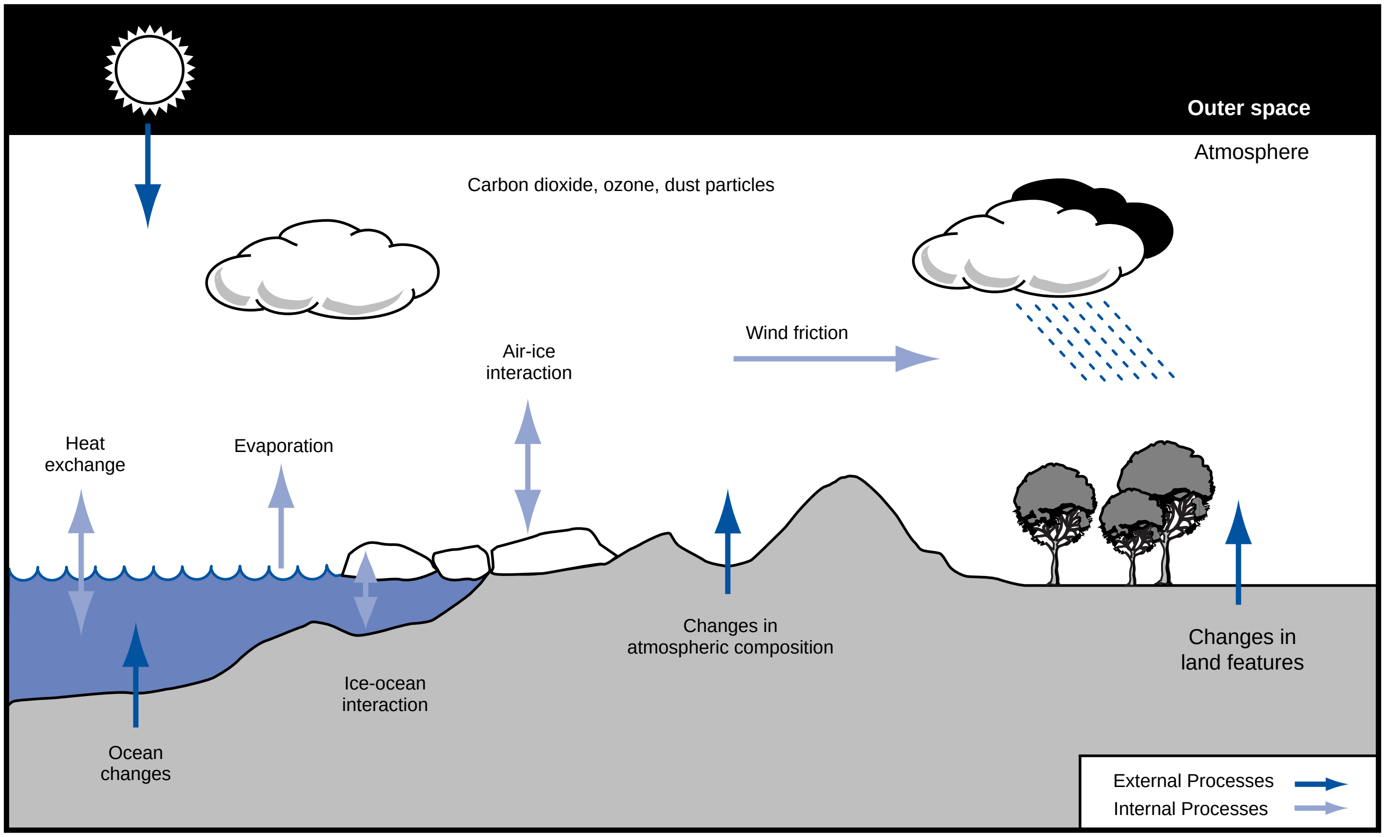
This large temperature difference between the tropics and the poles is the primary driving force for Earth's atmospheric winds and ocean currents. Essentially, these carry warm air and water from the equator towards the poles while cold air and water move in the opposite direction. This flow is modified, however, by the Earth's spin and the effects of land masses to produce a complex pattern of currents. These are shown in simplified form in Figures 2 and 3.

Since atmospheric moisture is transported by air currents, precipitation patterns are also influenced by the global atmospheric circulation. But ocean currents, landforms, and evaporation over continental areas exert a considerable influence as well. As a result the distribution of precipitation around the globe presents an even more complex pattern than the atmospheric circulation (Figure 4). Thus, some areas receive large surpluses of rainfall which support very lush, rich ecosystems, while others do not receive enough to nourish vegetation and so become deserts.

Numerous other factors may also affect the Earth's climate. In addition to the circulation of the air and the currents of the ocean, we must also consider the effects of clouds and large masses of snow and ice, the influence of topography, surface soils, and vegetation, and the impact of processes and activities within the biosphere. To these we must add the effect of differences in solar heating, not only between regions but also between seasons and even between night and day.

All of these elements are interconnected, interacting parts of a balanced system (Figure 5). If a change in one of them upsets this balance, it is likely to initiate complex reactions in the others as the system adjusts to establish a new equilibrium. Some of these reactions may increase the initial change (a process known as *positive feedback*), while others may oppose and partially offset it (a process known as *negative feedback*). Since the climate system is driven by the sun's radiation, anything that changes the amount of solar energy it absorbs or the net amount of heat energy it releases will cause

Figure 5
Major elements affecting the global climate system



Source: Adapted from McKay and Hengeveld 1990.

climatic changes. These changes will adjust the system until its net balance of input and output energy is once again restored.

Possible primary causes for such changes include variations in the aerosol and gaseous content of the atmosphere, changes in the reflective properties of the Earth's surface, and alterations in the intensity of sunlight reaching the Earth's atmosphere. It is clear from studies of past climates that such changes are constantly taking place—chronologically on time scales of months to millions of years and geographically on regional as well as global scales. Yet, remarkably, reconstructions of past temperature patterns suggest that these natural fluctuations, though sufficient to cause tremendous shifts in global ecosystems, have always remained within the relatively narrow margin needed to support terrestrial life.

Climates of the past

Reconstructing climate

Earth's natural climate system is in fact in a constant state of change. It is a dynamic system. Forces, both external and internal, are continually altering the delicate balances that exist within and between each of its components. Evidence from the Earth's soils, its ocean and lake bottom sediments, its ice caps, and even its vegetation provides a clear indication that major changes in climate have occurred in the past. This evidence also suggests that such changes are likely to occur again naturally in the future.

Our most accurate information about past climates comes from the scientifically collected data of the last 100 to 150 years. Recorded by trained observers using precision instruments, this information is not only reasonably reliable but also very comprehensive, covering daily and even hourly variations in conditions over almost all inhabited regions of the globe. Such detail makes these records an extremely useful database for identifying and analyzing recent climate patterns and even relatively small fluctuations in them.

To study larger climate variations over longer periods of time, scientists must turn to proxy data sources, that is, indirect evidence from which the nature of previous climatic conditions can be inferred or derived. Written accounts of weather conditions, especially in regions such as Europe and Asia where extensive documentation exists, can provide a useful basis for the analysis of climates of the past 1000 years. Though they lack the reliable quantitative data of recent records, these documents can nevertheless yield considerable qualitative information about former climates.

Beyond the last millennium, however, the reconstruction of climatic history must rely primarily upon the rich supply of paleoclimatic indicators that the Earth itself provides. Plant pollen deposited deep within old bogs, lake bottom sediments, and even ice caps can bear witness to the nature of growing seasons at the time of its deposition. Residues of aquatic life-forms attest to past water temperatures and quality. Old beaches indicate former shorelines and hence sea levels. Even the air pockets fossilized within the frozen ice caps of polar regions tell of the composition and temperatures of ancient air masses. Tree rings, soil composition and structure, and the thermal profile of the Earth's crust also tell their stories. From this varied and spotty assortment of clues, paleoscientists have given us enough information to construct a relatively continuous, though admittedly qualitative, picture of the world's surface temperature patterns over the past one million years.

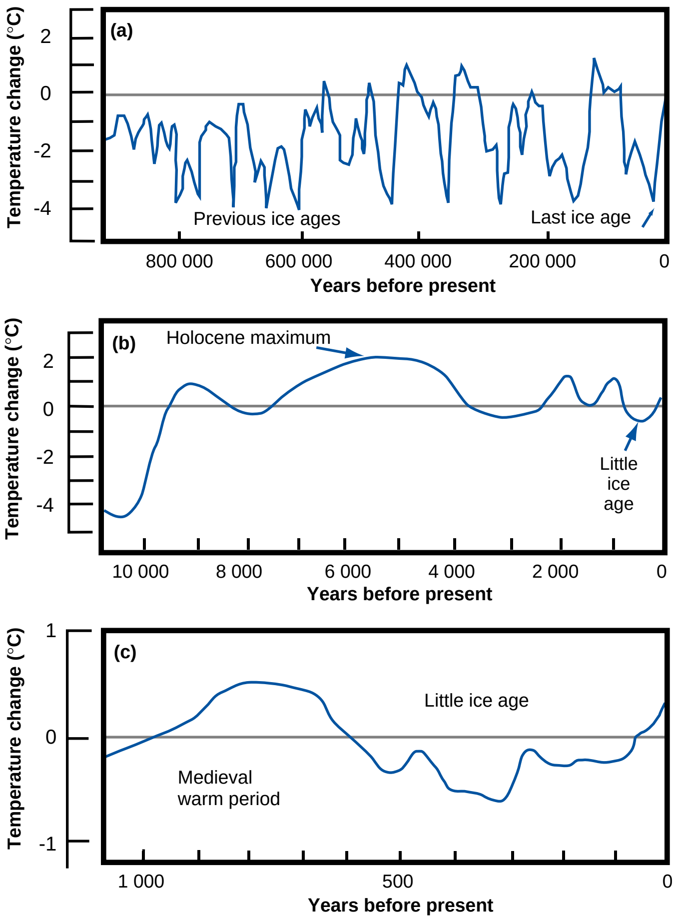
The past million years

Caution must be used in interpreting the reconstructed records of past climates, since they are based on many different indicators and these are of varying reliability. However, useful information on major patterns can be derived from the data, with increasing detail for more recent climates.

Some idea of the Earth's climate history during the past one million years can be gleaned from Figure 6a. Temperatures during much of this period seem to have followed a cycle of long-term, quasi-periodic variations. Extreme minimum temperatures, corresponding to major global glaciations, appear to have occurred at roughly 100 000-year intervals for the past 800 000 years. Each of these glacial periods has then been followed by a dramatic 4–6°C warming to an interglacial state. Within this 100 000-year cycle, smaller anomalies have occurred at approximately 20 000- and 40 000-year intervals.

More detailed temperature trends for the past 10 000 years are shown in Figure 6b. Temperatures peaked during the present interglacial period at about 5000 to 6000 YBP (years before present) and have gradually cooled since then. The warm peak of the interglacial is commonly referred to as the Holocene maximum. Several "little ice ages" or periods of greater cooling appear superimposed upon the subsequent cooling trend at approximately 2500-year intervals,

Figure 6
Global temperature variations of the past one million years



SOURCE: Adapted from Folland et al. 1990.

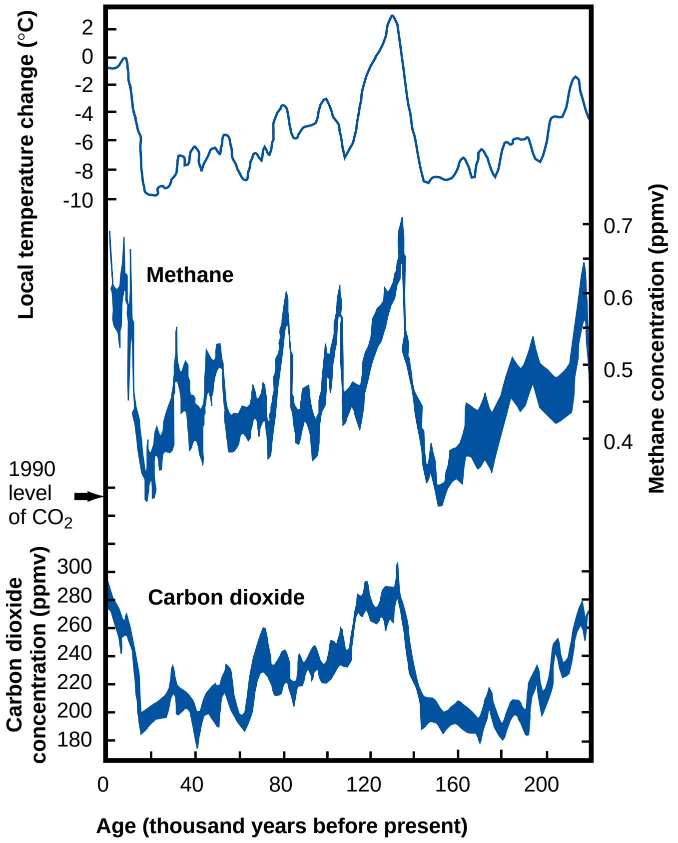
The graphs show departures of average global temperatures from current values: (a) over the past 1 000 000 years, (b) the past 10 000 years, and (c) the past 1 000 years.

the latest having occurred between about 1400 AD and 1900 AD. Today global average temperatures are believed to be almost equal to those of 1000 years ago, approximately 1°C below that of the Holocene maximum and about 1–2°C cooler than the last interglacial of 135 000 YBP (Figure 6c).

Many theories have been advanced to explain these temperature variations. One hypothesis that has gained wide acceptance suggests that the 20 000- and 40 000-year fluctuations are related to changes in the Earth's orbit around the sun. The cause of the 100 000-year pattern, however, is still subject to much controversy. Although it correlates well with a 100 000-year cycle in the eccentricity of the Earth's orbit, the magnitude of consequent changes in incoming solar radiation is far too small to explain the large glacial-interglacial cycles.

Recent analyses of Antarctic and Greenland ice cores, however, indicate a strong correlation between these climatic changes and the natural concentrations of atmospheric carbon dioxide (CO_2) and methane (CH_4), both important greenhouse gases. As Figure 7 shows, the correspondence between atmospheric carbon dioxide and methane concentrations and south

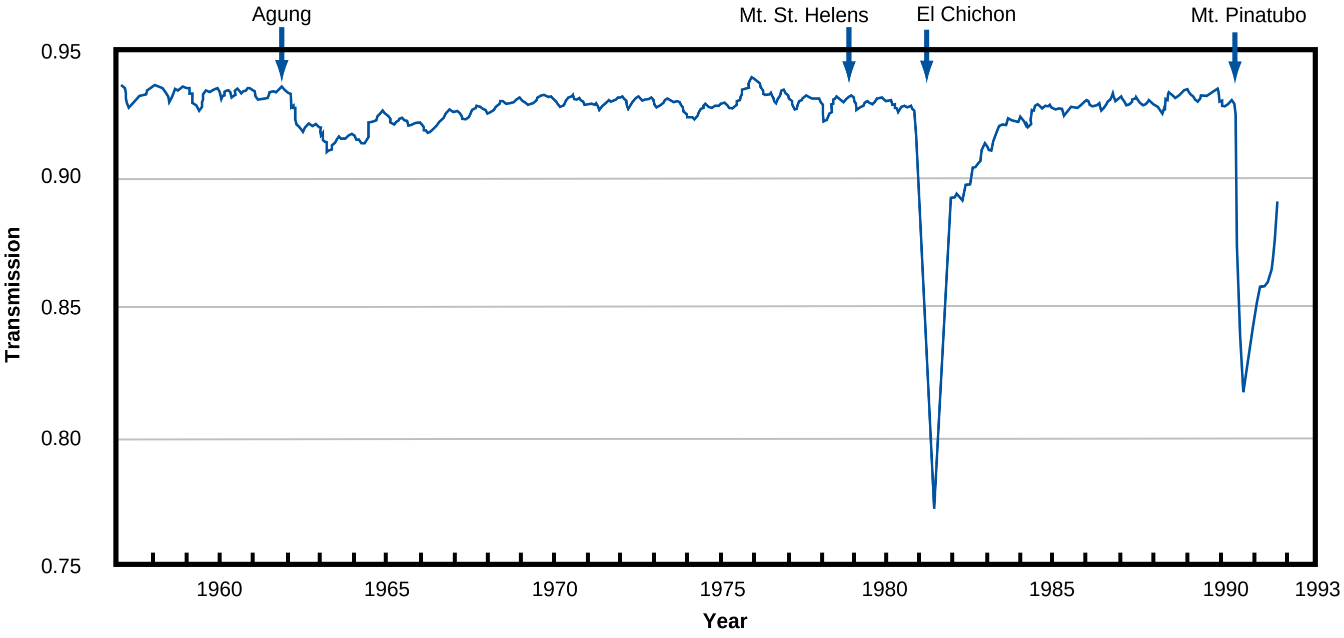
Figure 7
Comparison of local temperatures and atmospheric concentrations of methane and carbon dioxide in Antarctica over the past 220 000 years



SOURCE: Adapted from IPCC 1994.

The width of the plots for the two gases indicates the range of variability of the data. Temperatures are shown as departures from present values.

Figure 8
Effects of changing concentrations of atmospheric aerosols on light transmission



SOURCE: Adapted from NOAA 1993.

Increases in the atmospheric concentration of aerosols decrease the amount of solar light transmitted through the atmosphere. The graph shows light transmission data for Mauna Loa Observatory in Hawaii from 1958 to 1993 and indicates major volcanic eruptions during this period.

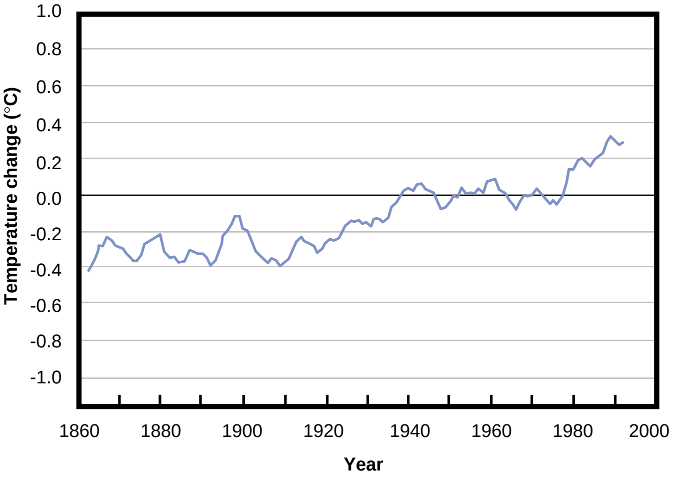
polar temperatures during the past 220 000 years has been very close. This relationship would suggest that external changes to the atmosphere's energy balance may be amplified significantly by a very powerful positive feedback mechanism involving the greenhouse effect.

The last millennium

For fluctuations on a shorter time scale, efforts at correlating solar irradiance cycles with temperature patterns, particularly at 180- and 80-year intervals, have provided some encouraging results. However, none of the correlations has yet been shown to be statistically significant. The natural climate forcing factor that correlates best with recent global temperature fluctuations is atmospheric loading of volcanic dust and aerosols (Figure 8). Changes in this loading can contribute significantly to the year-to-year variability of the global temperature record and may have much longer-term effects if such changes are sustained for extended periods of time.

Figure 9 provides a detailed and comparatively accurate reconstruction of global temperatures for the past century. In compiling this record, researchers have carefully allowed for any influence caused by heat released from cities (the city heat island effect) and have added data from observations over the world's oceans. Although the early decades of the century were significantly cooler than the present, temperatures rose steadily during the twenties and thirties, until reaching a warm peak in the mid-forties. Temperatures then declined slightly, and moderately cooler values prevailed until the mid-1970s. Since then, the warming trend has resumed, with global temperatures reaching new highs in the 1980s and early 1990s, when the eleven warmest years of the past hundred have so far been recorded. Currently, the Earth's average surface temperature is about 0.5°C warmer than it was during the nineteenth century.

Figure 9
Departures of annual average global surface temperatures, 1860–1994, from the 1950–79 average



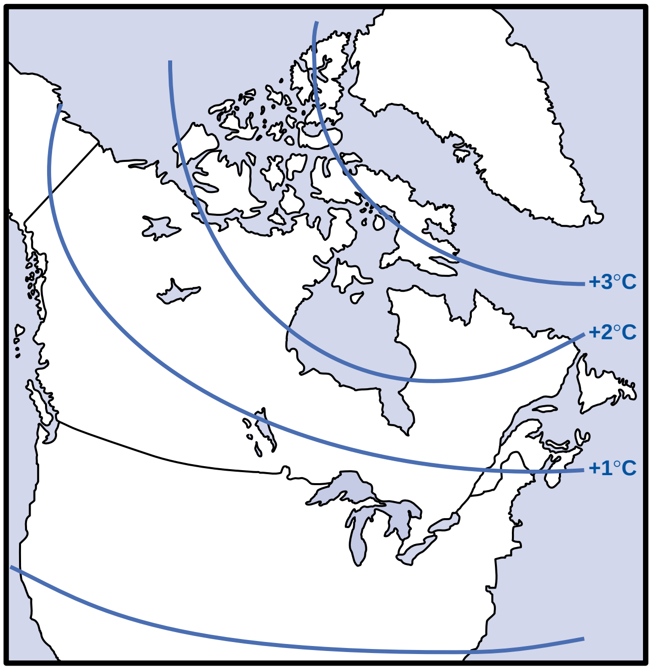
SOURCE: Adapted from Boden et al. 1994.

