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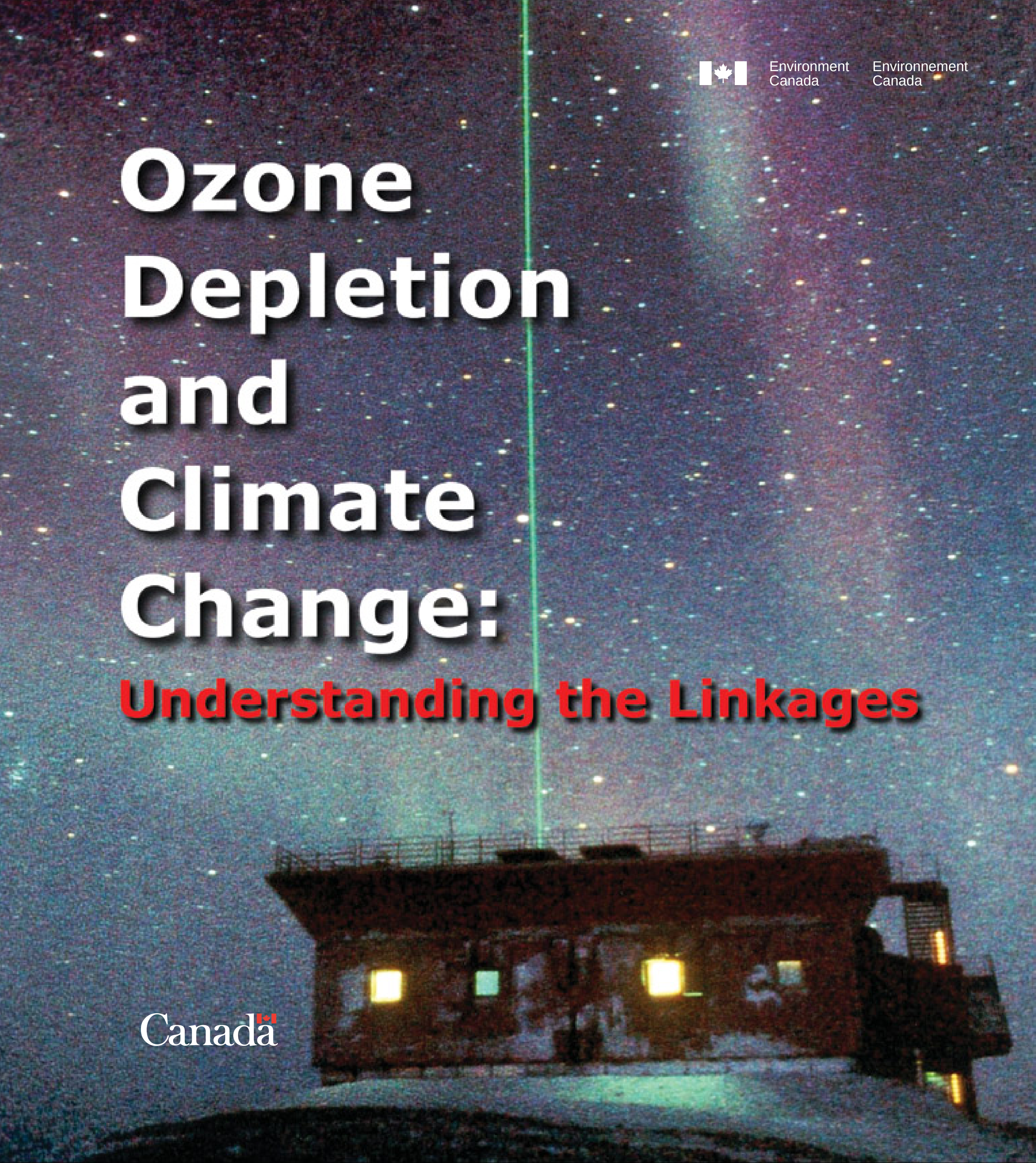
Ozone Depletion and Climate Change:

Understanding the Linkages



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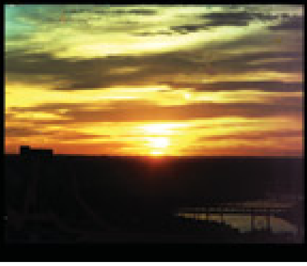
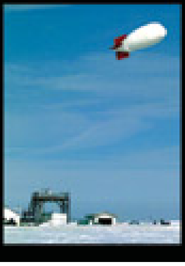


Ozone Depletion and Climate Change:

Understanding the Linkages

Angus Fergusson
Meteorological Service of Canada

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Author: Angus Fergusson *(Environment Canada)*

Editing: David Francis *(Lanark House Communications)*
David Wardle / Jim Kerr *(Environment Canada)*

Contributing Authors: Bruce McArthur *(Environment Canada):* Bratt Lake Observatory
David Tarasick *(Environment Canada):* Canadian Middle Atmosphere Model
Tom McElroy *(Environment Canada):* MANTRA Project

Special thanks for comments to: Vitali Fioletov *(Environment Canada)*
Hans Fast *(Environment Canada)*

Pictures: Angus Fergusson *(Environment Canada)*
John Bird *(Environment Canada)*
Brent Colpitts
Ray Jackson

Layout and Design: BTT Communications

Additional copies may be obtained, free of charge, from:

Angus Fergusson
Science Assessment and Integration Branch
Meteorological Service of Canada
4905 Dufferin Street
Downsview, Ontario
M3H 5T4
E-mail: Angus.Fergusson@ec.gc.ca

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Figure 1. Compared to the earth itself, the earth's atmosphere as seen from space looks remarkably thin, much like the skin on an apple. In this photograph, the two lowest layers of the atmosphere, the troposphere and the stratosphere, are clearly visible. The stratosphere is home to the ozone layer that protects life on earth from intense ultraviolet radiation. The troposphere is the layer where most weather activity takes place. The top of the thundercloud has flattened out at the tropopause, the boundary between the two layers. Interactions between the troposphere and stratosphere provide a number of important connections between ozone depletion and climate change.

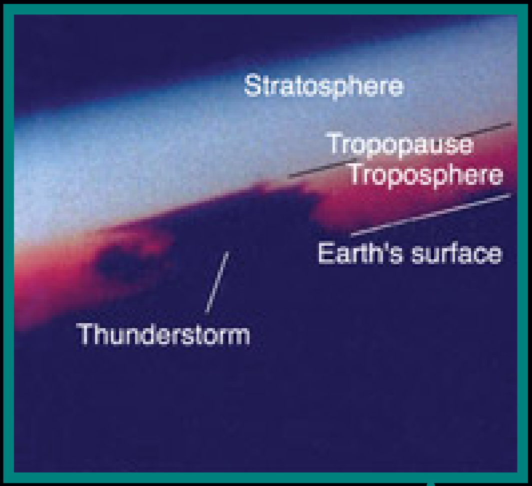
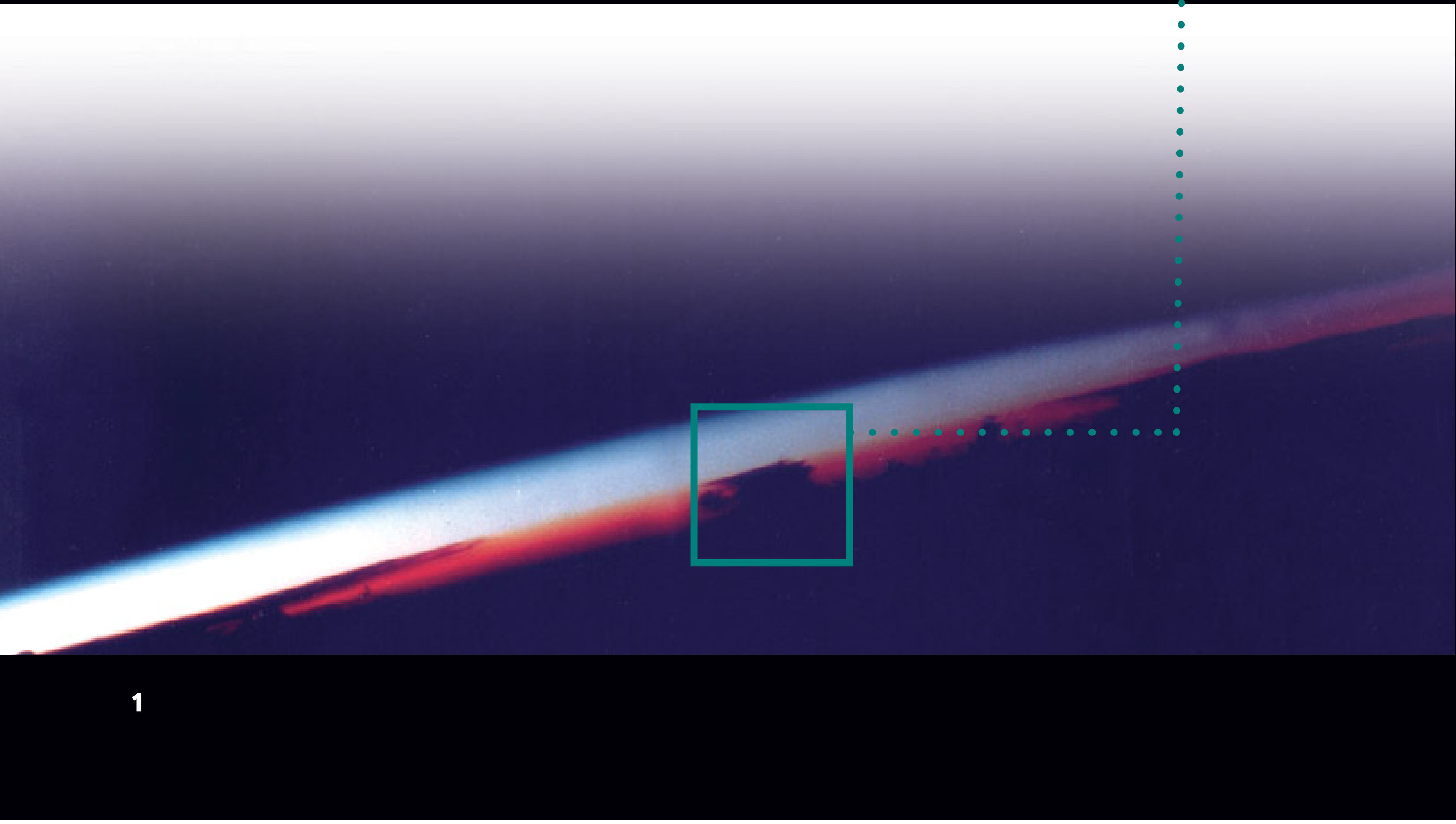