Climates of Canada's past

Over many thousands and millions of years, changes in global climatic trends have imposed a number of vastly differing climates on what is now Canada. By examining these variations, we can put Canada's present climate in context and find clues pointing to the kinds of changes it might undergo in the future. The present interglacial period—covering the last 10 000 years—is particularly useful in this respect. The evidence of the fossil record suggests that significant climatic variations have occurred during this time. Historical records and climatological documents of the past several centuries provide more detailed evidence of recent fluctuations. A look at three different phases within this period—the Holocene maximum 5000 to 6000 years ago, the past 1000 years, and the past 100 years—gives some idea of the natural variability of climate even within a relatively consistent long-term feature like the present interglacial.

The Holocene maximum—During the warmest peak of the current interglacial, Canada's climate appears to have been warmer, drier, and windier than that of today. Research results suggest that, while increases in summer temperatures in southern Canada were relatively modest, the higher Arctic experienced summer temperature increases in excess of 3°C (Figure 10).

Figure 10
Estimated increase in North American temperatures over present values during the Holocene maximum, 6000 years ago



SOURCE: Adapted from Folland et al. 1990.

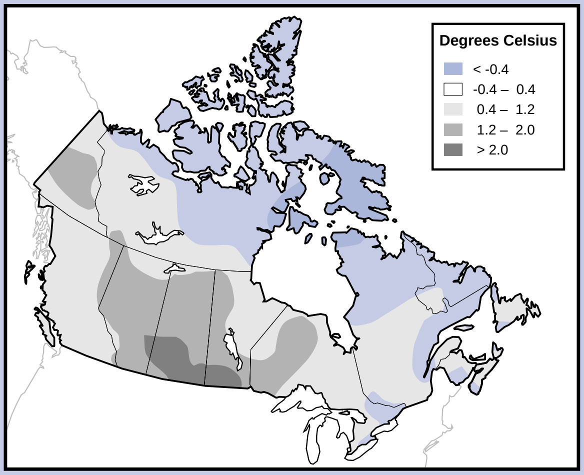
The medieval warm period—About 1000 years ago, the climate of the Northern Hemisphere appears to have been much the same as it is today but significantly warmer (by 1/2 to 1°C) than it was during several of the intervening centuries. Since this warm episode lasted several hundred years, treelines and other natural vegetation boundaries gradually moved northwards. Milder Arctic climates brought substantial decreases in sea ice cover. These conditions may have encouraged not only the migration of Inuit within the Arctic but also the arrival and settlement of the European Vikings in Iceland and Greenland (Figure 11). The Vikings appear to have navigated freely throughout much of the Canadian Archipelago, and in Greenland they were able to carry on a viable agriculture. Ironically, European attempts from the seventeenth to the nineteenth centuries to find a Northwest Passage to India failed, primarily because they began after the medieval warm period had given way to a "little ice age" lasting from about 1400 to 1900 A.D. If only Franklin had tried six centuries before! Since today's temperatures are similar to those of the medieval warm period, it is likely that the vegetation and ice regimes that prevailed 1000 years ago will return if these temperatures persist.

Canada’s changing climate

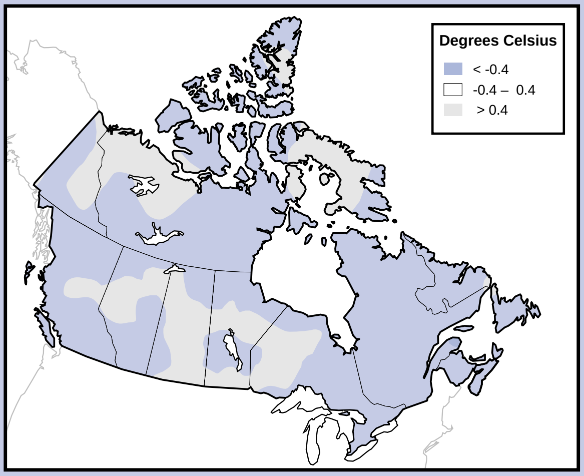
While mean global temperature trends, as illustrated in Figure 9, suggest that the world as a whole has become warmer in the last century, the detailed picture is more complex. Indeed, there are sometimes substantial differences between trends for neighbouring regions or for different seasons of the year.

The accompanying maps show how average seasonal temperatures for the 1980s have changed in different parts of the country, relative to average conditions during the preceding 30 years. For summer, the data indicate no significant differences. Winter and spring, however, both show a strong band of substantial warming extending from the southern Prairies through the Yukon and the western region of the Northwest Territories to Alaska. This contrasts with a modest cooling over the northwestern part of Labrador and the Arctic islands. Elsewhere, there is little change. During the autumn, western Canada again experiences substantial warming, while in the East the cooling pattern becomes more intense and extensive, expanding into Quebec and Ontario.

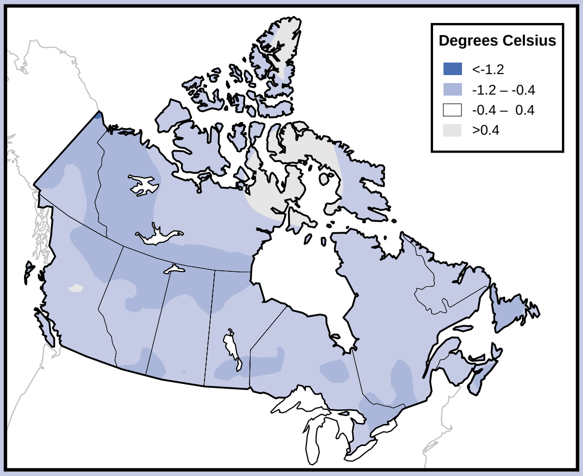
Spring Temperature Departures from the 1951–1980 Average for the Decade 1980–1989



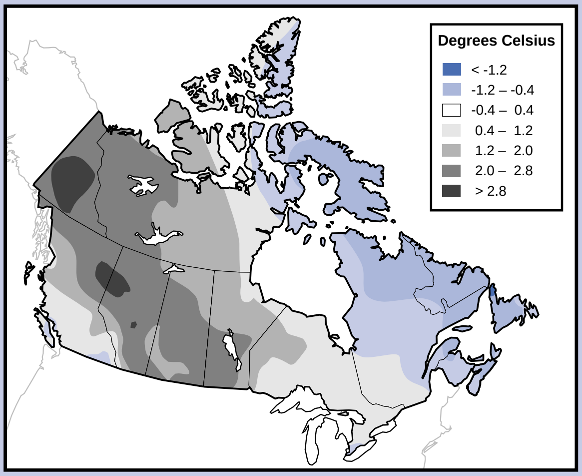
Summer Temperature Departures from the 1951–1980 Average for the Decade 1980–1989



Autumn Temperature Departures from the 1951–1980 Average for the Decade 1980–1989

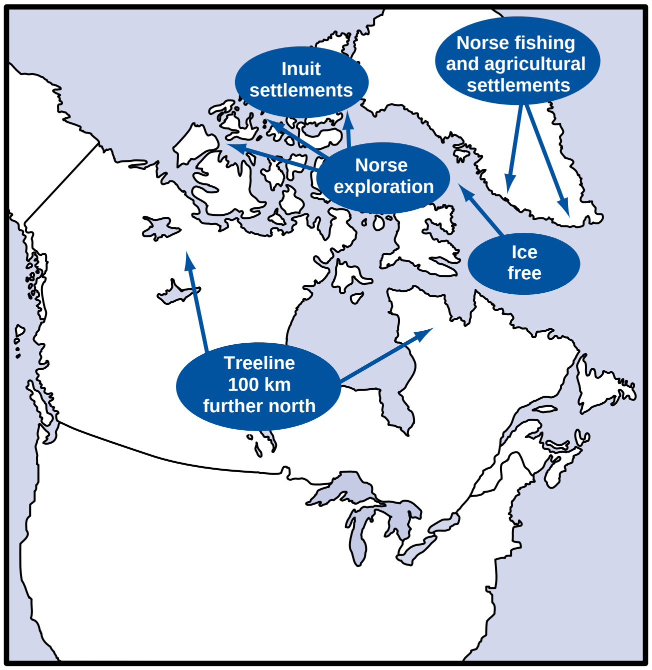


Winter Temperature Departures from the 1951–1980 Average for the Decade 1980–1989



These maps illustrate that, at a regional level, the global trend to warmer climates has been modified by shifts in seasonal wind patterns. By altering the net flow of cold and warm air masses in different parts of the country, these shifts have amplified the warming in some areas and seasons and offset it in others. This provides an important reminder that future global warming, if it continues to escalate, will not be uniform in time or space.

Figure 11
Arctic conditions during the medieval warm period, 1000 years ago

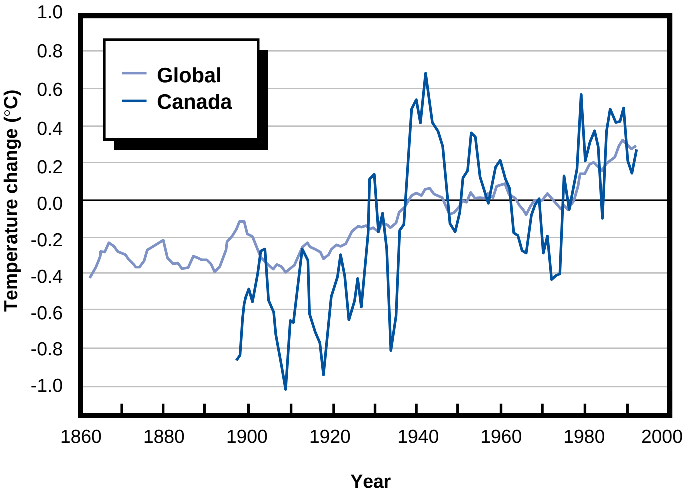


Source: Environment Canada, Atmospheric Environment Service.

The last hundred years—Climatic change during the past century can be studied with much greater precision than earlier periods, thanks to the existence of a large body of scientifically collected climate records. These records make it possible to analyze both the spatial and temporal patterns of change in significantly finer detail and with a smaller margin of error.

Studies of these records show that, even within the relatively short span of a century, Canada's climate has experienced noticeable variations (Figure 12). Average Canadian temperatures for these years show much the same broad pattern as global temperatures—a warming until the early 1940s, then a moderate cooling until the mid-1970s, followed by a renewed and pronounced warming continuing through the 1980s. The Canadian temperature swings, however, have been more extreme.

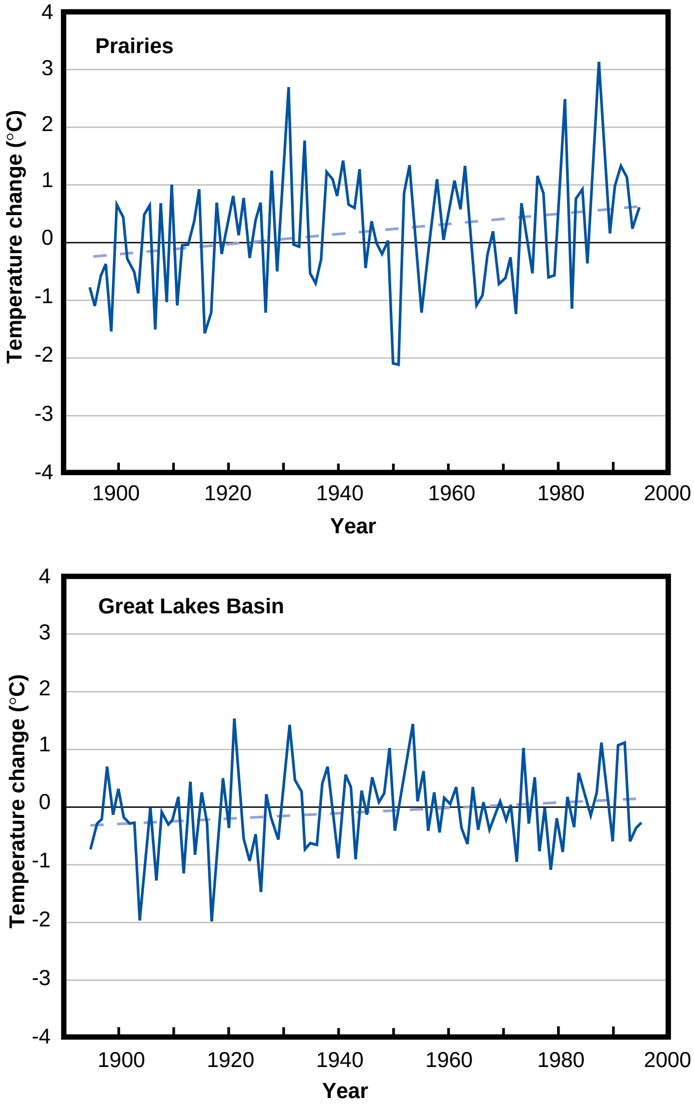
Figure 12
Global and Canadian surface temperature trends since 1860



Source: Boden et al, 1994, and Environment Canada, Atmospheric Environment Service.

The graph plots departures of annual average temperatures from the temperature average for 1950–79 (represented by the 0° line).

Figure 13
Temperature trends in two regions of southern Canada



SOURCE: Environment Canada, Atmospheric Environment Service.

Variations of average annual temperatures are given for Prairie and Great Lakes Basin regions of southern Canada. Temperatures are shown as departures from the 1950–79 average. Dashed lines represent long-term trends.

If we look at regional climate patterns within Canada (Figure 13), the mid-century cooling trend appears to have been much stronger on the Prairies and begins almost a decade earlier than in the Great Lakes Basin. In addition, while trends over the past 30 years show marked warming in winter and spring, particularly in western Canada, summers show little change, and eastern cooling is most significant in autumn (see "Canada's changing climate").

All of these trends serve to remind us that the increasingly warm weather of recent years is not without precedent in the world's climate history. What we have experienced so far is within the bounds of natural climatic variation experienced in pre-industrial times. However, should the warming trend of recent years continue, those bounds will soon be exceeded, and we may enter a period of climatic change unlike any which has occurred within the last several hundred thousand years.

Chapter 2

Enhancing the greenhouse effect

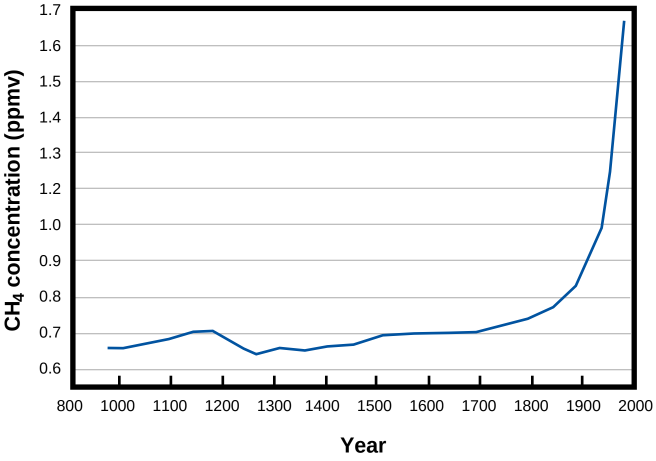
Analyses of cores extracted from the polar ice caps provide some important clues about the past relationship between the natural greenhouse effect and the Earth's climate. The Antarctic and Greenland cores—the deepest of which penetrated more than 2 km beneath the surface of the south polar ice—have been especially informative. From them, scientists have reconstructed records of temperatures as well as records of carbon dioxide and methane concentrations in the polar regions for the past 220 000 years.

When compared, these two sets of records show a remarkable correlation, particularly during the transition from cold glacial periods to warm interglacials (Figure 7). The processes that cause this relationship are as yet not well understood. However, the evidence does suggest that concentrations of greenhouse gases have varied significantly in the past and that these variations may have played an important part in the very large changes in global temperatures that have occurred.

While the ice cores confirm that concentrations of greenhouse gases are variable, they also suggest that these variations may have natural limits. During the past 220 000 years, carbon dioxide concentrations have never gone lower than approximately 190 parts per million by volume (ppmv), nor, until recently, had they ever gone higher than 290 ppmv (Figure 7). Likewise, concentrations of methane appear to have remained within a relatively narrow range of 0.3 to 0.7 ppmv over the same period.

However, recent measurements of greenhouse gas concentrations over the past several centuries, again obtained from ice cores, reveal that a major departure from past patterns is emerging. As Figure 7 shows, carbon dioxide concentrations today are greater than 355 ppmv, exceeding the highest values of the past 220 000 years by more than 20%. Methane concentrations appear to have more than doubled over pre-industrial values (Figure 14), while nitrous oxide levels have undergone a much more modest increase of about 8%. If, indeed, these gases are primary players in the natural greenhouse effect, their increasing concentrations portend a possible enhancement of that effect well beyond the level suggested by the ice core record.

Figure 14
Changes in atmospheric methane concentrations during the past 1000 years



Source: Adapted from IPCC 1994.

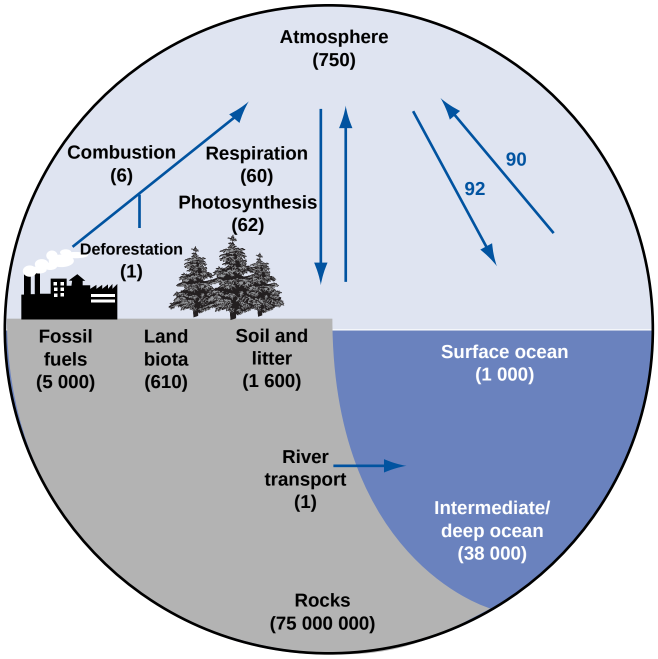
During recent decades, intensive research has been devoted to measuring the concentrations of these gases more accurately. At the same time, scientists have been trying to achieve a better understanding of the processes involved in their release and removal from the atmosphere and to estimate likely concentrations in the future.

Carbon dioxide

Understanding how the amount of carbon dioxide in the atmosphere changes is not a simple task. Carbon dioxide is constantly being removed from the air by the transfer of the carbon atom to biotic substances through photosynthesis and by direct absorption into water. In turn it is released into the air by plant and animal respiration, decay of dead biomass, outgassing from water surfaces, and combustion (Figure 15). Carbon dioxide is also injected directly into the atmosphere by volcanic emissions.

The more active carbon storage areas within the Earth's ecosystem are the living terrestrial biosphere, the atmosphere,

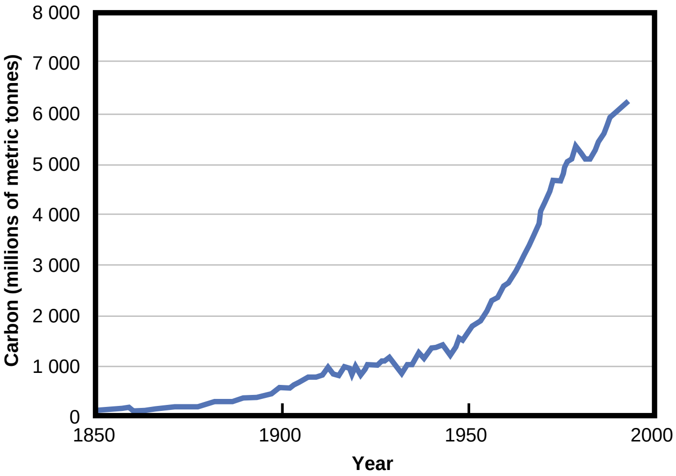
Figure 15
Global carbon cycle



Source: Data from IPCC 1994.

The diagram shows the global carbon cycle and carbon storage areas. All values are in billions of tonnes of carbon.

Figure 16
Carbon content of annual global carbon dioxide emissions from fossil fuel combustion and cement production, 1850–1991



Source: Data from Boden et al. 1994.

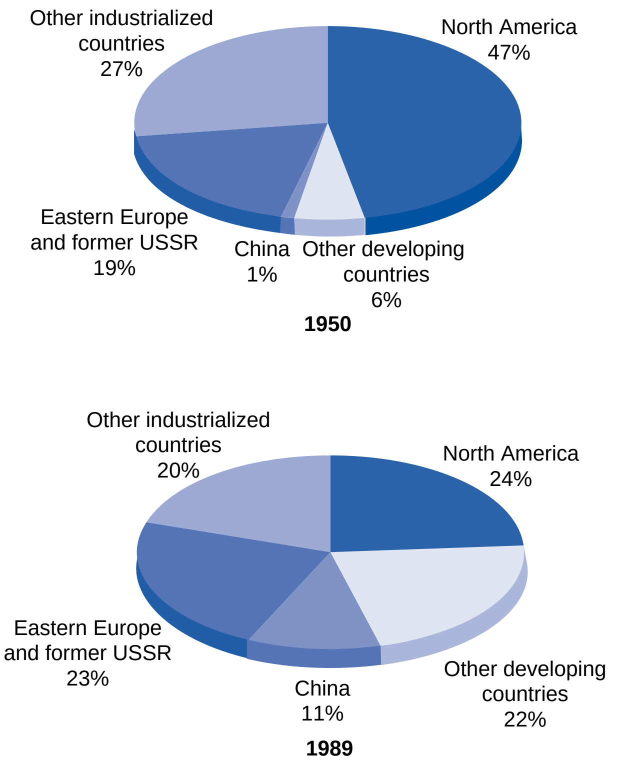
and the oceans. These contain about 600, 750, and 39 000 billion tonnes of carbon respectively. The atmosphere exchanges about 90 billion tonnes of carbon with the ocean each year and approximately 60 billion tonnes per year with living plants. Over a period of about a decade, the net amount of carbon taken into the atmosphere by natural processes is approximately equal to the amount released.

The Earth's soils, rocks, and carbon-based fuels are also large reservoirs of carbon. Estimates suggest that soils may contain up to 1600 billion tonnes of it. Carbon fuels contain about 5000 billion tonnes of carbon, while rocks store much more (an estimated 75 million billion tonnes). However, these reservoirs, unless unnaturally disturbed, only exchange carbon with the atmosphere very slowly and over very long periods of time.

Human activities now appear to be significantly affecting the natural balances that exist within the global carbon cycle. Large-scale conversions of forested landscapes to agricultural uses appear to have released more than 100 billion tonnes of carbon into the air over the past century. The annual rate of new carbon releases because of deforestation may be even more rapid now, primarily due to extensive slash-and-burn activities in the tropical forests of South America, Africa, and Southeast Asia. Although new forest growth in the Northern Hemisphere may be partially offsetting this release, the net biospheric contribution of carbon to the atmosphere due to human activities is estimated at between 0 and 2 billion tonnes per year.

However, of much greater significance is the ever-increasing extraction of fossil fuels (coal, oil, and natural gas) from the Earth's crust to meet the energy demands of an increasingly industrialized global society. During combustion, the carbon content of fossil fuels is oxidized and released as carbon dioxide. For every tonne of carbon burned, 3.7 tonnes of carbon dioxide are produced. Production of cement also adds a modest amount (approximately 2%) to these releases. These sources now add an estimated 6.2 billion tonnes of carbon, or 23 billion tonnes of carbon dioxide, to the atmosphere each year, more than ten times the rate at the turn of the century (Figure 16).

Figure 17
Regional distribution of carbon dioxide emissions from fossil fuel combustion, 1950 and 1989



SOURCE : World Resources Institute, 1992.

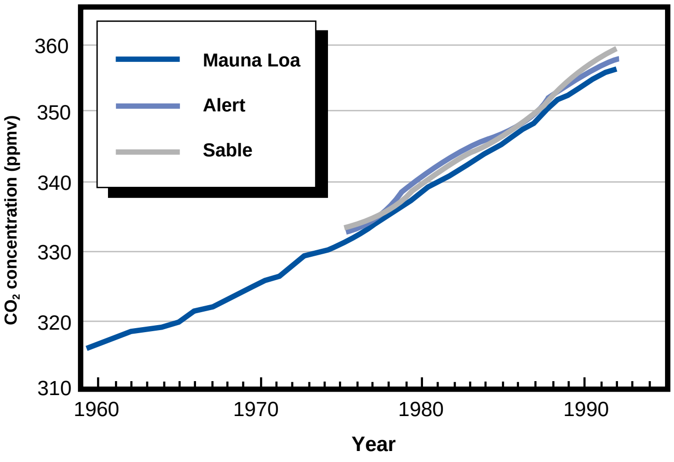
Not surprisingly, the release of carbon dioxide from fossil fuel burning is very unevenly distributed around the world, with the largest share being released by developed countries in the Northern Hemisphere. However, emissions are increasing most rapidly in many of the nations of the developing world (Figure 17), particularly China and India. Should these trends continue, global emissions of carbon dioxide are likely to be much larger in the future.

Anthropogenic releases of carbon dioxide (those from human activities) appear as yet to be relatively small compared to the truly enormous amounts that enter and leave the air through natural processes. In fact, human activities annually produce about 1/20 of the amount of carbon dioxide produced by nature. However, this amount is a net addition to one side of a global carbon cycle that is already in approximate balance. It is also cumulative with time.

Over the past three decades, carbon dioxide concentrations have been carefully measured at many locations around the world, and the consequences of these additions are clearly evident in the results. The trends (Figure 18) show current rates of increase of about 1.8 ppmv, or 0.5%, per year and a net rise over 35 years of 13%. This rate of increase is, in fact, significantly less than should occur if all carbon dioxide releases due to human activities were to remain in the atmosphere. However, approximately 50% of the anthropogenic carbon emissions appear to be finding their way back into the natural carbon cycle. Although the net sink for this carbon removal process is poorly understood, both the oceans and terrestrial ecosystems are believed to be important recipients. In other words, the natural system appears willing to forgive a part of the human interference, but only part.

Predicting future concentrations of atmospheric carbon dioxide is very difficult. The largest uncertainty pertains to future rates of carbon dioxide emission from human activities. These will depend on a number of variables. How fast, for example, will the world's population grow? Will we be using the same sources of energy in the future as we do now? Will our energy use be more efficient? And how far will developing countries improve their standards of living and hence increase their consumption of energy? The answers to such questions, in turn, will depend on human decisions, political actions, and technological and socio-economic develop-

Figure 18
Atmospheric carbon dioxide concentrations



SOURCE: Data from Boden et al. 1994 and Environment Canada, Atmospheric Environment Service.

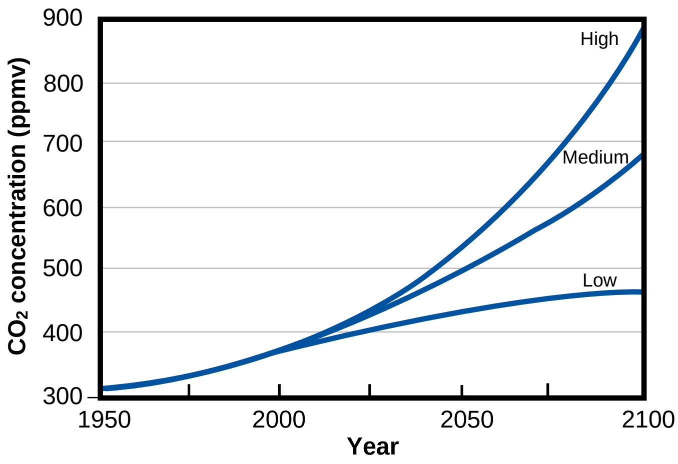
The graph shows atmospheric carbon dioxide concentrations measured at a tropical location and two Canadian locations.

ments that are themselves largely unpredictable. By 2050, it is estimated that annual carbon dioxide emissions from human sources could range from a low of 40% of today’s levels (assuming a maximization of energy efficiency and the use of non-fossil fuels) to a high of 400% (assuming no improvements in energy efficiency and a heavy use of coal).

Lesser but still important uncertainties relate to how much of these carbon dioxide releases will be retained in the atmosphere. Will the natural system continue to remove up to 50% or even more of the carbon dioxide releases through absorption into the terrestrial biosphere or oceans? Or will the fraction remaining in the atmosphere increase with time? The answer is as yet unclear and must await the results of further intensive research and observation of the natural carbon cycle.

Taking these uncertainties into account, our best estimates of future atmospheric concentrations of carbon dioxide yield a variety of scenarios. The most pessimistic suggests a possible doubling of concentrations over pre-industrial levels as early as the middle of the next century. A slightly less pessimistic version suggests a probable doubling by the end of the next century. An optimistic scenario, however, envisions a stabilization of concentrations before the doubling level is reached (Figure 19).

Figure 19
Projections for future atmospheric carbon dioxide concentrations



Source: Adapted from IPCC 1994.

The high scenario represents a high-growth, high fossil fuel use future. The low scenario assumes low economic growth and decreasing use of fossil fuels for energy.

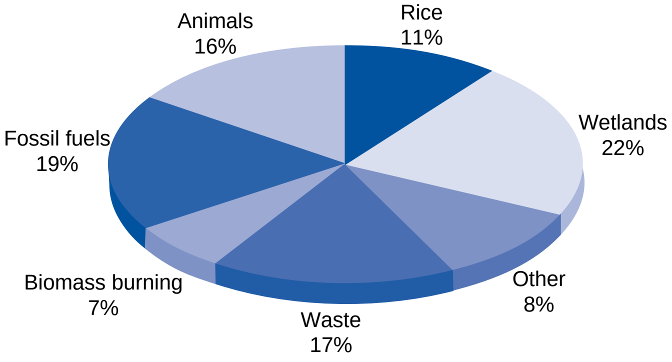
Methane

Methane (CH_4) is produced naturally by the decay of organic material in the absence of oxygen. Although methane concentrations have not been measured continuously for as long as those of carbon dioxide, studies over the past decade suggest they are currently increasing at approximately 0.7% per year and are already more than 100% higher than pre-industrial values measured in ice cores (Figure 14).

Like carbon dioxide, methane cycles naturally between the Earth’s surface and atmosphere. Wetlands are a primary source—hence its popular name, “swamp gas.” It is also released through the digestive processes of certain insects and ruminant animals, such as termites, sheep, and cattle. Although the global area of natural wetlands may actually be decreasing due to human interference, the total acreage of rice paddies appears to be increasing rapidly, while the global population of domestic cattle has quadrupled during the past century. Other sources include industrial processes, fossil fuel extraction, and garbage dumped in landfill sites (Figure 20).

The increase in methane emissions is primarily a result of changes in land use caused by the continuing rapid growth of the global human population and the concurrent increase in the use of fossil fuels for energy. Since the world’s population is unlikely to stabilize for at least the next century, a continuation of these changes and further increases in methane releases can be expected. At the same time, the rate of removal of methane from the atmosphere by natural processes could slow down in the future. Reaction with the hydroxyl radical (OH) is the

Figure 20
Estimated contribution of various sources to total global emissions of methane



Source: Data from IPCC 1994.

major atmospheric sink for methane, but concentrations of OH are likely to decrease as a result of more frequent reactions with growing concentrations of both methane and various urban air pollutants. The combination of these trends suggests that the contribution of methane to the enhancement of the greenhouse effect will continue to increase over the next century.

Other greenhouse gases

Nitrous oxide (N_2O) concentrations are now increasing by 0.2–0.3% per year, and present levels are about 8% greater than pre-industrial values. Although both the natural cycle and the magnitudes of human sources of nitrous oxide are poorly understood, emissions from the agricultural use of ammonia-based fertilizers (both in chemical form and as natural wastes from domestic animals) are believed to be the largest contributor to increases in the atmospheric concentrations of N_2O. Other important contributors include the industrial production of adipic acid (used in making nylon), biomass burning, and the combustion of fossil fuels in cars equipped with catalytic converters.

Ozone (O_3) is found naturally in the lower 10–15 km of the atmosphere (known as the troposphere) in minute concentrations. Some of it is transported down from the upper atmosphere (the stratosphere), where it is produced directly from oxygen by sunlight. However, during the past century it has also been produced in increasing quantities near the Earth's surface through chemical processes involving nitrogen oxides, carbon monoxide, other air pollutants, and sunlight. Although ozone in the troposphere decays very quickly, over recent decades concentrations near the surface appear to have increased by up to 50% in many industrialized areas of the Northern Hemisphere. This regional rise in low-level concentrations is associated mainly with pollution from transportation and stationary combustion processes. However, the rate of growth in low-level ozone concentrations in industrialized regions appears to have decreased significantly during the 1980s. Furthermore, trends in concentration in the upper regions of the troposphere, where ozone is most effective as a greenhouse gas, are as yet poorly understood. Thinning of the ozone layer in the lower stratosphere by chlorofluorocarbons (CFCs) and other ozone-depleting substances (see below) may also significantly offset the warming effects of ozone increases in the troposphere. Consequently, the net impact of changing ozone concentrations on the greenhouse effect is still not clear.

Halocarbons containing chlorine, fluorine, and bromine are, molecule for molecule, among the most potent greenhouse gases in the atmosphere (see "Greenhouse gases: a comparison"). They do not occur naturally but are produced industrially in large quantities. The best-known members of this group of chemicals are the CFCs, which have been widely used as solvents, refrigerants, spray can propellants, and foaming agents. Also significant are the halons, bromine-based compounds that are used as fire-extinguishing agents.

Because these and many other halocarbons are very stable and do not readily react chemically with other gases, each molecule released into the atmosphere can remain there for decades and even centuries until it is finally broken down in the upper atmosphere by intense ultraviolet radiation. This breakdown releases chlorine and/or bromine, the substances mainly responsible for depleting the ozone layer (see Chapter 6). Although atmospheric concentrations of the principal CFCs are very low, some had been increasing until recently at rates of more than 4% per year and had come to be considered significant factors in the enhancement of the greenhouse effect. However, growth rates of CFC concentrations have recently begun to decline as a result of international action under the Montreal Protocol. Furthermore, the direct greenhouse effects of these substances, like those of tropospheric ozone, may be offset indirectly by the depletion of the ozone layer and a consequent cooling of the lower stratosphere. Hence, as with ozone, the net effect of ozone-depleting halocarbons on the climate system remains uncertain.

Water vapour, while actually the most powerful of all the greenhouse gases, is not itself a primary factor in the enhancement of the greenhouse effect. It will, however, be a factor in both positive and negative feedback effects as temperatures begin to rise. Since warmer air can hold more moisture and higher temperatures will cause more water to evaporate from the Earth's surface, the water vapour content of the atmosphere will increase. This will add to the greenhouse effect, but the additional moisture in the atmosphere will also increase cloud formation. The effect of this may significantly reduce the amount of solar energy warming the Earth's surface, thus partly offsetting the increase in greenhouse warming caused by water vapour.

Other human influences

The enhancement of the natural greenhouse effect will undoubtedly be humanity's primary impact on global climate. However, human activities can also affect climate significantly in other ways on local and regional scales. The effects of some of these activities could ultimately become globally significant.

Land use change—As humans replace forests with agricultural fields, or natural vegetation with asphalt or concrete, they sub-

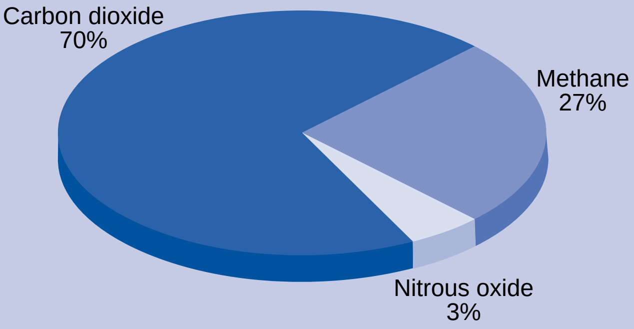
Greenhouse gases: a comparison

Molecule for molecule, carbon dioxide is the least effective of the major greenhouse gases. Methane, by comparison, absorbs and reradiates about 21 times as much heat energy, while nitrous oxide is about 206 times as effective. Some CFCs are even more powerful, with each molecule absorbing about 15 000 times more heat than a molecule of carbon dioxide.

The overall contribution of each gas to the greenhouse effect, however, depends on several other factors as well. One is the amount of each gas that we release into the atmosphere each year. By weight, methane emissions are only about 1% of those for carbon dioxide, while those for other greenhouse gases are much lower. Another is the atmospheric lifetime of each greenhouse gas—the length of time it remains in the air before being destroyed by chemical reactions or absorbed into the biosphere or the oceans. The effect of methane relative to other greenhouse gases, for example, is diminished to some extent because its atmospheric lifetime is relatively short (about 10 years). Thus, increased releases of methane tend to accumulate slowly, like money in a bank account in which deposits are only slightly greater than withdrawals. With longer-lived gases such as nitrous oxide and CFCs, however, the withdrawal rate is significantly lower, and new releases have a greater cumulative effect. Although accurate comparisons are difficult, it is likely that over the long term each tonne of CFC gas released into the atmosphere will have several thousand times the warming effect of the same amount of carbon dioxide. The effect of nitrous oxide can be expected to be several hundred times greater, unit for unit, while the direct effect of methane will probably be a bit more than a factor of 10 greater than carbon dioxide.

A third important factor is the indirect effect that emissions of each greenhouse gas will have on atmospheric chemistry and the concentration of other greenhouse gases. Methane, for example, reacts with the OH molecule to produce CO_2 and water vapour. However, by reducing the concentrations of the OH molecules, methane both increases its own lifetime in the atmosphere and contributes to an increase in ozone concentrations. These indirect effects may be even more significant than its direct effects. On the other hand, the indirect ozone-depleting effect of the CFC gases can contribute to a regional surface cooling that can significantly offset their direct greenhouse effect.

Taking all of these factors into account, it is estimated that the net contribution of carbon dioxide emissions to the past decade's increase in potential global warming is about 2 to 3 times that for methane and about 15 times that of nitrous oxide. The net effects of halocarbon emissions and changes in ozone concentrations and distribution remain uncertain but could also be very significant.



stantially alter the way the Earth's surface reflects sunlight and releases heat. In general, flooded lands and wet soils absorb more sunlight than a forest canopy, and paved parking lots more than grasslands. On the other hand, deserts created by deforestation and overgrazing reflect more sunlight than the trees and grasslands they replace, and snow-covered fields more than forests. All these changes also affect regional evaporation, runoff, and rainfall patterns. Although they can have a substantial influence locally, in most cases they are unlikely to have a significant effect on climate globally.

Atmospheric aerosols—Humans are adding large quantities of fine particles (aerosols) to the atmosphere, both from agricultural and industrial activities. Although most of these aerosols are soon removed by gravity and rainfall, they still affect the radiation balance in the atmosphere. Whether this effect adds to or offsets any warming trend depends on the quantity and nature of the particles as well as the nature of the land or ocean surface below. The regional effects, however, can be significant. Scientists have recently suggested that high regional concentrations of sulphate and other aerosols from fossil fuel and biomass burning may be significantly reducing solar heating in some parts of the world, particularly in the Northern Hemisphere. That is because sulphate aerosols not only reflect more sunlight back to space directly but also increase condensation rates in low clouds, thus making them more reflective. These processes may have temporarily reduced the magnitude of any hemispheric warming that may be occurring due to an enhanced greenhouse effect. However, the net global effects of changes in aerosols are not yet properly understood.

Arctic haze—Since the 1940s, observers in the Arctic have reported the increasing presence of layers of reddish-brown haze. The haze, which is observed primarily during winter and spring when the Arctic air is very calm, consists of industrial aerosols, mostly from Europe and northern Asia, that have been transported long distances into the Arctic by prevailing winds. These aerosols include sooty and acidic particles which increase the net absorption and diffusion of spring sunlight in the lower atmosphere. They also increase the surface absorption of sunlight as they settle out on snow and ice. The haze may cause spring temperatures in the Arctic to become slightly warmer. If that happens, changes in hemispheric wind patterns could also occur.

Urban heat islands— City environments are substantially different from the rural environments they replace. Buildings and vehicles release heat directly to the air, while air pollution and the dark surfaces of pavements and roof tops add to the absorption of sunlight. Buildings also alter wind flow: wind speeds increase between large buildings but may drop to zero in their lee. The net result is that cities are significantly warmer than the surrounding countryside, particularly in the winter. Central Toronto, for example, is on average about 3°C warmer than surrounding regions. The effect is strictly local, however. All the urban heat islands in the world added together do not significantly affect global climate conditions.

Water diversions and storage—Water, whether flowing in streams and rivers or stored in lakes, is a source of moisture for the air above it and an important means of storing heat. Bodies of water help to cool local climates in summer and warm them in winter. Large-scale projects to dam or divert water flows can therefore have a significant influence on regional climates.

Chapter 3

Predicting climate change

Major climatic change inevitably creates the possibility of a radical transformation of the global ecosystem. Should that happen, human societies would be faced with physical, social, and economic dislocations that could equal or even surpass any the world has yet experienced. Responding to such changes would be a priority for all societies, and it is therefore vitally important to know what changes could occur and what their consequences would be. But, given the complexity of the Earth's climate system, can we in fact predict with any reasonable degree of certainty what changes are likely to take place?

Unfortunately, the complex processes and interactions that make up the global climate system are far too large and intricate to reproduce in a laboratory experiment. Studying the climate systems of other planets, such as Mars and Venus, does not help significantly either, since those systems do not include oceans or terrestrial biospheres.

Studies into the past behaviour of Earth's climate can provide much information on how previous climates have evolved and can point to possible causes of change, but these studies tell us little about the physical processes involved. Nor can we simply extrapolate the trends and variations of past and recent climates to predict the future, particularly when the forces involved in future changes may be uniquely different from those of the past.

Fortunately, most of the detailed processes, interactions, and changes that occur within the climate system can be explained in terms of statistically derived relationships and well-defined physical laws such as the law of conservation of mass and energy or Newton's laws of motion. These physical relationships can be developed into mathematical expressions and, with the help of advanced computer facilities, can be used to calculate how the system will respond to forces of change.

Such mathematical models are now being used extensively to study the climatic effects of current phenomena such as volcanic eruptions or ocean temperature anomalies. They are also being used to help explain past climate events and to simulate how the climate system might respond to such major disruptions as a nuclear war or an enhanced greenhouse effect.

Mathematical climate models

Because of limitations in mathematical techniques and computer capabilities, we cannot replicate every process of the climate system in full detail. Modellers must therefore simplify and approximate these processes, making assumptions about which ones are most important and which are least affected by such adjustments. Many different kinds of models can be developed. The nature of each depends on the application for which it is intended, the simplifications required, and the amount of spatial and chronological detail needed.

An extremely simple climate model is one that simplifies the temperature of the Earth to a global average at a single point. It can be used to calculate the Earth's average surface temperature as an energy balance arising from the reflective and greenhouse properties of the Earth's atmosphere.