Figure 1
Source: NASA



Summary

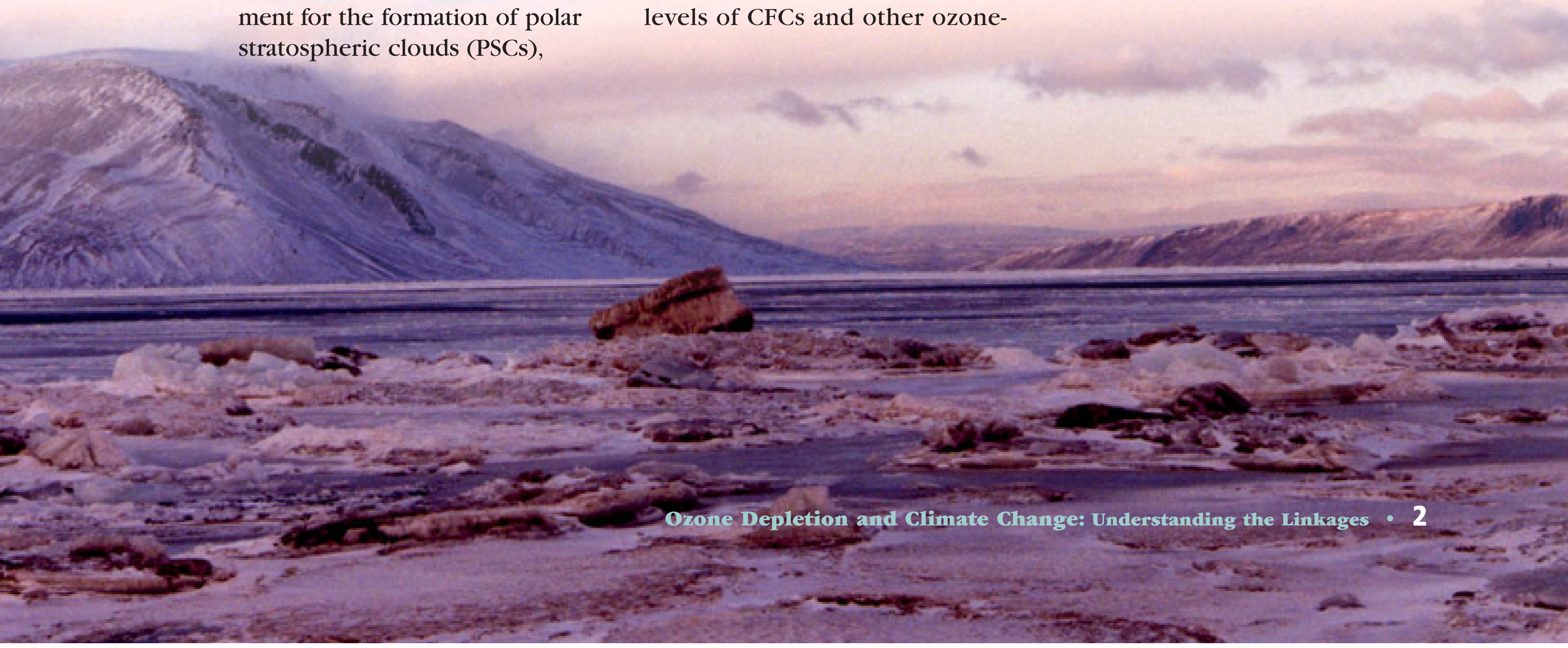
Ozone depletion and climate change have usually been thought of as environmental issues with little in common other than their global scope and the major role played in each by CFCs and other halocarbons. With increased understanding of these issues, however, has come a growing recognition that a number of very important linkages exist between them. These linkages will have some bearing on how each of these problems and the atmosphere as a whole evolve in the future.