At the opposite extreme are the very complex and sophisticated general circulation models (GCMs), which use the physical laws of conservation of momentum, mass, moisture, and energy to create a detailed three-dimensional model of the oceans and atmosphere. These can simulate how different climate parameters—temperature, humidity, wind speed and direction, soil moisture, and a large range of others—will evolve over time anywhere on the globe as various conditions are altered.

In between are a large variety of one- and two-dimensional models that are used to study various climate processes and interactions in varying degrees of complexity. These can be very effectively used to study many smaller-scale climatic relationships, and the results of these investigations can help to improve the equations used within the GCMs.

But even the most complex general circulation model is, in fact, only a very crude description of the real climate system. Despite the tens of thousands of spatial points within the atmosphere and oceans for which such a model makes calculations and the 200 000 or more lines of computer code used for these calculations, such simulations cannot fully describe the climate characteristics and processes of continuous space and time.

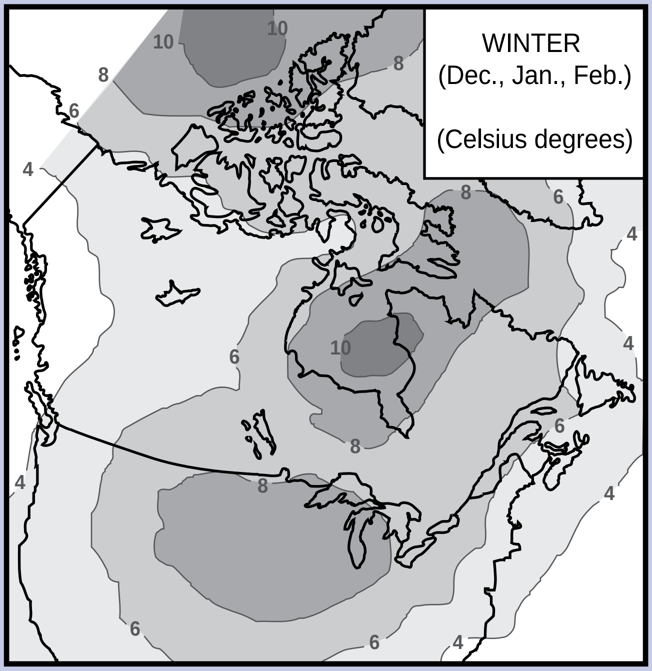
The Canadian GCM

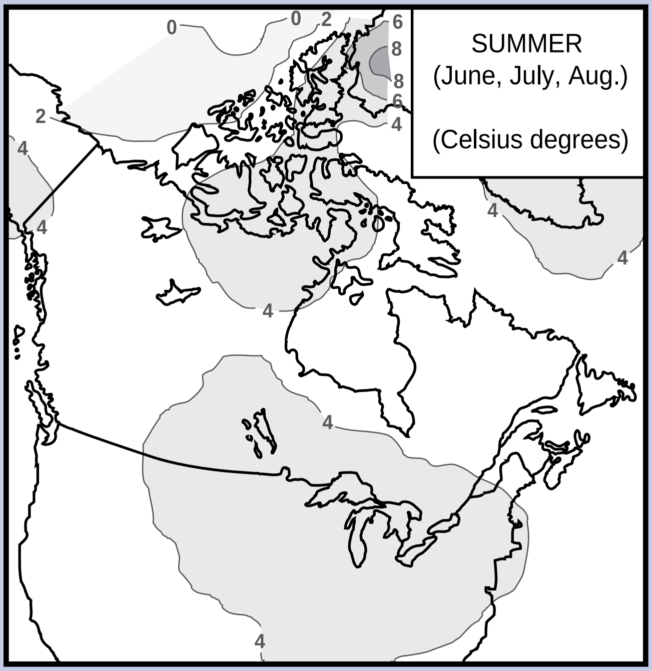
One of the most advanced GCMs in use today is that developed by a group of researchers at the Canadian Centre for Climate Modelling and Analysis in Victoria (formerly in Toronto). Their model incorporates a number of improvements over GCMs used in earlier climate modelling experiments by other groups. In particular, it provides a much higher spatial resolution (i.e., a finer grid) than previous GCMs, giving more than twice the information coverage and allowing a much more detailed representation of local climatic processes. It also provides a more accurate simulation of the reflective and absorptive properties of clouds, annual and daily solar heating, and ocean temperature and ice boundaries. In common with most other models, however, it lacks a fully interactive, circulating ocean.

The first major experiment with this model—a study of the climatic effects of a doubling of carbon dioxide in the atmosphere—was completed near the end of 1989. Despite the improvements in the model's design, the results of the experiment do not depart significantly from those of earlier global warming simulations. The Canadian group's projection of a net global surface warming of 3.5°C, for example, is near the centre of the range produced by other modellers. And although their prediction of a 3.8% increase in average planetary evaporation and precipitation is significantly lower than the other groups' values (which range from 7.1% to 15.8%), it is still in the same direction.

For Canada, the Canadian GCM shows a warming of 4–8°C in the south, with little season-to-season change. In the north, the warming is amplified to 8–12°C in winter, with a more modest 0–6°C warming occurring in summer. Because of a greater increase in evaporation than precipitation, the availability of soil moisture across most of Canada diminishes in all seasons, with the greatest decrease—more than 20%—occurring in the south-central region. Increases in water supply are evident in the Yukon in summer, and in much of the Arctic and along the west coast in winter.

Canadian modellers are now developing a third-generation GCM that improves many of the present features of the current model while adding important new capabilities. These include a fully circulating ocean, inclusion of atmospheric chemistry, and better simulations of land-air interactions.





A typical GCM divides the Earth's surface into a grid or series of boxes. Early low-resolution models used boxes that were relatively large—with each one covering an area as great as 640 000 square kilometres or about the size of Manitoba. Today's highest-resolution models use boxes that are about 90 000 square kilometres in area or roughly 20% bigger than New Brunswick. Vertically, the atmosphere is represented by anywhere from two to thirty layers, depending on the resolution of the model.

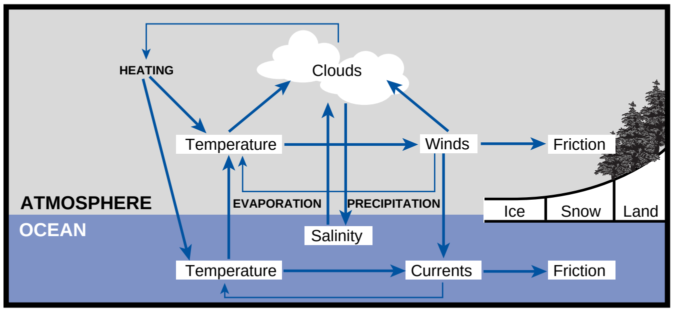
Many important climate processes, however, take place on scales much smaller than even the smallest of these grid boxes and must be dealt with collectively rather than individually. Values for these processes are established through a procedure known as parameterization. This involves the development of physical and statistical relationships between these processes and large-scale variables that can be calculated by the model. Cloud characteristics, evaporation, precipitation, and land surface characteristics are examples of processes and variables that must be parameterized. Models must also include the complex feedback mechanisms that exist between the various processes.

A very simplified description of typical elements included in a GCM is illustrated in Figure 21. Uncertainty about how these processes and feedbacks are best described is a primary reason why different models can disagree significantly on the consequences of a change imposed upon the system and why the results of experiments with these models cannot as yet be used as reliable predictors of future climates.

The ultimate test of a model's power to simulate the real world, of course, is its ability to replicate changes that have already happened. This can be done by using the model to simulate current climate conditions. If its results differ significantly from the observed data, it can be assumed that the model is also unsuitable for other experiments. Most of the GCMs used in the study of climate change today are able to simulate current climates reasonably well. However, none can be considered highly accurate, particularly with respect to regional climates, although some perform better than others.

GCM experiments have added significantly to our understanding of how climates are likely to change. Even so, our knowledge remains far from complete, and many questions about the details of future climate change continue to go unanswered. Scientists believe that getting those answers will require the use of much larger, yet to be developed, computers and a much better understanding of some of the physical processes of the climate system. Such developments could take at least another decade of research.

Figure 21
Major elements of a general circulation model



SOURCE: Adapted from Gates 1985.

Model experiment results

What do GCM experiments tell us about the kind of climate we can expect from an enhanced greenhouse effect?

The most common GCM experiment—one that has been performed many times with a number of different models—involves simulating an atmosphere in which the carbon dioxide concentration is double the level existing in pre-industrial times. While the results of these doubled-CO_2 experiments are not always consistent with each other, they do nevertheless agree on a number of points (Table 2). Among the more reliable conclusions, the following stand out as the most important.

- Average global surface warming due to a doubling of carbon dioxide will be large (1.5°C to 4.5°C) and likely without precedent in human history.
- Warming will be significantly amplified in polar regions during winter and will be greater over land than over oceans.
- Average global evaporation and precipitation rates will increase. There is a significant probability that summer soil moisture conditions in the middle latitudes of the Northern Hemisphere will be drier, while generally moister conditions will prevail in winter in polar regions.

Certain other aspects of future climate, however, have been harder to predict. One of these is the distribution of rainfall. Where rain falls is largely determined by the tracks taken by storms. However, the location of these depends on extremely complex circulation patterns, which GCMs cannot yet model in sufficient detail. Consequently, GCM predictions about changes in storm tracks, and hence in local

Table 2
Agreement of doubled-CO_2 experiment results

Climate factor	Nature of change	Level of agreement
global temperature	– at least 1°C increase – greater warming towards poles – about 3°C increase	– high – high – medium
local temperature	– varies with locality	– low for specific localities
global precipitation and evaporation	– small to moderate increase – amount of increase	– high – low (predictions range from 3% to 15%)
local precipitation	– varies with locality	– low for specific localities
soil moisture	– increased summer dryness in mid-latitudes	– medium to low

Source: Canadian Climate Centre.

precipitation patterns, are not very reliable. Nevertheless, it is clear that there will be important changes in the distribution of rainfall from place to place. And, as some regions become drier and others wetter, the climate conditions that determine the natural growth of vegetation around the world will shift significantly.

Another shortcoming of current doubled-CO_2 GCM experiments arises from their inability, as yet, to describe effectively how the real climate system will respond over time to gradual or “transient” increases in carbon dioxide. To simulate the changes that would happen on the way to a doubled-CO_2 atmosphere, modellers have to allow for the delaying influence of the oceans, which will absorb some of the additional heat in the atmosphere. Simple models of transient response suggest that the oceans may delay the full impact of an enhanced greenhouse effect by several decades or more. More complex transient response experiments with a new generation of GCMs are now being undertaken. Although preliminary results from these experiments show some ocean areas warming more slowly as a result of changes in ocean circulation, they generally confirm the results of the doubled-CO_2 experiments. However, more GCM experiments must be completed over the coming decade before these conclusions can be accepted with confidence.

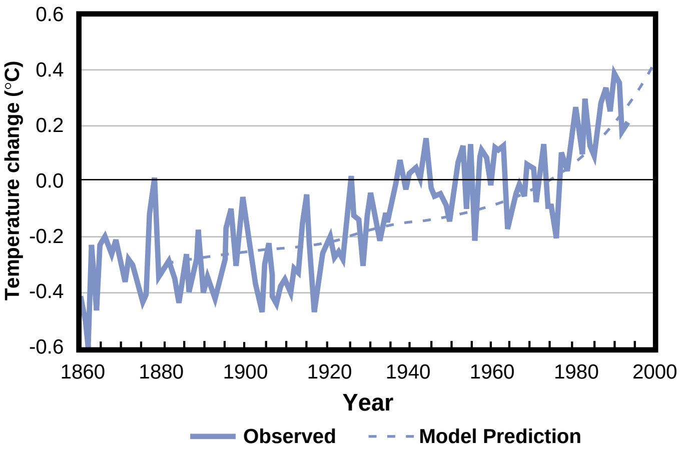
Although GCMs give us some insight into the effects of increased concentrations of carbon dioxide (or equivalent effects resulting from increases in other greenhouse gases), there are many additional factors that they do not take into account. Other natural forces, such as large volcanic eruptions or variations in solar radiation, which have influenced climate throughout the history of the Earth, will continue to have their effect in the decades and centuries to come. During some periods these forces will cause the climate to warm even more rapidly. In others, they could slow down or even reverse the expected greenhouse warming.

Human influences in addition to those that are already enhancing the greenhouse effect may also be important. Changes in land use, increases in the quantity of fine sulphate particles in the atmosphere, the presence of airborne pollutants in the Arctic, and large-scale water diversions may all have local effects on climate and, in some cases, possibly even global effects. However, our best scientific estimates suggest that over the next century the Earth’s climate will be shaped more by the enhancement of the greenhouse effect than by all of these other influences put together.

Is the Earth getting warmer?

According to simple climate models, we have added enough greenhouse gases to the atmosphere over the past 200 years to raise average global temperatures by 1–2°C. However, like a furnace boiler, the Earth’s climate system, with its deep oceans and frozen poles, responds slowly to these changes. Allowing for this slow response, scientists estimate that the Earth’s average temperature should already have risen by 0.4°C to 1.3°C over the past 100 years.

Figure 22
Model predictions and observed global temperature trends



SOURCE: Data from UKMO 1994.

Increases in global temperatures during the past 100 years follow a trend very similar to GCM predictions of the effects of increased greenhouse gases and aerosols. The 0° line represents the average annual global temperature for 1950–79.

Has a temperature increase of this order actually happened? The answer is yes, but just barely. Figure 22 shows that global temperatures over the past 100 years have increased by about 0.5°C, slightly above the lower end of the predicted range. However, model studies that include the estimated effects of increased concentrations of sulphate aerosols in industrial regions of the Northern Hemisphere show much better agreement between their projections and the observed temperature changes.

Is this evidence enough, however, to confirm that an enhanced greenhouse effect is already influencing the world's climate? A few scientists argue that it is, but most agree that it is too early to draw definite conclusions. The temperature trends of the past 100 years, while consistent with predictions of greenhouse warming, are also within the bounds of the natural fluctuations that have occurred during the past 1000 years and so could still be explained by natural causes. At least another decade of continued increases in global temperatures may be required to provide conclusive evidence that the world's climate has begun to respond to the enhancement of the greenhouse effect.

Chapter 4

A warmer world

Each biological species has a unique set of climatic limits within which it flourishes and beyond which it stagnates or dies. Air and soil temperature, the type and amount of precipitation and its variability, the strength of the wind, the amount of sunshine, and other climatic factors play a role in determining which species will occupy a given region. The influence of climate on biological survival is clearly seen in the distinctiveness and variety of the world's many vegetation regions—from tundra and boreal forest to grasslands and tropical rain forest. Each of these regions can be seen as a distinct ecological entity—an ecozone—whose characteristics have been largely shaped by a corresponding ecoclimate which is unique to the region and essential to the life within it.

When local and regional climates change, as has often happened in the past, the boundaries of the ecozones change also, forcing the ecosystem to adjust. Species whose climatic requirements no longer match those of the region migrate or die out, while other species, once foreign to the region, begin to enter it. Climatic change is a stimulus to the migration of both plants and animals. If the changes are gradual, the process usually occurs with minimal disruption. If rapid, the transformation can be dramatic and result in the extinction of species.

Human societies, like natural ecosystems, are attuned to the characteristics of regional climates. Our behaviour and tolerances, our cultures and economies, and, in particular, our sources of food are climatically influenced. In the past, as climates fluctuated over extended periods of time, people have learned to respond and adapt. In some cases, such adaptation was a spur to social and technological development. In others, failure to cope brought adversity and even catastrophe.

Given the possibility that, within the next two to three decades, global temperatures may exceed the warmest we have experienced within the last 10 000 years, history may not be a reliable guide to the effects of future climatic change. What indications do we have, then, of how such rapid and large changes may affect natural ecosystems and human societies?

Climate model projections are as yet far too uncertain to help us accurately predict regional effects on vegetation or threats to human health and well-being. However, the models do provide a basis for constructing plausible scenarios that can be used to assess the sensitivities of nature and society to changes of the type anticipated. Many such "what if" case studies have been conducted by scientists in recent years. Complemented by research into the effects of past climatic changes, they provide important clues as to which ecosystems and which sectors of society are highly vulnerable and which are more resilient or less sensitive to these changes. Although the results of these studies must be used with caution, they nevertheless provide us with a number of tentative conclusions about both the human and ecological implications of climatic change for the world in general and for Canada in particular.

Natural unmanaged ecosystems

On land, warmer climates will likely have their greatest impact on unmanaged ecosystems, particularly forests. If the changes are slow (i.e., less than 0.1°C per decade), these ecosystems will encounter stress along their warmer and drier margins, but in general they would adapt by migrating in step with the changing climate, as they have done in the past. In higher latitudes, for example, the margins of different forest ecozones would gradually shift poleward by about 100 km for each 1°C of warming. However, at high rates of warming (e.g., 0.5°C per decade) the reproductive success of most species would diminish rapidly, while mortality rates would increase. These species would then die back at rates well in excess of their capacity either to adapt to the new conditions or migrate to a more favourable environment.

Agriculture

Because carbon dioxide is a plant nutrient, increased concentrations of it in the atmosphere are likely to have a beneficial effect on most plants, or at least on those grown under controlled agricultural conditions. Carbon dioxide can not only enhance the growth potential of plants but can also improve their efficiency in using water and thus increase their drought tolerance. The effects vary from species to species. Some plants, such as maize and sugar cane, show only a minimal response to increased levels of carbon dioxide. Others, however, including cereal crops such as wheat and rice, experience major improvements in growth. Unfortunately, many varieties of weeds do so as well. As yet, we are still uncertain about the effects on vegetation in natural environments, where many species compete for growing space. Nor do we know for sure whether plants grown in an enriched carbon dioxide atmosphere will maintain their food quality.

The impacts of warmer climates on global food production will be variable. They will depend very much on how regional precipitation patterns change in the future, but at present the critical details of future rainfall distribution, intensity, and variability cannot be predicted with a high level of certainty. In higher latitudes, such as those of Canada, Scandinavia, and Russia, warmer temperatures can be expected to encourage plant growth and allow the expansion of agriculture into regions with suitable soils but currently unsuitable climates.

In mid-latitudes, including southern Canada, regional changes in agricultural productivity are likely. Some areas will become more productive, as the benefits of warmer and longer seasons are enhanced by increases in soil moisture. But in others these benefits will be offset by decreases in soil moisture, and productivity could decline. Projections for generally drier conditions in these latitudes suggest that major local disruptions may occur, particularly in interior continental areas. However, if the changes are not too rapid, modified agricultural methods may allow the mid-latitudes to maintain their net food output. A far more challenging problem, though, is the increased probability of extreme events such as floods, droughts, and heat waves. Because of their severity and unpredictability, these cannot be responded to easily.

Of all the world's regions, however, it is the tropics that are likely to be most vulnerable to the disruptions of global warming. In most tropical areas, the distribution of rainfall is highly variable, both seasonally and spatially. Some areas are already marginal for agricultural production and highly sensitive even to minor changes in the occurrence of precipitation. Projections from climate models suggest that most tropical regions will receive more rain as the climate becomes warmer. However, the added rainfall may not bring any benefits, as increased evaporation may return more moisture to the atmosphere, particularly in semi-arid regions. It is therefore likely that drought, and the attendant scourges of malnutrition and famine, will become even greater problems in these areas than they are today. In addition, it is expected that tropical storms will increase in frequency and intensity. Affecting a larger area than at present, these storms may also cause greater levels of flood and wind damage in the tropics.

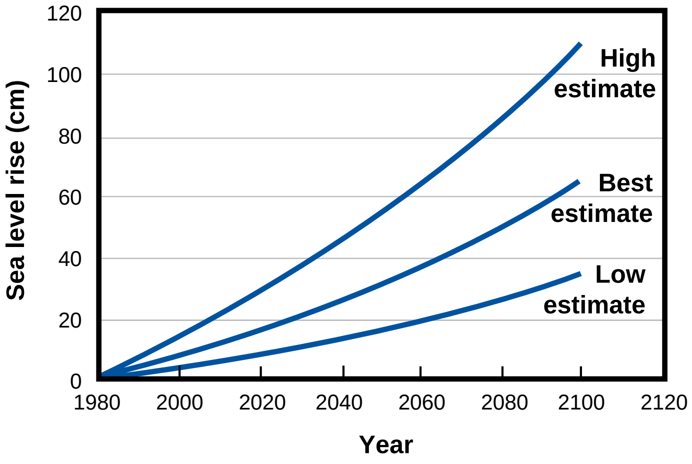
Coastal regions

The mean levels of the world's seas have been rising slowly over the past 100 years at a rate of nearly 1.5 cm each decade. This rate, however, appears likely to increase as the global climate warms. In the future, sea levels could rise somewhere between 3 cm and 10 cm per decade. Best estimates at the moment suggest that a rate of 6 cm per decade is probable (Figure 23). The primary reasons for these rises are the expansion of sea water as it warms and the melting of land ice. By the middle of the next century, ocean levels are likely to have risen by 35 cm and possibly by as much as 60 cm.

Human societies are highly vulnerable to such changes. Approximately one quarter of humanity inhabits the Earth's coastal regions. These regions are already under great pressure from accelerating population growth, pollution, upland water diversions, flooding, and coastal erosion. Some 70% of the world's beaches are currently receding. A major rise in sea levels would seriously aggravate these trends. Among the effects would be:

- increased beach erosion and loss of coastal wetlands
- increased frequency and extent of coastal flooding during high tides and storm surges

Figure 23
Estimated rates of sea level rise to 2100



SOURCE: Adapted from Warrick and Oerlemans 1990.

- damage to coastal structures, port facilities, and water management systems
- loss of agricultural land

Many countries will be able to defend themselves against these consequences by building defence structures such as dykes and sea walls. But such actions would be costly. In the U.S.A., for example, a complete defence of the East Coast against a 1-m sea level rise would cost an estimated 10 to 100 billion dollars. The Dutch, already defending themselves against the sea with a finely tuned but costly coastal defence infrastructure, would also need to invest an additional several billion dollars to cope with the effects of a similar increase in ocean levels.

However, the most significant effects of rising seas will be on those countries whose low-lying coasts are largely indefensible. As the seas advance and storm surges reach new heights, these countries are likely to experience great loss of land, property, and life. Nations such as the Maldives, an island chain in the Indian Ocean whose highest point is about 6 m above the current sea level, could virtually disappear, while countries such as Egypt and Bangladesh, with most of their population settled on low-lying deltas, could lose a major portion of their habitable lands (Figure 24).

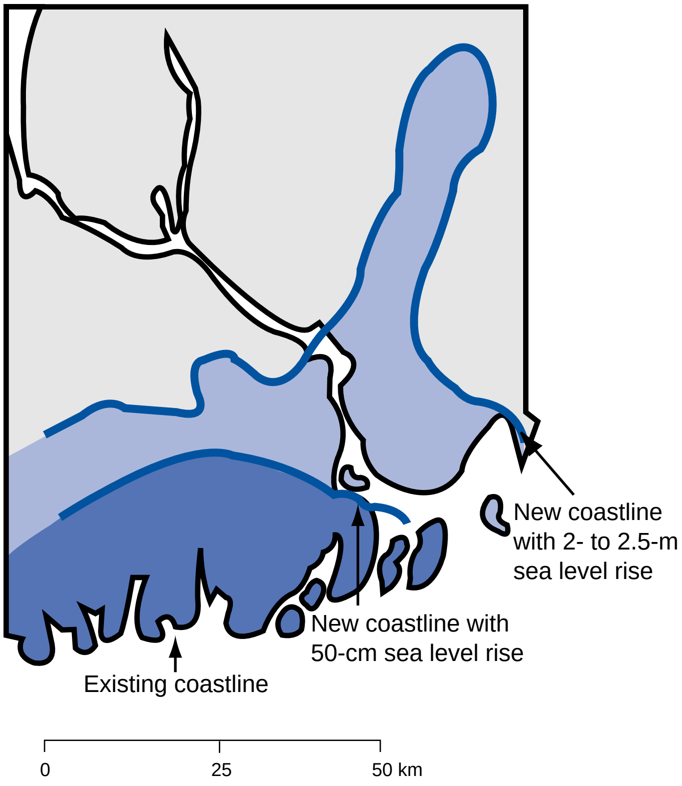
There is also a remote prospect that the West Antarctic ice cap could slide into the Antarctic Ocean as surrounding ocean temperatures increase. A complete disintegration of this ice cap would cause a global sea level rise of 5–6 m. Such an event, however, is not likely within the next several centuries, and, if it should occur, it would take decades to complete.

Other impacts

While the impact of climate change on sea levels, agriculture, and unmanaged ecosystems will undoubtedly have the largest effects on humanity, there will be other important consequences. These include:

- less hostile and more accessible high-latitude regions as winters become much warmer and sea ice recedes poleward
- changes in the distribution and productivity of marine life as ocean temperatures rise and currents change
- increased problems with tropical diseases and insects in mid-latitudes as these migrate with changing climates
- decreased availability and quality of water in many areas
- intensification or, in some cases, moderation of ecological stress from other sources of pollution
- heat stress on humans

Figure 24
Effects of a rise in sea level on the coastline of Bangladesh



SOURCE: Adapted from McKay and Hengeveld 1990.

Implications for global security

Shifts in agricultural productivity, sea level changes, and other direct consequences of global warming may also trigger a number of disturbing secondary impacts. Perhaps most disturbing are the implications for the world's economic and political security.

Access to food and water is the most fundamental of all human concerns. Yet we do not know for sure what the net effect of global warming on food production and fresh water supplies will be. It could be negligible. It could even be positive. But it is almost certain that the regional distribution of these essentials will change dramatically, aggravating existing uncertainties in food and health security. These effects will be most acute for the world's poorer regions, which are least able to cope with the costs of supplementing deficient food and water supplies.

Carbon dioxide and plants

In addition to its role as a greenhouse gas, carbon dioxide is also an important plant nutrient. Through photosynthesis, carbon dioxide is removed from the atmosphere through leaf pores, or stomata, and used to produce carbon compounds such as chlorophyll and sugars, which are stored in plant tissues.

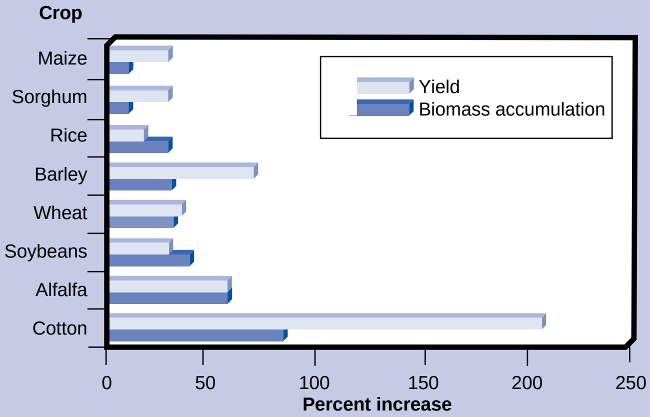
Laboratory experiments demonstrate that most plants grow much better if the concentration of carbon dioxide is increased by up to three times the normal atmospheric level. These experiments also demonstrate that, because the plant stomata partially close as carbon dioxide levels are increased, the amount of water evaporated through the leaves decreases, making the plant more tolerant to drought stress.

The improvement in plant growth, however, varies substantially from one species to another. In some species, the initial fixation of carbon dioxide involves hydrocarbons containing three carbon atoms. These plants (known as C_3 plants) respond remarkably well to a doubling of carbon dioxide in the laboratory, with yields of some increasing by more than 50%. Wheat, rice, potatoes, and most other food crops are in the C_3 category.

However, varieties in which the fixation process involves hydrocarbons with four carbon atoms (C_4 plants) do not respond nearly as well. These plants, which include maize, sorghum, sugar cane, and millet—all of them major tropical food crops—show only a modest increase in growth and yield under doubled-CO_2 conditions.

It is still uncertain how these same plants will respond to increased carbon dioxide outside the controlled laboratory, where many other stresses become a factor. In unmanaged ecosystems, for example, some species will respond much better to the enhanced carbon dioxide levels than others and crowd out those plants that are less responsive. This process could significantly alter the natural composition of many ecosystems. In cultivated fields, the reduced evaporation from the plants will also decrease the air humidity over them. Hence, while most plants will become more drought tolerant, the drought stress on them could also increase. Weeds will present a greater problem as well, since most weeds show a substantial increase in growth when carbon dioxide levels are raised.

Recent research also suggests that, while the volume of plant matter may increase significantly under higher carbon dioxide levels, the food quality may be lower, with plant tissue becoming richer in carbon but poorer in nitrogen. It has been observed, for example, that pests need to consume significantly more of the carbon-enriched plant material to maintain their normal growth rate.



Significant changes in the environment, particularly if they bring major human disasters in their wake, will present grave obstacles to sustained economic and social development in the affected regions. In the past, such effects have led to armed conflicts and massive human migration, and they could do so again. Certainly, recent experience has shown that, at the very least, famine and other environmentally related crises necessitate large transfers of relief funds to the countries that have been affected.

In an increasingly interconnected global society, one nation’s problem inevitably becomes every nation’s problem.

Chapter 5

A warmer Canada

Canadian scientists working under the co-ordination of the Canadian Climate Program are investigating the possible environmental, social, and economic effects of climate change in Canada. As a basis for their analyses, projections from several GCM experiments have been used to indicate how the general characteristics of the climate might change. Historical climate data, factored into these projections, provide further information about how day-to-day weather patterns might be affected and make it possible to calculate the likely frequency of extreme weather events, such as hot or cold spells and wet or dry periods. The material in this chapter is based on recent studies of this kind.

Canada's forests

Much of Canada is covered by trees, from the black spruce and birches of the cold boreal forests to the pine and hardwoods of the warmer and more humid southern latitudes. The two regions that remain treeless do so partly for climatic reasons—the Prairie grasslands because of low soil humidity and the northern tundra because of low temperatures.

Given the extent of this resource, it is not surprising that forestry is Canada's largest industry. Companies involved in the harvesting and processing of wood products in this country generate revenues in excess of $45 billion and employ more than 280 000 people. Forests are also of major importance from an ecological perspective. They constitute vital habitats for wildlife, significantly affect the hydrological and radiative processes of the climate system, and form a major part of the global reservoir of living carbon. Hence, their future health is important not only to Canada's economic well-being but also to the elemental processes of the biosphere.

In general, the combined effects of higher carbon dioxide concentrations, longer and warmer growing seasons, and milder winters should bring a major improvement in the productivity of forests in many areas of Canada. Under the type of climate expected for the middle of the next century, for example, Quebec's forests could increase their annual yields by anywhere from 50% to 100%. However, the boundaries of the different forest types will undergo radical alterations (Figure 25). These shifts will decrease the total area in Canada covered by trees, with most of the losses occurring as Prairie grasslands expand northward and eastward, in step with reductions in available soil moisture.

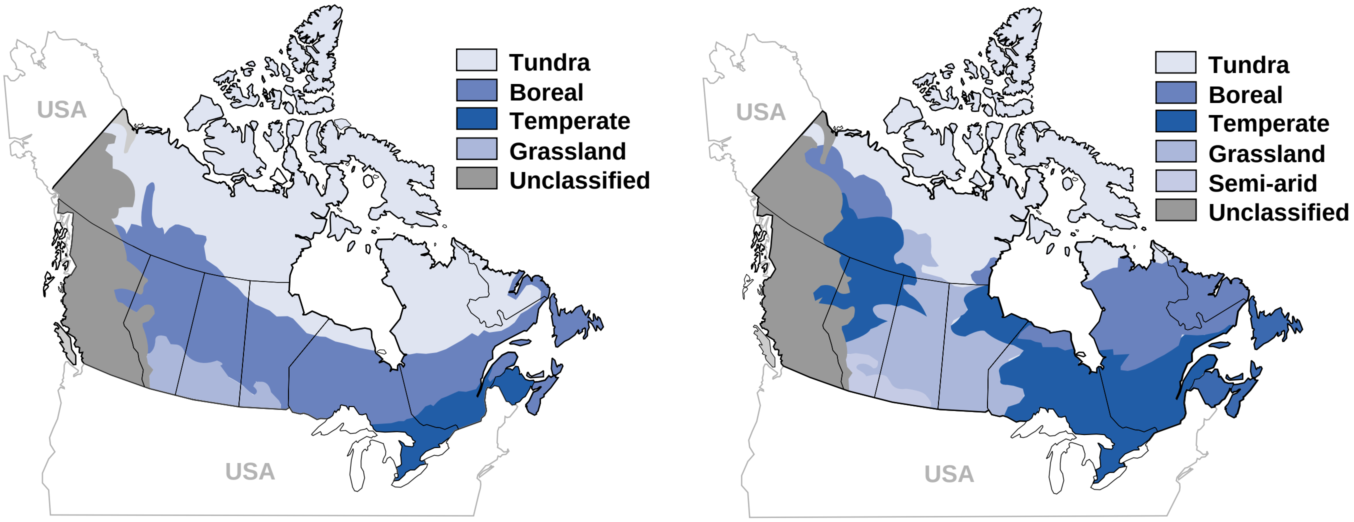
The largest changes would occur in the area now covered by boreal forests. At the southeastern edges of these forests, the dominant black spruce would gradually yield to the encroachment of the evergreens and hardwoods of the cool temperate forests. Meanwhile, at the northern margins of the boreal forest, expansion into tundra regions would be greatly delayed by poor soils and the comparatively slow decay of the underlying permafrost.

Just how disruptive these changes may be will depend to a considerable extent on how quickly they occur. Canada's temperature patterns can be expected to shift northward by about 100 km for every 1°C of warming. However, in responding to changes in climate, many tree species migrate slowly, at rates of 700 m or less a year. Consequently, a smooth transition from one forest type to another, with retreating species being replaced quickly by advancing species, will occur only if the pace of climatic change is very gradual. Even then, the transition from one forest type to another will be sporadic and uneven, since forest fires are a key element in the replacement of existing tree species with new ones. Unfortunately, climate models suggest that temperature and precipitation values will change quickly. If so, the consequences are likely to be severe, particularly along the southern and low soil-moisture limits of each species.

Where trees are exposed to additional stresses, such as acid rain, ground-level ozone pollution, increased ultraviolet radiation, or leaching of harmful chemicals from the soil, forest destruction could occur on a large scale. Recent diebacks of maple stands in Ontario and Quebec may be symptomatic of such changes.

Warmer climates will also bring with them the danger of increased insect and disease infestation, as pests and diseases once alien to our forests migrate northwards. In addition, the accumulation of greater amounts of dead biomass, together with drier summer conditions, could cause large increases in the frequency and severity of forest fires. In fact, such increases have already occurred during the warm, dry years of the 1980s and

Figure 25
Changes in forest and grassland boundaries resulting from a typical doubled-CO$_2$ climate



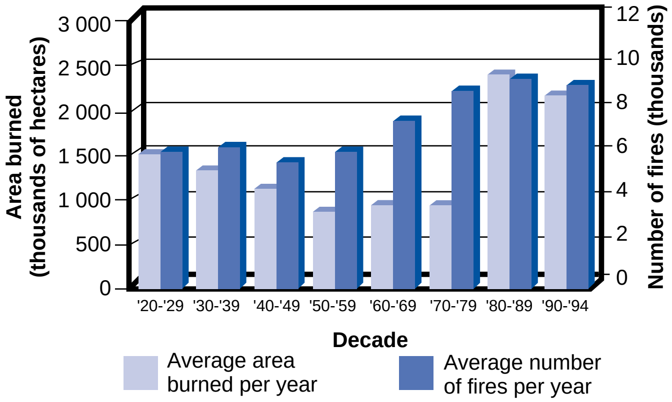
Present day

Doubled-CO$_2$ climate

SOURCE: Rizzo 1990.

1990s (Figure 26). Finally, the destruction of forest cover will result in more carbon dioxide being added to the atmosphere, thus further enhancing global warming.

Figure 26
Average number of forest fires per year and average area of forest burned per year (by decade)



SOURCE: Stocks 1994.

Agriculture

Canada's agricultural potential is limited by, among other things, its cold climate. With the length of frost-free growing seasons restricted to between about 200 days in the extreme south and merely a matter of weeks in the far north, Canadian soils remain inactive for a major part of each year. Furthermore, severe winters can cause frost damage even to dormant vegetation, thus restricting the cultivation of overwintering crops, such as winter wheat, on the Prairies and in other similarly affected areas. When growing seasons do arrive, growth rates of plants in Canadian climates are further restricted by the amount of heat energy available to them during the season. These factors impose major limitations on the types of crops that can be grown in Canada, as well as on the yields and the number of crops that can be harvested in one year.

It would seem, therefore, that warmer temperatures would be very good for Canada's agriculture. For example, under typical climate scenarios for 2050 AD, growing seasons around Whitehorse and Yellowknife would be similar to those in the Edmonton area today, while conditions in New Brunswick would resemble those of the Niagara peninsula.

The growth potential of vegetation in regions such as southern Quebec, central Ontario, and southern Saskatchewan could improve by 40–50%, assuming that all other variables, such as soil moisture and pest infestation, remain constant.

Hence, there would be considerable potential for cultivating higher-yield crops requiring a longer and warmer growing season, for increased multicropping in more southerly latitudes, and for the expansion of frontier agriculture northward. Grain corn could become an important agricultural crop in areas such as Manitoba and northern Ontario, winter wheat would do well on the Prairies, and apples and grapes could become highly productive in Quebec. The nutritional effects of higher carbon dioxide concentrations would further add to these benefits, perhaps enhancing productivity by 15% or more.

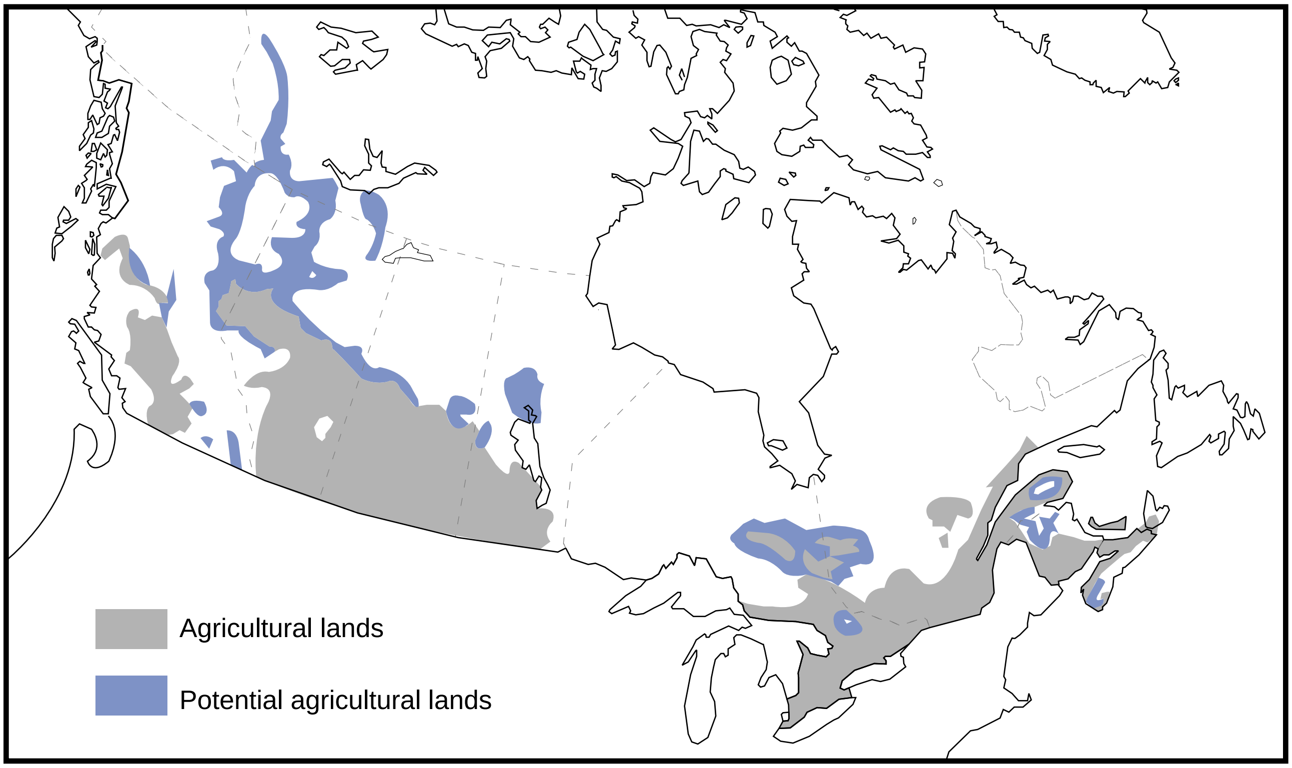
There would be advantages for livestock production as well. Warmer temperatures would allow longer forage periods and reduce the need for supplemental feeding.

Unfortunately, other variables will not remain constant or unrestrictive. In the first place, the availability of soils suitable for agriculture in Canada is limited. At the present time, only about 10 million hectares of potential agricultural land in Canada are currently unutilized because of climate constraints (Figure 27), and much of this land consists of marginal soils that are unsuitable for cereal grain production. Furthermore, some areas that do have suitable soils are covered with valuable timber stands. Consequently, the potential for expanding agriculture into the northern frontier is not large.

Secondly, because insects, pests, and plant diseases are responsive to climatic shifts, the probability of severe infestations in future decades is increased. Many crops are also sensitive to heat stress, particularly during key stages of development, and may be adversely affected by the increased frequency and severity of summer heat waves. Dairy cows are vulnerable to heat stress as well, and unless farm operations were modified to reduce the stress, milk production would decline.

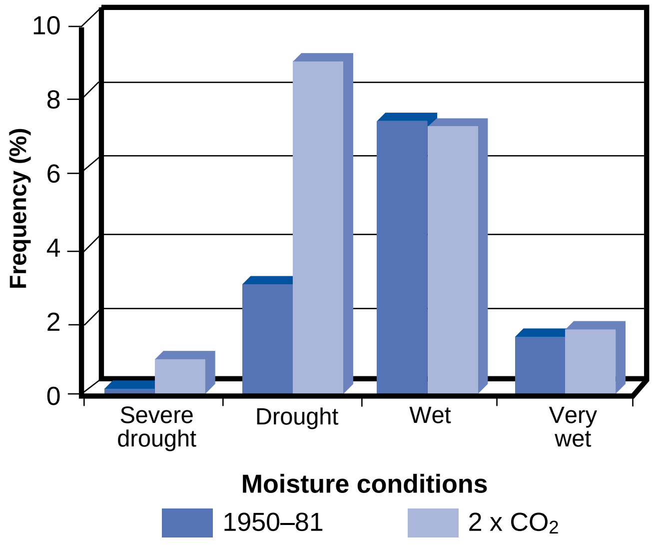
Finally, higher temperatures will significantly increase the rate at which vegetation and soils lose water to the atmosphere, thus reducing available soil moisture. In areas where rainfall increases significantly during the growing season, this loss will normally be replenished. However, drought studies suggest that even under such conditions, drought years that occur everywhere as part of natural year-to-year climate variability will become more frequent and more severe (Figure 28).