Some of the most important of these linkages involve the way that ozone-depleting substances and greenhouse gases alter radiation processes in the atmosphere so as to enhance both global warming and stratospheric ozone depletion. These changes result in a warming of the troposphere (the bottom 8–16 km of the atmosphere) and a cooling of the stratosphere (the layer above that extends to an altitude of about 50 km and contains the ozone layer). Stratospheric cooling creates a more favourable environment for the formation of polar stratospheric clouds (PSCs), which are a key factor in the development of polar ozone holes.

Enhancement of the greenhouse effect may also be causing changes in circulation patterns in the troposphere that are, in turn, altering the circulation in the stratosphere. It is suspected that these changes are increasing the cooling forces acting on the stratosphere over the poles and are thus making the formation of ozone holes more likely. There is evidence as well that changes in the stratospheric circulation may be altering weather patterns in the troposphere. Other linkages between climate change and ozone depletion are related to the effect of increased levels of ultraviolet radiation on sun-driven chemical reactions in the atmosphere and to changes in biological processes that affect the composition of the atmosphere.

The net effect of these linkages is an intensification of both climate change and ozone depletion and possibly a delay in the recovery of the ozone layer as it responds to diminishing levels of CFCs and other ozone-depleting substances covered by the Montreal Protocol. To understand these connections better, researchers are now looking more closely at how the troposphere and stratosphere interact *(Figure 1)*. Environment Canada scientists are contributing to this research in a variety of ways, including the monitoring of ozone concentrations and solar radiation levels and collaboration in balloon-based stratospheric research and atmospheric modelling.

Both greenhouse warming and the thinning of the stratospheric ozone layer are a result of human activities that have changed the composition of the atmosphere in subtle but profound ways since the beginning of the industrial revolution more than 200 years ago. By taking an integrated approach to ozone depletion and climate change, governments and scientists will have a better chance of understanding and moderating the enormous changes that human activities have had and will continue to have on the atmosphere.