Figure 27
Potential increase in agricultural land as a result of global warming



Source: Agriculture Canada.

Figure 28
Potential effects of climate warming on soil moisture in southern Saskatchewan



SOURCE: Data from Williams et al. 1987.

The graph shows the potential effects of climate warming on soil moisture conditions in southern Saskatchewan as forecast in a typical doubled-CO_2 climate scenario. It is estimated that under such a climate abnormally wet years would occur about as often as they do now. In fact, this particular scenario projects a 15% increase in precipitation. Even with the extra precipitation, however, the scenario forecasts a marked increase in the number of drought and severe drought years.

In areas where rainfall is projected to remain constant or decrease, significant increases in drought frequency and severity will cause major crop stress and economic hardship. Many of Canada's key agricultural regions, including the Prairies, southern Ontario, and southern Quebec, could experience such conditions. In fact, the 1988 growing season in Canada, which witnessed large crop losses through most of these regions due to major drought stress, provides a very useful example of how the average summer climates of Canada may appear in the future. While such events are not unprecedented in Canada's history, they are likely to occur more frequently during the decades to come.

Water resources

Although climate models disagree on the future distribution of rain and snow amounts across Canada, they do agree on the following points:

- During the winter the quantity of precipitation is likely to increase across Canada.
- The snow season, however, will be significantly shorter. In most areas snow accumulations will be less and spring melts and runoffs will occur earlier, although snow accumulation in northern latitudes could increase significantly.
- During the growing season precipitation amounts are likely to increase in northern Canada and decrease or remain relatively unchanged in southern Canada, as dominant storm tracks push further north.

These changes will have profound effects on our management and use of water resources. From a simple perspective, water runoff from land surfaces to streams and rivers is provided by moisture left over from rain and snowfall after the losses due to evaporation, vegetation needs, and soil saturation are accounted for. Many of our lakes and streams receive a large proportion of their annual water supplies from the melting of snow cover in the spring, when the soil underneath is still frozen, vegetation is still dormant, and evaporation losses are comparatively low. Significant changes in the annual accumulation of snow, the timing of the spring melt, and the rate of evaporation loss from soil and vegetation will therefore dramatically alter the behaviour and conditions of Canada's rivers, lakes, and reservoirs.

Although uncertainty about the nature and extent of local precipitation changes makes it impossible to predict how the water resources of each region of Canada will be specifically affected by climatic change, some useful clues can be drawn from the results of climate modelling experiments. This information suggests that water resources in northern Canada are likely to become more abundant, although the annual spring runoff will likely be smaller and will occur earlier. Such a situation could substantially increase the potential of northern watersheds for hydro-electric production. In northern Quebec, for example, power output could increase by 15% or more.

However, these benefits might be offset to some degree by growing demands for large-scale water diversions to parched regions in the south, where warmer temperatures are likely to bring higher rates of evaporation and increased soil dryness. Drier soils are expected to reduce runoff, in some cases dramatically, causing lower stream flow and lake levels. These effects would be particularly severe during drought years.

Typical scenarios suggest that water levels in the Great Lakes could fall by 0.5 to 1.0 m or more on average, while the amount of water flowing out of the St. Lawrence River could be reduced by up to 20%. Extremely low lake levels, such as

Table 3
Frequency of low water levels in the Great Lakes (percentage of years with water levels equal to or less than the severe low levels of 1963–65)

Lake	Historical (1900–1979)	Doubled-CO_2 climate	Doubled-CO_2 + increased water consumption
Superior	10	61	79
Michigan	8	57	77
Erie	5	38	77

SOURCE: Sanderson 1987.

those of 1963–65, could occur four out of every five years (Table 3). As well as causing a deterioration in water quality, such changes could also cause shipping costs in the Lakes to rise by as much as 30%, as large vessels would be forced to load more lightly in order to pass through canals and shallow waterways. Total revenue from hydro-electric power generation at southern sites could also fall off by $30–60 million per year. Finally, drier conditions would lead to the disappearance of many ecologically important wetlands, such as those at Point Pelee on the shore of Lake Erie.

Snow and ice

Snow and ice play a major role in Canada's geography, its climate, and its culture. They cover nearly all of Canada's land surfaces and most of its water surfaces for at least part of the year and, in some areas, for the whole year. In the form of permafrost, ice in northern Canada is also a major factor in the drainage of water, in the growth of vegetation, and in land stability. Glaciers and ice caps exert a major influence on regional climates and are major sources for the icebergs that populate the waters off our east coast and the ice islands that travel the Arctic Ocean.

Warmer temperatures and projected increases in winter precipitation will significantly alter these characteristics. In northern regions, snow seasons will likely become much shorter but more intense. The duration of ice cover on lakes and oceans will be shortened by up to several months. Hudson Bay could become largely ice-free all year, while the Arctic Ocean may become virtually ice-free in mid-summer. As a result, Arctic waters would become much more accessible to marine navigation and other offshore activities, including fishing and resource exploitation. On the other hand, scientists suggest that increased snow accumulations on top of the Arctic ice caps and longer and warmer melt seasons at their margins will accelerate glacial flow and increase iceberg calving by as much as 300%.

Meanwhile, gradual decay of the southern edges of the Arctic permafrost will drastically alter surface water drainage patterns and increase the instability of the land. As a result, significant disruptions to pipelines, rail lines, roads, and other facilities could occur. The effect on ice roads could be particularly unfortunate. Built across frozen wetlands and lakes, these roads provide a valuable supply link to many remote communities and give access to large areas of timber in the boreal forest. Under milder conditions, they will be more difficult to construct and won't last as long. Their load-bearing capacity will be reduced too, because of thinner ice. In some areas they could cease to be a reliable means of transportation.

In more southerly latitudes, the reduction of snow and ice cover would have profound effects on several activities. By and large, transportation would benefit, as roads required less snow clearing and waterways became more navigable. The Great Lakes and the Gulf of St. Lawrence would likely become predominantly ice-free year-round, while the multimillion-dollar snow removal budgets for large urban centres such as Montreal and Toronto could be virtually eliminated. However, seasons for traditional winter sports such as skiing, snowmobiling, ice fishing, and outdoor skating would be greatly shortened or, in the case of southern Ontario, might disappear altogether (Table 4). The economic impact on related industries would be considerable.

Table 4
Duration of ski seasons in Ontario and Quebec (in days)

Location	Present climate	Doubled-CO_2 climate
Thunder Bay	131	80
Quebec City	109	63
Sherbrooke	87	51
Southern Georgian Bay	70	0

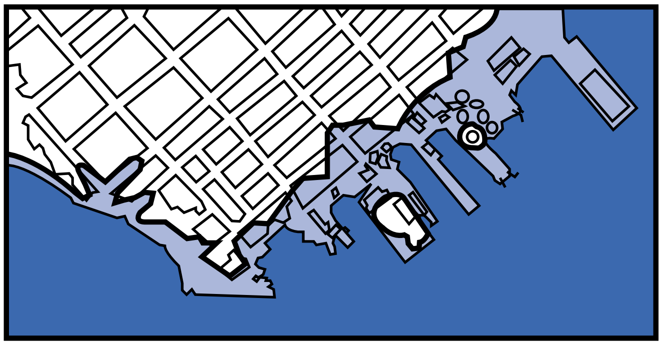
SOURCE: Canadian Climate Centre.

Coastal flooding

Because of the ruggedness of its coastline, Canada is much less vulnerable to coastal flooding than many other nations. Yet it will not remain unaffected if sea levels rise. Important coastal wetlands such as the Hudson Bay lowlands and the Mackenzie Delta could undergo large-scale flooding. Beaches and shorelines elsewhere will recede and erode.

However, the largest impacts on Canadians will occur in the populated centres along the Atlantic and British Columbia coasts where large city blocks and shorefront facilities lie close to sea level. As sea levels rise, lower Vancouver and other municipalities on the Fraser River Delta, already confronted by occasional flooding problems, would require large investments in new and improved protective barriers to avoid major inundations. At Charlottetown, a 1-m rise would flood the city's new harbourfront development at high tide, while major storm surges, which occur about once every 20 years, would be high enough to inundate large parts of the downtown residential and commercial districts (Figure 29). In Saint John, N.B., road and rail transportation would be vulnerable to frequent flooding, as would sewage disposal systems and downtown buildings. Other problems would include contamination of water supplies, loss of farmland in rural areas, and increased flooding of rivers upstream of the coast during spring runoff.

Figure 29
Effect of a 1-m sea level rise on flooding in Charlottetown



SOURCE: Adapted from Lane and Associates 1986.

Rising sea levels will increase the frequency and severity of flooding in many coastal communities. The flooding risk will be greatest during storm surges, when maximum high tides are amplified by severe storms. The dark line indicates the extent of flooding in downtown Charlottetown resulting from a 1-m sea level rise and a heavy storm surge that occurs approximately once every 20 years.

Some of these effects could be reduced, or aggravated, by the natural vertical movement of the land. The Hudson Bay region, for example, is still rebounding from the last ice age, and its shoreline is rising at a rate comparable to projected sea level rises due to global warming. The Nova Scotia land mass, on the other hand, is gradually sinking, thus enhancing any water level effects that may result from global warming.

Other effects

Since most social and economic activities are sensitive to weather and climate, the impacts of warmer climates will go well beyond those already mentioned. The following additional effects are of particular significance.

Energy consumption—Requirements for space heating in homes, offices, and factories will be much lower during warmer winters. Such reductions will vary from more than 30% in the warmer climates of southern Canada to about 20% in Canada's cold north, where heating requirements are very high. These benefits will be partially offset in the south by increased requirements for summer cooling. Warm climates would also generally improve the efficiency and, hence, the energy consumption of surface and marine transportation.

Temperature stress—Warmer winters will result in a substantial reduction in the number of very cold spells to be endured each year and in their severity. Summer heat waves, however, will occur more frequently and reach new extremes.

Human health—Heat stress can cause illness or death in the most susceptible segments of the population, especially the very young and the elderly. More frequent heat waves would increase mortality in summer months, especially when the heat is accompanied by the influx of polluted air masses. A warmer climate would allow different species of plants to flourish, changing the amount and types of pollens which could affect allergy sufferers. Presently, many natural disease carriers are unable to survive our cold winters. A reduced cold season may allow some diseases (such as malaria) and insects harmful to ecosystems to extend their range northward into southern Canada.

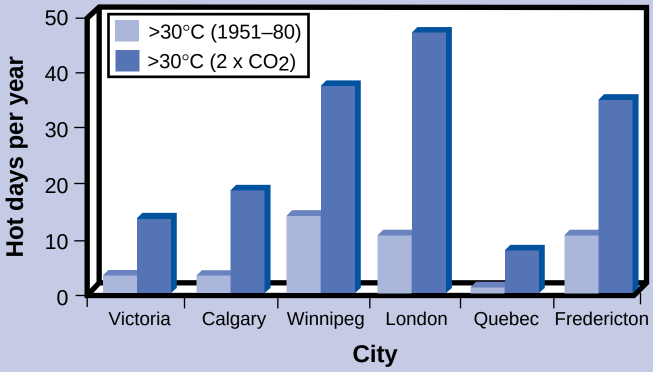
Fisheries—The types and growth rates of fish and marine life found in freshwater lakes are significantly influenced by seasonal temperature limitations. Because of this, fish populations and species will change across Canada as the climate becomes warmer. In general, the changes will benefit the less-valued dark species, while the higher-quality white species will suffer

Climate change and extreme weather

In spite of the uncertainties associated with them, GCMs provide a reasonably clear indication of the probable direction of change of the world's average surface climate in the decades to come. However, both humans and ecosystems are much more vulnerable to the occurrence of extreme events such as droughts, floods, heat waves, and cold spells than to gradual shifts in climate. Because of their severity and unpredictability, these events can bring with them hardship, economic loss, severe social disruption, and even loss of life.

Determining the influence of a warmer climate on the frequency and severity of extreme weather events is therefore critical to our understanding of the impact of an enhanced greenhouse effect, but so far climate models have provided few useful insights into the variability of future climates. Some preliminary indications have been obtained, however, by combining the projected average change from climate model studies with detailed climate data from the past 30 years.

Not surprisingly, such an analysis suggests that hot spells in summer will become more frequent and more severe in Canada, while very cold periods in winter will become less frequent (although they will still occur). In Saskatoon, for example, the frequency of July days exceeding 31°C could increase under a doubled-CO_2 climate from the current average of 3 days a year to 8. Conversely, extremely cold January days below –35°C could decrease from the current average of 3 days each year to 1 day every 4 years. Meanwhile, studies into southern Saskatchewan drought frequencies suggest that, even if average conditions were to become moister, severe droughts could become twice as frequent because of higher evaporation.



from decreasing habitats. At the same time, these changes will be complicated by additional stresses from changing water quality and nutrient supplies. In Canada's coastal waters, changes in salinity, temperature, and current flow will all affect the distribution of marine species and their numbers. Warmer climates will likely benefit fish farming.

The effect on offshore fisheries is much more uncertain, since these are largely influenced by ocean currents. However, in the past, ocean warming has brought exotic fish species into the Pacific coastal waters and has had major impacts on the abundance and distribution of cod along Canada's east coast.

International security—The effects of climate change on other regions of the world will have wide-ranging implications for the economic, social, and political security of Canadians. Changes in the global distribution of food production, for example, will alter traditional food trade patterns. Canada, as both a major importer and exporter of food, will have to adapt to the new conditions, finding new sources of supply in some cases and new markets in others.

Meanwhile, chronic food shortages or other disasters arising from climate change in the developing world will place pressure on Canada to provide emergency relief assistance, accept environmental refugees, and perhaps help resolve armed conflicts. Furthermore, while pursuing aggressive and perhaps costly domestic action to reduce their own emissions of greenhouse gases, Canada and other industrialized countries will be expected to transfer financial and technical resources to help developing nations undertake similar action.

Chapter 6

Ozone layer depletion

Ozone represents only a tiny fraction of the total atmosphere. Its average global concentration is about 300 parts per billion by volume (ppbv). If all the ozone in the atmosphere were compressed into a band of pure gas at the temperature and pressure of the Earth's surface, its total thickness would be only 3 mm, about as thick as three dimes. Yet, because of its ability to absorb solar ultraviolet radiation, which is extremely harmful to living cells, it is of vital importance to most life on Earth. It is, in fact, the primary absorber of UV-B, one of the most damaging portions of the ultraviolet spectrum. By shielding the Earth's surface from most of this radiation, the ozone layer helps maintain suitable conditions for life in the lower atmosphere.

Ozone also absorbs infrared radiation and helps to regulate the flow of heat energy through the atmosphere. The concentration and distribution of ozone, therefore, have a significant effect on the atmosphere's temperature structure and on the movement of air currents around the world.

The chemistry of the ozone layer

Ozone is not evenly distributed throughout the atmosphere. Most of it (about 90%) is found in the upper part (the stratosphere), between about 10 and 40 km above the Earth's surface, with the highest concentrations occurring at about 25 km (Figure 30). This distribution results from the fact that ultraviolet radiation itself plays a primary role in the formation of ozone. In the upper atmosphere, intense ultraviolet radiation causes oxygen molecules to break up, creating free oxygen atoms which then attach themselves to intact oxygen molecules to form ozone. As the ultraviolet rays pass downward, they encounter increasing concentrations of oxygen and produce correspondingly greater amounts of ozone. The increasing ozone concentration, however, eventually absorbs most of the ultraviolet rays before they reach the lower atmosphere, and so the reaction fades out, leaving a layer of ozone in the upper atmosphere.

Air currents, of course, can carry ozone into the lower atmosphere (the troposphere), but most ozone molecules are rapidly destroyed there by chemical reactions with other gases. Consequently, natural concentrations of ozone near the Earth's surface are quite low. Since ozone can be toxic to both plants and animals, its relative sparseness at ground level is as important to the survival of life on Earth as is its greater abundance in the upper atmosphere.

The total amount of ozone in the atmosphere represents a balance between the rate at which it is produced by sunlight and the rate at which it is destroyed by photochemical processes involving other gases. These processes are complex, involving more than 300 different chemical reactions and over 100 different types of molecules.

Once ozone is formed in the stratosphere, it can be transported to other locations by the general circulation of the atmosphere around the Earth. Because these photochemical and transport processes vary with season and latitude, ozone concentrations are not uniform throughout the year or from one part of the globe to another (Figure 31). The net effect of these processes, however, is an ozone layer that is thinner over the equator than over the poles, although ozone concentrations over any given location may vary from day to day because of the changing positions of the dominant air currents around the Earth.

Changing the ozone layer

Concerns about the ozone layer first surfaced in the early 1960s, with the testing of nuclear bombs. Soon after, plans for the building of large fleets of high-flying supersonic transports also raised fears about the possible destructive effects of water

Figure 30
Vertical distribution of ozone in the atmosphere

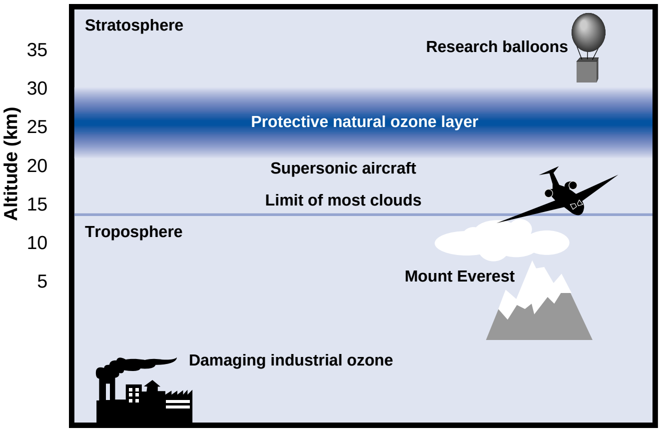
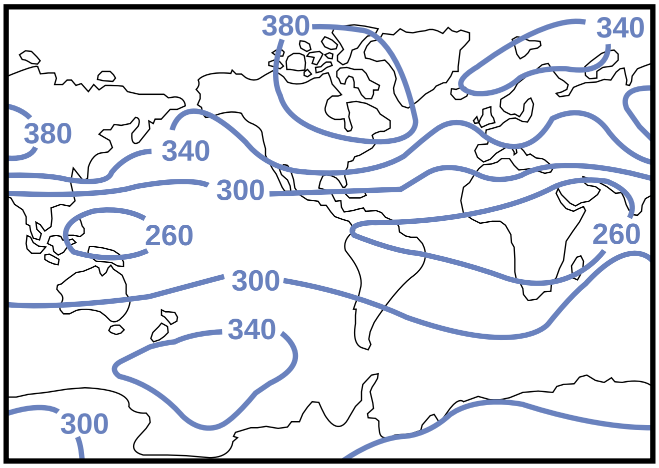


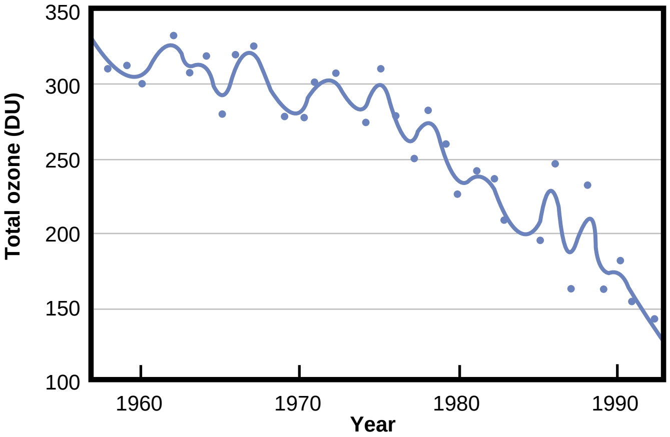
Figure 31
Average global distribution of natural ozone



SOURCE: Adapted from London and Angell 1982.

Ozone concentration is measured in Dobson units (DU). One hundred Dobson units are equal to 1 mm of ozone at surface temperature and pressure.

Figure 32
Total ozone amounts over Halley Bay, Antarctica, 1956–1993



SOURCE: Adapted from WMO 1994.

Measurements of total ozone amounts over Halley Bay in the Antarctic during the southern spring have shown more than a 50% decline between 1975 and 1993. The curve represents the smoothed average of the annual measurements.

vapour and nitrogen oxides from the exhaust gases of these aircraft.

In 1972, scientists at the National Aeronautics and Space Administration (NASA) added another worry—the effect of chlorine compounds that would be emitted from the space shuttle when it became operational in the 1980s. As it turned out, the amounts of these compounds were too small to be significant. However, in 1974, as part of NASA's investigations, scientists predicted that a similar threat to the ozone layer could be materializing as a result of large amounts of chlorine already being injected into the atmosphere by the use of chlorofluorocarbons.

CFCs were developed in the 1890s and came into widespread use in the 1930s as a substitute for ammonia in refrigeration applications, but their distinctive properties made them ideal for many other uses. Chemically inert, non-toxic, and easily liquified, CFCs have come to be used not only in refrigerators and air conditioners but also as blowing agents in the production of foam packaging and insulation, as solvents for cleaning electronic circuit boards, and as propellants for aerosol sprays.

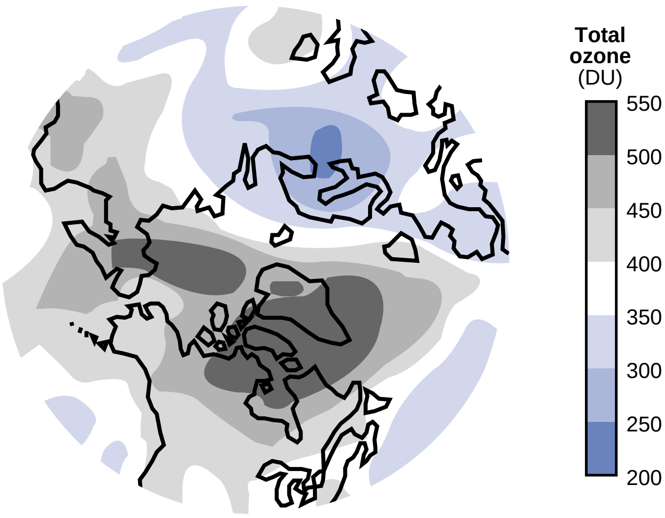
In May 1985, scientists from the British Antarctic Survey published data which sent shock waves throughout the scientific community. Their observations showed that for the period from September to mid-November ozone concentrations over Halley Bay, Antarctica, had declined by 40%, compared to levels in the 1960s (Figure 32). These findings were totally unpredicted and unexpected. No such losses had previously been reported, either from ground-based instruments in operation since 1957 or from the extensive satellite measurements initiated in the 1970s. However, both U.S. and Japanese scientists quickly began sorting through their data and confirmed that the phenomenon was indeed real.

With the existence of the ozone hole thoroughly established, the research community considered a variety of related questions. Was the phenomenon part of a natural cycle linked to solar activity? Was it caused by meteorological conditions specific to the region? Why did the existing atmospheric models fail to simulate such losses? Were CFCs the lone culprits or were they acting in combination with other chemicals or conditions?

As part of the search for scientific clues, an urgent research effort was quickly put together. The Americans sent four different teams to the Antarctic in 1987 to make more extensive measurements of ozone and other chemical compounds when the ozone hole reappeared in September. Their results showed that neither solar activity nor meteorological forces alone could adequately explain what was happening. They did, however, find high concentrations of bromine and chlorine in the lower stratosphere inside the large and stable atmospheric vortex that forms around the south pole in the winter and isolates the Antarctic air from the rest of the Earth's atmosphere. The release of these large quantities of bromine and chlorine was also shown to be related to unusual chemical processes taking place inside polar stratospheric clouds that form in the lower stratosphere during the extremely cold winter night conditions. When relatively stable forms of chorine and bromine come in contact with the ice particles found within these clouds, a reaction takes place which converts them into a much more destructive form. With the return of sunlight in the spring, these highly reactive chemicals are now ready to interact with the surrounding ozone and ozone depletion rises quickly to a maximum. The process ends when warmer temperatures initiate the breakup of the polar vortex. The formation of the Antarctic ozone hole was thus seen to be the result of a complex interaction between bromine and chlorine from human sources and the special physical characteristics of the Antarctic atmosphere.

Since 1986, Canadian scientists have been searching for evidence of a similar late-winter phenomenon in the Arctic. However, since the atmospheric circulation over the Arctic in winter is less stable than over Antarctica, the lower stratosphere in the Arctic mixes more with air from lower latitudes and does not reach the extremely cold temperatures found in the Antarctic stratosphere. Consequently, polar stratospheric clouds do not form as frequently over the Arctic. While some evidence of late-winter Arctic ozone depletion in the lower stratosphere has been found (Figure 33), it is not nearly as severe as that observed during Antarctic ozone hole events.

Figure 33
Total ozone abundance over northern regions of the Northern Hemisphere, March 1986



Source: Environment Canada, Atmospheric Environment Service.

The map was compiled from measurements taken by satellite-based instruments. An area of ozone depletion is evident in the upper right quadrant over Russia.

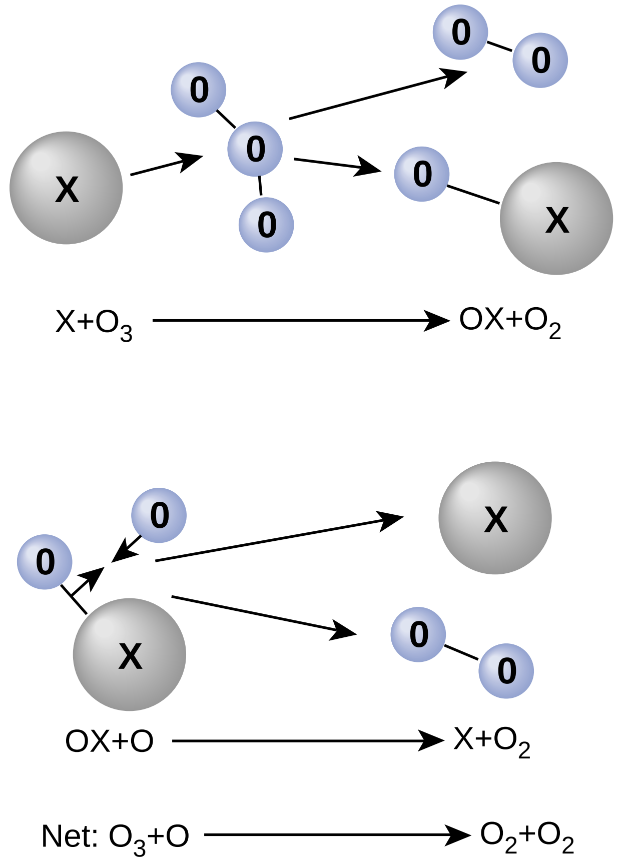
Smaller decreases in stratospheric ozone have also been observed in mid-latitude regions of the world. In early 1993, record low seasonal values were recorded over much of Canada, with total ozone concentrations falling to about 15% below the pre-1980 average. At some altitudes in the lower stratosphere, the decrease was as much as 30%. These record low concentrations appear to be linked to aerosols formed from gases injected into the stratosphere by the eruption of Mount Pinatubo in June 1991. However, the extent to which these aerosols affected ozone destruction is still uncertain. By early 1994, ozone amounts over Canada had recovered to their pre-Pinatubo levels, but they still remained well below the long-term averages recorded prior to 1980.

The basic chemistry of ozone depletion by substances such as bromine and chlorine is shown in Figure 34. Free chlorine atoms, for example, react very quickly with the ozone, creating chlorine monoxide as a by-product. In subsequent reactions, the chlorine releases its oxygen atom to form molecular oxygen, and the chlorine atom is freed to repeat the process of destroying ozone. Through this continuing cycle of reactions, each chlorine atom acts as a catalyst, destroying perhaps 100 000 or more molecules of ozone before the chain reaction is eventually ended.

Because of their stability, CFCs are a particularly effective vehicle for transporting chlorine into the upper atmosphere. The most commonly used CFC compounds (CFC-11, CFC-12, and CFC-113) have been estimated to have atmospheric lifetimes lasting from 50 to 100 years. These do not break down until they are exposed to the harsh radiation of the upper atmosphere, a fact that guarantees that their eventual disintegration will take place precisely where it will do the most harm—within the ozone layer.

Other important ozone-depleting substances also tend to be very stable and thus remain in the air long enough to reach the stratosphere in significant amounts. Hydrochlorofluorocarbons (HCFCs), methyl chloride, and carbon tetrachloride are the other major carriers of chlorine to the stratosphere, while halons and methyl bromide are the main sources of bromine. Hydrogen, nitrogen, and fluorine can accelerate the breakdown of ozone as well and can be carried into the upper atmosphere by stable and relatively insoluble molecules such as nitrous oxide, methane, and fluorinated gases.

Figure 34
Ozone destruction by catalysts



The diagram illustrates the process by which catalysts (X) such as chlorine, bromine, nitrogen oxide, and hydrogen destroy atmospheric ozone.

Observed atmospheric concentrations of all three major CFCs increased rapidly during the 1970s, when the use of these chemicals by industry and consumers became particularly widespread. By 1974, yearly production was approaching one million tonnes worldwide. At the same time, the amount of chlorine in the atmosphere also increased significantly. The “natural” level of free chlorine in the atmosphere before 1900 is believed to have been about 0.6 ppbv, almost all of it coming from methyl chloride. The present chlorine level is about 3.6 ppbv, and has been increasing rapidly. While the concentration of bromine in the atmosphere is still quite low, the presence of some bromine compounds, such as Halon 1301 and Halon 1211, in the atmosphere has been growing at rates of more than 10% per year. However, as a direct result of measures taken under the Montreal Protocol and its amendments (see Chapter 7) to limit and eventually eliminate emissions of the most significant ozone-depleting substances, the rate of increase in both chlorine and bromine in the upper atmosphere has slowed significantly and is expected to stop rising by 2000. Despite this important accomplishment, the long lifetime of the ozone-depleting substances already within the atmosphere will cause the decline of the chlorine and bromine levels from their peak concentrations to be quite slow and to continue until 2100 and beyond.

The depletion of ozone by CFCs and other compounds has now been studied for more than a decade, and current estimates of the extent of the depletion are not too much lower than some of the original estimates of the 1970s. The Antarctic ozone hole has continued to occur seasonally every year since it was first reported in 1985, with both its depth and areal extent gradually increasing with time. The hole was particularly severe in 1992 and 1993 when, during the month of October, virtually all of the ozone disappeared at altitudes between 14 and 19 km. It has also been found that the overall problem is much more complex than originally believed and that there are several other substances, such as volcanic aerosols, that can affect the total amount of ozone in the atmosphere. In the lower atmosphere, production of chemical smog from road transportation in industrialized regions has actually led to increases in the amount of ozone near the Earth’s surface. Furthermore, high-altitude temperature changes resulting from the enhancement of the greenhouse effect will tend to increase the natural production of ozone in the lower stratosphere and slow down the ozone-depleting reactions. Hence, while some of these processes can aggravate the depletion of the ozone layer by ozone-depleting substances like CFCs, others can partially compensate for such effects.

Effects of ozone layer depletion

The depth of the ozone layer varies naturally with latitude, largely due to the vertical temperature structure of the atmosphere. In general, its thickness is greatest at the poles, where solar radiation is weakest, and least at the equator, where solar radiation is strongest. As a result, the tropical regions of the world receive significantly higher amounts of UV-B radiation than higher latitudes. In fact, at the equator, nearly 30% of the UV-B rays entering the atmosphere reach the Earth’s surface, whereas in higher latitudes, the amount may vary from nearly 30% on a clear summer day to as little as 10% on a cloudy winter day. Scientists estimate that the average UV-B surface exposure in continental North America increases by 1% for each 2–3° latitude of movement southward.

Measuring ozone concentrations

Total vertical ozone concentrations over one location can vary naturally by as much as 15% in any year. This variability makes it difficult to measure long-term trends of the order of a few percent per decade, and even harder to detect clear evidence of depletion. Because careful monitoring of the ozone layer is important, the international scientific community has established a worldwide network of measuring stations. Observations from these stations are assimilated at the World Ozone Data Centre, operated by Environment Canada in Toronto.

A variety of techniques are used to measure ozone concentrations in the upper atmosphere. Huge helium balloons, carrying instrument packages to altitudes as high as 40 km, and high-altitude rockets are used to measure the vertical distribution of the gas. Some instruments are sensitive enough to measure upper atmospheric concentrations from the ground, while others are placed on satellites to help provide global overviews of the total depth of the ozone layer. Even the space shuttle has been put to use. In 1984, Canadian astronaut Marc Garneau measured ozone and haze concentrations in the upper atmosphere, using a sunphotometer developed by Canadian scientists. In 1992, another Canadian astronaut, Steve McLean, repeated the experiment with a sunphotospectrometer.

In Canada, ground measurements have been taken at five stations—Toronto, Edmonton, Churchill, Goose Bay, and Resolute—since about 1960. In recent decades, eight new stations across Canada have been added. One of the instruments first developed for use in Canada—the Brewer Ozone Spectrophotometer—has proved to be the world's most accurate ozone-measuring device and is now in use at over 100 locations within the global network of measuring stations.

Concentrations of ozone in the atmosphere are generally recorded in Dobson Units. One hundred Dobson Units (DU) equal 1 mm of ozone at surface temperature and pressure. Studies suggest that concentrations can vary from more than 400 DU in polar regions in spring to less than 250 DU at the equator year-round. In Antarctica, concentrations can vary as much as 50% between spring and autumn. The Antarctic ozone hole, which occurs during the southern spring when ozone levels should be at their maximum, has yielded measurements lower than 100 DU.

In general, results from stations in the higher latitudes of the Northern Hemisphere show a decreasing trend (as illustrated in the table below). These decreases are generally of similar magnitude in both middle and Arctic latitudes and are far greater in winter than in summer. Most recent trends further suggest that the rate of decrease may be accelerating. Concentrations over Toronto, for example, have decreased by about 4% during the last 10 years. While these trends could be partially due to natural fluctuations caused by such phenomena as the 11-year sunspot cycle, the magnitude of the trend is indeed cause for concern.

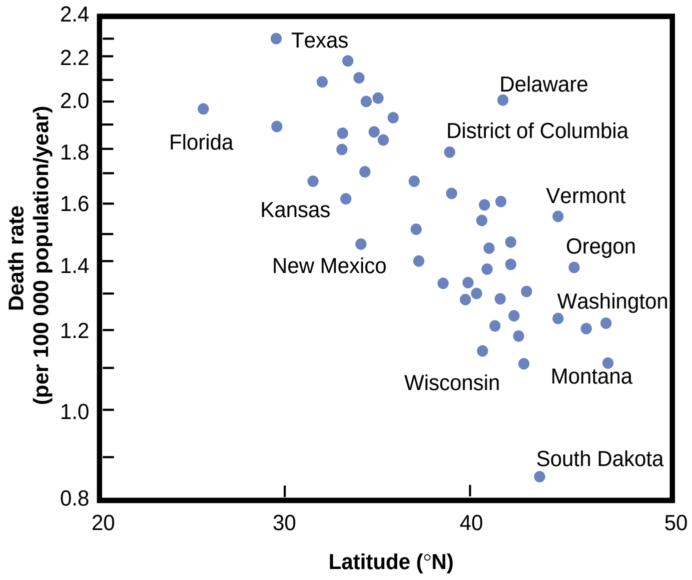
Changes in average total ozone concentrations 1970–91

		% change/decade		
Station	**Latitude**	**May-Aug.**	**Dec.-Mar.**	**Annual**
Churchill	58.8	-3.2	-4.2	-2.5
Edmonton	53.6	-0.7	-2.6	-1.4
Goose Bay	53.3	-1.5	-1.4	-1.3
Toronto	43.8	-1.3	-3.1	-1.5

In recent years, a large increase in surface UV-B radiation has been observed in Antarctica and high-latitude regions of South America during the ozone hole events. A significant increase was also reported over Toronto, in the Northern Hemisphere, during the periods of low ozone concentrations in 1993. While the changes are in good agreement with those predicted by radiation models, the record of good quality surface UV measurements is still too short to provide irrefutable proof of a long-term increase in UV-B intensity since the late 1970s, when ozone concentrations began to decline.

Natural variations in UV-B intensity with latitude give some clues about the possible consequences of ozone layer depletion. The most disturbing possibility is an increase in the incidence of skin cancer, particularly among white-skinned populations. Studies show that the incidence of cancer correlates closely with latitude and hence with the intensity of UV-B exposure. In one area of Texas, for example, the rate of incidence for all types of skin cancers (379 cases per 100 000 population per year) is three times the rate further north in Iowa. In the U.S.A. as a whole, the death rate for melanoma-type

Figure 35
U.S. melanoma cancer death rates by latitude



SOURCE: UNEP 1987.

skin cancer in southern states is double the rate in the north (Figure 35). In the former Soviet Union, skin cancers represent 15–26% of all cancer cases in southern regions compared to only 9–14% in northern regions. The highest rates of skin cancer among white-skinned people are found in northern Australia—a high UV-B exposure region.

Increased UV-B exposure may affect other aspects of health as well. Research has shown that the body's immune system becomes less effective under increased UV-B exposure and that eye diseases, such as cataracts, are more likely to occur.

Other animals and life-forms also face increased risks. Since UV-B can penetrate into clear water, even some forms of marine life—such as algae, plankton, and fish larvae—are vulnerable. Laboratory studies of UV-B effects on plants show that photosynthesis generally decreases because of damage to plant hormones and chlorophyll. Experiments with plants such as cotton, peas, beans, melons, and cabbage show a distinct decrease in yields under higher UV-B exposure, although some other plants appear to be more resistant to damage because of natural protective substances within their cells. Recent research results also suggest that the decline in populations of some species of amphibians may be linked to increased UV-B exposure. All of this implies that the depletion of the ozone layer could have serious consequences for global food production and natural ecosystems.

Greater intensities of ultraviolet radiation at the Earth's surface will also accelerate those processes that produce photochemical smog, adding additional hazards to human health and causing further damage to plants. Even inanimate material will be affected by higher levels of UV-B exposure. Paints will fade faster and plastics will deteriorate more quickly, thus shortening the lives of many everyday products.

Finally, changes to the ozone column—the vertical distribution of ozone in the atmosphere—will affect global climate. As more ultraviolet radiation passes through a depleted ozone layer it will cause an increase in the amount of ozone produced at lower levels. Since ozone itself absorbs both sunlight and infrared heat energy, changes in its distribution will affect atmospheric temperatures, which influence global circulation patterns and precipitation.

Chapter 7

How do we respond?

Ozone depletion and climatic change are not separate environmental concerns but related consequences of a more fundamental issue—the effect of human activities on the chemical composition of the atmosphere itself. Ozone depletion and climatic change not only share some of the same causes but also interact in complex ways. Chlorofluorocarbons, for example, both threaten the ozone layer and enhance the greenhouse effect. So does the burning of gasoline in a car engine, which produces not only carbon dioxide (a greenhouse gas) but also nitrous oxide (a greenhouse gas that also destroys the ozone layer).

Moreover, changes in climate can have a direct effect on the distribution of ozone. An enhanced greenhouse effect, for example, though increasing temperatures in the lower atmosphere, would actually decrease them in the upper atmosphere. Since the net rate of ozone production increases as air temperatures decrease, these lower temperatures would help to offset the chemical depletion of the ozone layer.

But the converse is true as well: changes in ozone distribution can also affect climate. Since ozone absorbs incoming sunlight and heats the air around it, altering the amount of ozone in a particular layer of the atmosphere will affect the temperature of the surrounding air. This temperature change, in turn, could cause a shift in atmospheric circulation, resulting in a change in global climate patterns.

The human activities now driving atmospheric change fall into three broad and related categories: changes in land use, industrial activities, and the burning of fossil fuels. These same activities are also the source of other major problems of atmospheric contamination, such as local air pollution, acid rain, and arctic haze, and these, in turn, often have their own complex relationship with global warming and ozone depletion. For example, ground-level ozone, a major constituent of smog, contributes to greenhouse warming both directly and by removing the hydroxyl molecules that cleanse the atmosphere of methane. Similarly, arctic haze is of concern, not only because of its effects on arctic ecology but also because it enhances winter warming in the far North and thus affects the global climate system.

Environmental damage is sometimes the result of several of these stresses acting together. Forests stressed by increased soil acidity, for example, may be much more vulnerable to climatic changes or extremes. Scientific evidence suggests that the large-scale dieback of European forests has been the result not of any one specific cause but of a combination of low-level ozone damage, acid precipitation, and drought.

Understanding these links is therefore fundamental to the formulation of an effective response to these issues. Since action with respect to one problem will obviously affect some or all of the others, there can be no place for piecemeal strategies. Only a holistic approach can yield decisive results.

Dealing with scientific uncertainty

In June 1988, an international group of policy makers, scientists, economists, and other experts assembled in Toronto for the World Conference on the Changing Atmosphere. They were deeply concerned that the human impact on the atmosphere had now become so powerful and so significant as to amount to “an unintended, uncontrolled, globally pervasive

Scientists and policymakers discuss global warming in a workshop session at the 1988 Toronto Conference.

experiment whose ultimate consequences could be second only to a global nuclear war." Seven months later, the UN General Assembly echoed these concerns and encouraged governments around the world to treat climate change as a priority issue. Subsequent ministerial conferences, in the Netherlands in November 1989, in Norway in May 1990, and in Switzerland in November 1990, stressed the need to start negotiating international agreements to stabilize emissions of greenhouse gases as soon as possible.

Such expressions of profound concern by the world's leading politicians and scientists are not surprising. Since it may take decades for the atmosphere to respond to our actions, most experts agree that decisive action must be taken now. This conclusion is reinforced by the fact that many of the consequences of atmospheric change may be irreversible and by the recognition that society is often very slow to change. The decisions we make—or fail to make—today will determine the future of our society and our environment for decades, and perhaps centuries, to come.

Yet, particularly with respect to global warming, there are also strong arguments that say we must not be too hasty in taking action now. These arguments suggest that we still don't know enough about what is happening to the atmosphere and how it will respond. Much of the scientific information is speculative, and some of our conclusions may be completely wrong. Indeed, there are scientists and decision-makers today who suggest that, given the cost of cutting pollutant emissions, we should not act until we are certain it is necessary and have a better understanding of our options.

We are faced, therefore, with a choice in which we must weigh the economic and social costs of acting now against the possibility of future environmental changes that could be catastrophic but that also might never materialize. How do we respond to such a dilemma? How do we weigh scientific uncertainty against potentially disruptive costs on the one hand and the potentially enormous risks of incorrect action on the other? An appropriate strategy can be found in risk assessment and analysis—a technique commonly employed in the equally uncertain worlds of economics and actuarial science and a process that we often use subconsciously in our personal decision-making activities.

In making decisions of this type, we run the risk of committing two kinds of errors. The first (a type I error) involves taking action for something that does not happen. The second (type II) is the failure to take pre-emptive or anticipatory action for something that eventually does happen. Decisions are usually based on the probability of the event occurring, the cost of anticipatory action, and the possible consequences of the event should it occur. If the cost of anticipatory action is too high, given existing uncertainties, and the costs of inaction are manageable, then we may wish to risk a type II error and do nothing. In other cases, where the cost of action is sufficiently small or the consequences of inaction are potentially large, it is better to choose to act. Thus, we commonly insure our homes against fire, even though the event is unlikely, because the cost of insurance is small in proportion to the cost of a fire. Through the application of such strategies, we can identify those areas where action should be pursued immediately and those where better understanding and more accurate assessments are needed.

Towards an international consensus

Using risk assessment as a planning tool, individual nations can undertake many useful initiatives. But valuable though such unilateral actions may be, it is also crucially important that the nations of the world work together if the response to atmospheric change is to be globally effective. Consensus building is therefore a critical part of any response to atmospheric change.

In recent years, the international policy community and its advisors have attempted to formulate a common understanding of the issues and explore the feasibility of co-operative global action. What has emerged is the beginning of an international consensus on the basis for responsive action, the main points of which are summarized in the following principles.

1. *Any action strategy must be based upon the fundamental principle of sustainable development.* Economic development, both in industrialized nations and developing nations, can be sustained only if environmental resources are managed and protected. Far from being contradictory interests, the economy and the environment are in many ways dependent upon each other. New approaches are needed to integrate environmental and social concerns into economic decision-making in a more systematic, focused, and co-ordinated way.

2. *Action must be based upon the best available scientific knowledge.* The World Meteorological Organization, in co-operation with the United Nations Environment Programme and the International Council of Scientific Unions, has been very active in assessing the climate

change and ozone depletion issues and organizing further research around the world. However, the success of these international programs depends also on the vitality of programs at the national level. While many countries have such programs, they need significantly enhanced resources and greater co-ordination. More work must also be focused on developing the strategies and technologies needed to respond to these issues.

3. *Action must be taken now to limit atmospheric change*. The precautionary principle dictates that, where a threat of serious or irreversible damage exists, lack of full scientific certainty should not be a reason for postponing measures to prevent environmental degradation. Thus, action to limit atmospheric change is essential and by no means premature. Indeed, it may already be overdue. The Montreal Protocol on Substances that Deplete the Ozone Layer is an example of what can be achieved. As a result of this agreement, the use of CFCs will be virtually eliminated by the end of the century. Major reductions in the emission of carbon dioxide are also achievable and need to be pursued simultaneously through the improvement of energy efficiency and through the development of alternatives to fossil fuels.

4. *Action must be fair*. While the industrialized nations have been, and still are, the primary source of the pollutants that are causing atmospheric change, the developing nations may well be most vulnerable to the consequences of such changes and least able to deal with them. The industrial nations, therefore, must bear the primary responsibility for reducing emissions of atmospheric pollutants. However, the developing nations presently account for almost all carbon emissions from tropical deforestation, and the 30% which they now contribute to global carbon emissions from fossil fuels will likely increase to more than 50% by 2050. Consequently, it is essential that they too take active measures to control future releases of pollutants. However, if they are to do so, while at the same time enhancing their development prospects and preparing for the impacts of climate change, innovative funding mechanisms and partnerships will be needed.

5. *Action must be co-ordinated and co-operative*. The atmosphere is a critical part of the environment that is common to everyone but belongs to no one. Its protection, therefore, not only is essential to global well-being but is also a global responsibility.

6. *Action requires an enhanced public awareness*. In many respects this is the most important principle, since effective action depends on a climate of opinion that is neither complacent nor hysterical about the issues involved.

The global response

Atmospheric change did not become a significant public issue until the early 1970s, and it was not until the end of that decade that major international research programs to deal with it got under way.

An important step towards world collaboration in the study of global warming and climate change was taken in 1979, when the World Meteorological Organization (WMO) and two other international scientific bodies launched the World Climate Programme (WCP). The WCP was given the mandate of promoting and co-ordinating international research into global climate processes and into the impacts of climate variability and change. In 1986 the International Council of Scientific Unions established its ambitious International Geosphere-Biosphere Programme to improve our understanding of how and why the Earth supports a living ecosystem and to examine how this system has changed in the past and is changing now. A complementary program on the Human Response to Global Change has also been established jointly by another group of international scientific agencies.

These programs have already contributed substantially to our understanding of the global climate system and the sensitivity of human society to changes within it. Continued research is now expanding our knowledge of how such elements as clouds, sea ice, and the hydrologic cycle affect climatic processes. It is also unravelling such major uncertainties as the complex role of the oceans as a reservoir for greenhouse gases and as a sink, source, and transporter of heat. Because the effects of climate shifts on ecosystems will vary from one area to another, efforts are being made as well to develop credible scenarios for regional climatic change. As these research efforts continue, impact studies will need to identify those natural and human systems that are most sensitive to climatic change and investigate these in much greater detail than present studies are capable of providing. Such studies will also need to look carefully at the total impact of all assaults on natural ecosystems, including acid precipitation, increased ultraviolet radiation, and local air pollution as well as climate change.

The implementation of international research programs such as these depends on the existence of strong and adequately funded national programs. Canada is one of several countries that have national climate research programs involved in these multinational activities. However, the number of national programs is still too few, especially in the developing regions of the world, and most of the existing ones do not have sufficient resources to undertake all of the research that is necessary. A strengthening and broadening of these programs is therefore of major importance.

To ensure that evolving scientific knowledge is made available to the policy community in a timely and effective manner, regular and comprehensive international assessments of the current state of the science are required. Under the joint auspices of the United Nations Environment Programme (UNEP) and the WMO, formal international assessments of the ozone issue have been available at regular intervals since 1977. In 1988, UNEP and WMO co-operated in establishing the Intergovernmental Panel on Climate Change (IPCC) to conduct similar assessments of the science of climate change. The IPCC released its first comprehensive report in 1990 and published updates on the science in 1992 and 1994. A second comprehensive assessment will be completed in 1995.

The world's governments have also achieved some major milestones in efforts to initiate responsive action aimed at reducing the risks of atmospheric change. The 1988 World Conference on the Changing Atmosphere, sponsored by Canada and held in Toronto, was a pivotal event in this process. It brought together nearly 300 politicians, policy advisers, legal experts, environmental advocates, and scientists to discuss the scientific basis for concern about atmospheric change and to recommend a course of action to the world community. A significant outcome of the conference was its success in transferring concern about global warming from the scientific to the policy-making community. Equally important was its recommendation to reduce global carbon dioxide emissions by 20% of 1988 levels by the year 2005.

Following the Toronto Conference, the United Nations established an Intergovernmental Negotiating Committee to begin the task of developing a Framework Convention on Climate Change (FCCC). After less than two years of intensive negotiations, the FCCC was approved at the United Nations Conference on Environment and Development held in Rio de Janeiro in 1992, and has since been ratified by more than 90 member countries. The first meeting of the Conference of the Parties to the Convention was convened in Berlin in early 1995. The ultimate objective of the Convention is to achieve stabilization of greenhouse concentrations in the atmosphere at a level that would prevent dangerous human interference with the climate system. As a first step towards that objective, all industrialized nations that are parties to the Convention have committed themselves to develop national programs aimed at limiting their emissions of all greenhouse gases to 1990 levels by the year 2000.

While the international political response to climate change has only just begun, action to limit ozone depletion commenced in the early 1980s and is already much further advanced. UNEP began to explore the possibility of developing a global convention to protect the ozone layer in 1981 and succeeded in completing negotiations for the Vienna Convention for the Protection of the Ozone Layer by 1985. However, specific commitments for actions to reduce the threat to the ozone layer did not come into effect until the Montreal Protocol on Substances that Deplete the Ozone Layer was approved in 1987. The Protocol committed all industrialized nations to reduce their consumption of ozone-depleting substances (primarily CFCs) by 50% of 1986 levels by 1999. Developing countries were required to meet similar target levels by 2009. More than 130 nations have now signed and ratified both the Vienna Convention and the Montreal Protocol.

Although the initial targets of the Montreal Protocol helped to significantly reduce the threat of ozone depletion, many scientists believed that the 50% target was inadequate and that the protocol had to be strengthened to eliminate emissions of the most harmful CFCs altogether while further reducing emissions of other destructive gases. This view was strongly supported by several countries, including Canada, in further international discussions and led to two subsequent amendments to the protocol. The first, signed in London, England, in June 1990, committed Parties to complete the phase-out of the most damaging CFCs and halons by 2000. The second was adopted at Copenhagen, Denmark, in November 1992. It advanced the date for complete phase-out of CFCs to 1996, and of the most damaging halons to 1994. By September 1994, more than 90 countries had already ratified the London Amendment. Of these, Canada and some 30 other nations have now committed themselves to the more advanced commitments of the Copenhagen Amendment.

Canada's greenhouse gas monitoring station at Alert, N.W.T. Other stations are located at Sable Island, N.S., Fraserdale, Ont., and Estevan Point, B.C.

The Canadian response

While many universities and other research institutions in Canada are directly or indirectly involved in studies related to climatic change, our formal research efforts in this area are co-ordinated through the Canadian Climate Program (CCP), administered by Environment Canada. During the past decade, the CCP, in close co-operation with the WCP, has fostered extensive research into climatic processes and the implications of climate change for Canadians. As part of a WMO network of Background Air Pollution Monitoring stations, Canada measures concentrations of carbon dioxide and several other atmospheric gases at four stations (Alert, N.W.T., Sable Island, N.S., Fraserdale, Ont., and Estevan Point, B.C.). Studies into the climatic effects of an enhanced greenhouse effect are also in progress, using Environment Canada's advanced General Circulation Model.

Meanwhile, a large number of CCP-sponsored studies have been completed into the effects of typical doubled-CO_2 climates on ecosystems and economic and social activities across Canada. Other studies are examining prehistoric climates, current climate trends, and carbon flows between the atmosphere, the oceans, and the land. Bilateral agreements for scientific exchange and co-operation on climatic change issues have also been concluded with several countries, including China, Germany, the Netherlands, and Russia.

Canada has provided international leadership in developing policy responses to climatic change. In addition to the 1988 World Conference on the Changing Atmosphere, Canada also hosted the follow-up discussions by world legal experts on the establishment of an international framework convention to protect the atmosphere. It continues to be an active participant in both the work of the IPCC and the further development of the FCCC.

While Canada as a nation is not a major contributor to world emissions of chemicals that change the atmosphere, individually its citizens are. Canada as a whole emits only about 2% of global carbon dioxide emissions from fossil fuel, but, on a per capita basis, that amounts to about 17 tonnes for each Canadian every year. That is double the average per capita releases of developed nations in Western Europe and about four times the global average.

Canada's northern climate, large geographical expanse, and resource-intensive economy all contribute to a relatively high per capita use of energy. Nevertheless, Canadians have considerable potential for improving their energy use efficiency, and thus reducing the size of their carbon dioxide emissions—and we must do so if we are to maintain our credibility on environmental matters before the rest of the world. Furthermore, many of the actions needed to reduce those emissions will reduce the risk of other environmental problems. They may also benefit us economically and keep our economy competitive with other countries.

Given the need to reduce our output of carbon dioxide, how can we do so most effectively? Projections by energy experts indicate that, unless specific actions to limit emissions are taken, Canada's emissions in the year 2000 are likely to be about 13% higher than those of 1990. Studies into the potential for reducing these emissions have repeatedly confirmed the possibility of stabilizing emissions at 1990 levels by 2000 and making further reductions in subsequent years. However, such actions could cause significant hardships to some economic sectors and regions, even though many of the actions required would also have broad economic and social benefits. As a result, stabilization will not necessarily be easy to achieve.

Not surprisingly, these studies all agree that measures to improve energy efficiency are the first priority for action. Other options for reducing carbon dioxide emissions include the increased use of renewable biomass energy and further develop-

The National Action Program on Climate Change

Canada's National Action Program on Climate Change provides the strategic direction for stabilizing Canada's greenhouse emissions by 2000 and outlines a range of measures required to realize this commitment. As part of its response to climate change, the program also recognizes the long-term importance of reducing related scientific uncertainties and improving the ability of Canadians to adapt to the effects of climate change.

The National Action Program was developed through consultations involving the federal and provincial governments, the private sector, and environmental and other interest groups. Options were identified according to a number of common principles and criteria, such as effectiveness, adaptability and flexibility, minimization of costs, and sharing of responsibility among stakeholders.

Some of the identified measures cut across several social and economic sectors. These include a challenge to industry to develop voluntary measures to reduce emissions as well as actions to change consumer behaviour through altered commodity prices or public education. However, most measures are detailed and sector-specific, making it possible to relate actions directly to individual emission sources.

The program's major options focus on the following areas:

- development of incentives, regulations, and technical training to improve the thermal performance of new and existing buildings and to increase the energy efficiency of lighting, appliances, and other equipment in both the residential and commercial sectors
- analysis of subsidies to the energy, transportation, agriculture, and forestry industries
- implementation of measures to encourage motorists to buy fuel-efficient cars, to drive less, and to drive more efficiently
- development of new forests within Canada to enhance natural carbon sinks and remove more carbon dioxide from the atmosphere

ment of technologies and facilities for non-carbon energy sources such as solar, wind, and hydro-electric power. Some experts also suggest that an increased use of nuclear power, though itself a cause for environmental concern, is safer and more acceptable than the continuing use of fossil fuels.

In March 1990, Canada's environment ministers agreed to devise a national strategy to deal with global warming. That strategy, released for public consideration in November 1990, included three principal thrusts:

1. limiting greenhouse gas emissions from all sources,
2. helping Canadians anticipate and prepare for the potential effects of any warming that might occur, and
3. improving our scientific abilities to understand and predict climate change.

In late 1993, Canada's federal and provincial environment ministers held an unprecedented meeting with their energy counterparts to discuss Canada's commitments to limit greenhouse gas emissions. The ministers agreed to instruct their officials to proceed with the development of options that will meet Canada's current commitment to stabilize greenhouse gas emissions by the year 2000 and to develop sustainable options to achieve further progress in reducing emissions by the year 2005. The ministers met again in November 1994 to consider the report of the multi-stakeholder Task Group established to develop these options, and agreed that voluntary measures and energy efficiency initiatives would be key components of the action program. The draft program was approved in February 1995 and tabled at the first meeting of the Conference of the Parties to the FCCC in Berlin in April. The National Action Program is scheduled for review in December 1996.

As for efforts to reduce the depletion of the ozone layer, Canada has taken a leading part both in the area of scientific co-operation and in policy development. As a major element of our contribution to global monitoring of the ozone layer, Environment Canada scientists take regular measurements of the atmospheric ozone column and are collaborating with other countries in studying the north polar atmospheric vortex that periodically contributes to large seasonal decreases in ozone over the north pole. They also operate the World Ozone Data Centre, which collects ozone-related data from an international network of stations co-ordinated by the WMO and distributes this information to scientists around the world. In addition, Canadian scientists have developed sophisticated ozone-measuring sunphotospectrometers which have been used aboard American space shuttle flights and on high-altitude research aircraft during international experimental studies of the stratosphere. These instruments are now becoming the standard for the global ozone monitoring network.

On the policy front, Canada moved in 1980 to ban the use of ozone-destroying CFCs in most spray cans, an action which decreased the use of these chemicals by 45% nationally. In addition, it has been a strong advocate of more comprehensive international controls and in 1987 hosted the historic meeting that resulted in the Montreal Protocol. Since then, Canada has helped convince the international community to go beyond the 50% reductions called for in the protocol and eliminate the use of the most damaging CFCs completely by the year 1996. Because CFCs are also potent greenhouse gases, this action will eventually help to slow the enhancement of the greenhouse effect as well as diminish the rate of future ozone destruction.

Canada has also initiated a number of measures to help Canadians to become aware of and adapt to the possible effects of the thinning of the ozone layer that is already taking place. Since 1992 Environment Canada has issued a daily “UV Index” forecast to warn the general public of the health risks associated with sunlight exposure during outdoor activities. The index is based on day-to-day predictions of changes in the thickness of the overhead ozone layer and is produced for locations across Canada as well as for common holiday destinations. It is measured on a scale from 0 to 10, with higher values representing increasing risks of sunburn and skin damage during periods of sunshine exposure. While the index can change considerably from day to day, the largest variations are associated with seasonal changes in both sunlight intensity and ozone layer thickness. Values are also influenced by the time of day and the extent of cloud cover. The index is issued concurrently with weather forecasts on radio and television programs and in daily newspapers.

The role of the citizen

How can the individual citizen influence the outcome of a global environmental issue that is already challenging the wisdom and resources of the world’s governments and international agencies? The answer, simply put, is that it is individual citizens who must create the environment of opinion which will push governments into action. And it is individual citizens who must support the policies and make the changes that an effective response to our present crisis will demand.

Citizens influence politicians, manufacturers, and each other by their voting power, their behaviour as consumers, and their own day-to-day actions. The 23 billion tonnes of carbon dioxide that we pour into the atmosphere each year through the use of fossil fuels are not produced by governments but by the more than five billion people who now occupy the Earth. Canadians contribute more than most. Each time we turn up the thermostat, drive a car, turn on a hot water tap, or open a refrigerator door, we add to the problem. By changing our attitudes and lifestyles, by becoming more knowledgeable about the issues and rethinking our attitude to the environment, we can make a difference.

In addition to exerting our influence on policy matters, there are many other things that we can do in our personal lives to ease the burden that we now place on the environment. A list of such actions is included at the end of this report.

Ultimately, however, it is a change in the way we think of our natural environment that will count. The environment is not an endless supply of resources, nor is it a bottomless receptacle for the debris and detritus of our industrial society. Rather, it is a living system capable of almost infinite regeneration as long as its complex balances and interdependencies are respected. We must learn to live in harmony with its processes. Instead of being exploiters of the Earth, we must become Earthkeepers.

Protecting the atmosphere: a personal agenda

At home

- Ensure that your house is adequately insulated.

- Keep your thermostat turned down in winter.

- Reduce air conditioning demands in summer by installing window blinds and/or shading your house with trees or awnings.

- Insulate your hot water tank. A well-insulated tank uses up to 10% less energy.

- If you still heat with oil, consider converting to natural gas. For a fixed unit of energy, natural gas emits 40% less carbon (as carbon dioxide) than oil.

- Keep your oil or gas furnace properly tuned. A well-maintained unit uses 10–15% less energy.

- When shopping for new appliances, compare energy consumption rates and try to choose the one that is most efficient. For example, the average power consumption of a Canadian two-door, 50-litre refrigerator-freezer can vary from about 1200 kilowatt hours of electricity per year for the least efficient to as little as 650 kilowatt hours per year for the most efficient, and prototypes have been built that require less than 500 kilowatt hours per year.

Transportation accounts for about 30% of carbon dioxide emissions in Canada.

- Consider using more efficient lighting. Compact fluorescent bulbs for use in standard incandescent sockets are now available and are more than four times as efficient as an equivalent incandescent bulb and last 8 to 15 times longer. It has been estimated that, over its lifetime, each fluorescent bulb could decrease the carbon dioxide output of a coal-burning generating station by more than 350 kg.

- Turn lights off when they are not needed. To power a 100-watt incandescent light bulb, left on 24 hours a day for one year, a coal-fired generating station would emit about 800 kg of carbon dioxide or about 4% of our per capita emissions of carbon from fossil fuel consumption.

On the road

- Keep your car well tuned and its tires correctly inflated. A properly maintained vehicle can reduce fuel consumption by up to 10%.

- Drive with conservation in mind. Drive at the posted speed limit, avoid abrupt stops and starts, and plan your trips for the most efficient routes. Also, don’t idle your car excessively—a stationary vehicle with its motor running is returning a fuel economy of 0 km/L!

- Be selective when buying a car, and make fuel economy an important factor in your choice. If practical, consider installing an alternative fuel system, particularly natural gas. Where available, use gasohol.

- When commuting to work, consider taking public transit or using a carpool. Currently the average Canadian car uses about 12 L of fuel per 100 km travelled. If your round trip to work and back was 20 km per day, you would travel about 5000 km per year. Using the average urban fuel economy of a Canadian car, you would require 600 L of motor gasoline. The carbon dioxide released from the consumption of this amount of fuel would amount to more than 1400 kg or about 7% of our annual per capita emissions of carbon dioxide from fossil fuel combustion. In comparison, travelling the same distance to work by city bus would release less than 200 kg per passenger per year. As a point of interest, an increase of just 1L/100 km in the average fuel efficiency of Canadian cars would reduce our carbon dioxide emissions by about 3.3 million tonnes per year, the rough equivalent of closing two modern 450 MW coal-fired power plants.

In your lifestyle

- Be a selective consumer. Buy products that are energy efficient and that lend themselves to recycling and reuse. Refillable bottles, for example, use far less energy than disposables.

- Participate in local recycling programs. Products made from recycled materials require significantly less energy to manufacture. It takes 95% less energy, for example, to die-cast a part from recycled aluminum than from primary metal.

- Inform politicians of your concern for the environment and encourage them to enact appropriate legislation.

- Finally, contact your local utility, provincial Ministry of Energy, and/or Natural Resources Canada for more fuel-saving tips and consumer information.

Clearly the potential for individuals to reduce their contribution to the output of greenhouse gases (particularly carbon dioxide) is dramatic. Let us also remember that any improvement in energy efficiency also helps to reduce the emission of substances that contribute to other environmental concerns, including acid precipitation, urban air pollution, and depletion of the ozone layer.

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