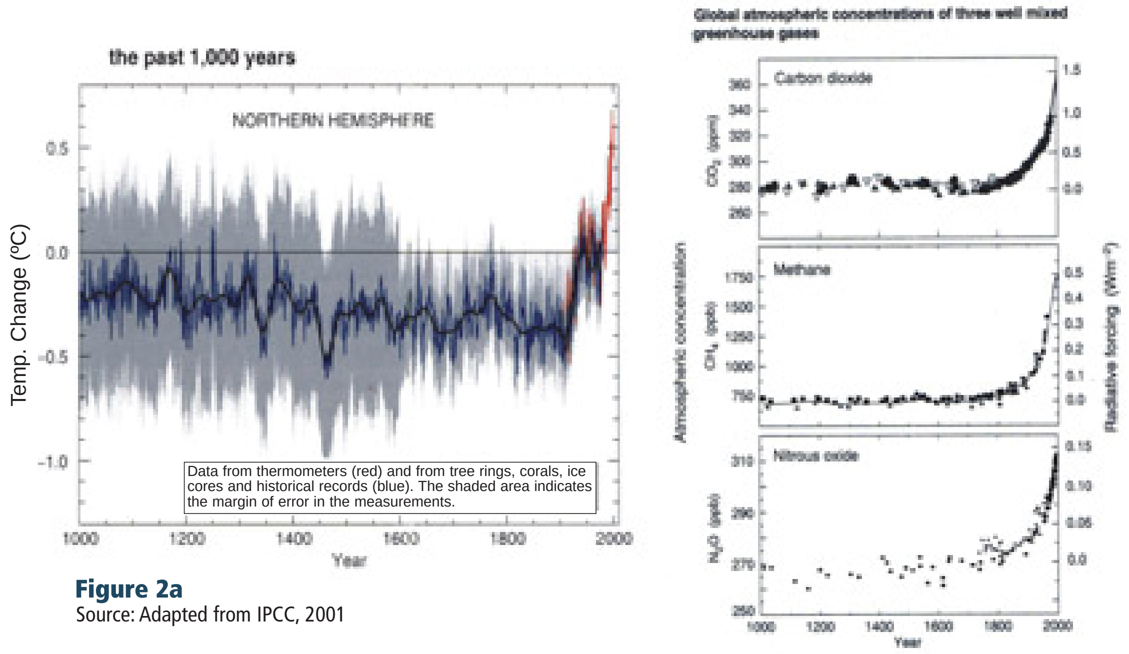


Figure 2a

Source: Adapted from IPCC, 2001

Figure 2a. Greenhouse gases, such as carbon dioxide, methane, and nitrous oxide, affect climate by retaining heat near the earth's surface. Concentrations of these gases began to rise in the 19th century and have increased exponentially in the 20th, paralleling the expansion of industrial economies and the growth of the human population. Over the past century the average global temperature has increased by about 0.6ºC, and significantly greater increases are expected for the 21st century. Warming of the atmosphere is also expected to cause changes in other aspects of climate, including changes in precipitation and evaporation, circulation patterns, and weather extremes.

Figure 2b. Thinning of the stratospheric ozone layer has been caused largely by long-lived chlorine and bromine compounds, such as CFCs and halons, that eventually make their way into the stratosphere. Use of these compounds increased considerably in the 1960s and 1970s. Evidence of ozone depletion in the stratosphere began to appear in the 1980s. Atmospheric concentrations of most ozone-depleting substances peaked, or their growth rate began to slow, as a result of the phasing out of these chemicals under the Montreal Protocol. Concentrations of ozone-depleting substances are expected to decline over the coming century, bringing a gradual recovery of the ozone layer.

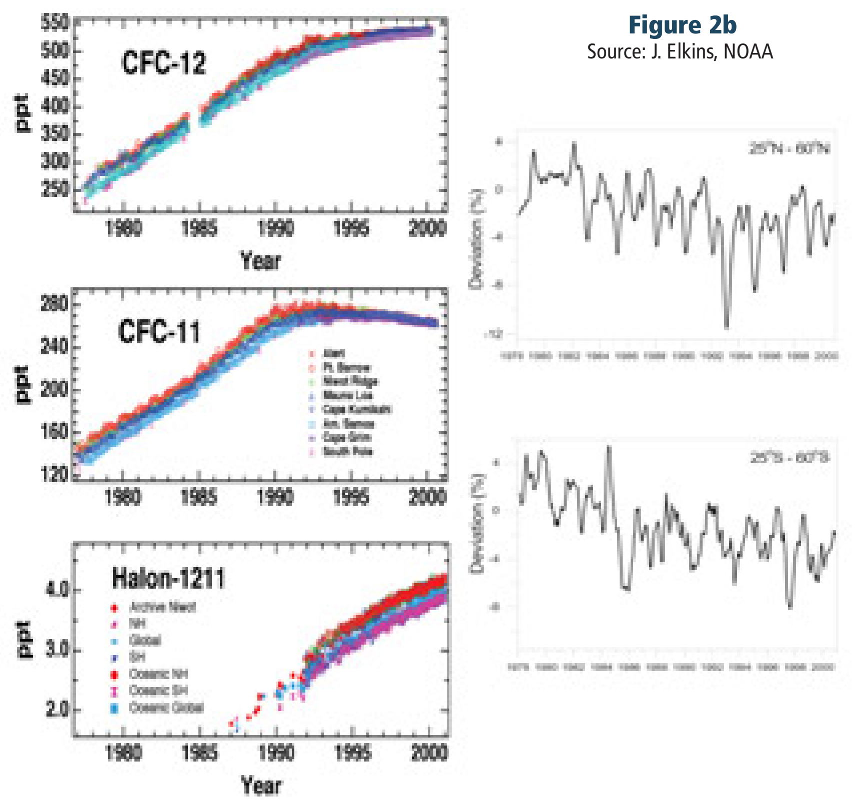


Figure 2b

Source: J. Elkins, NOAA

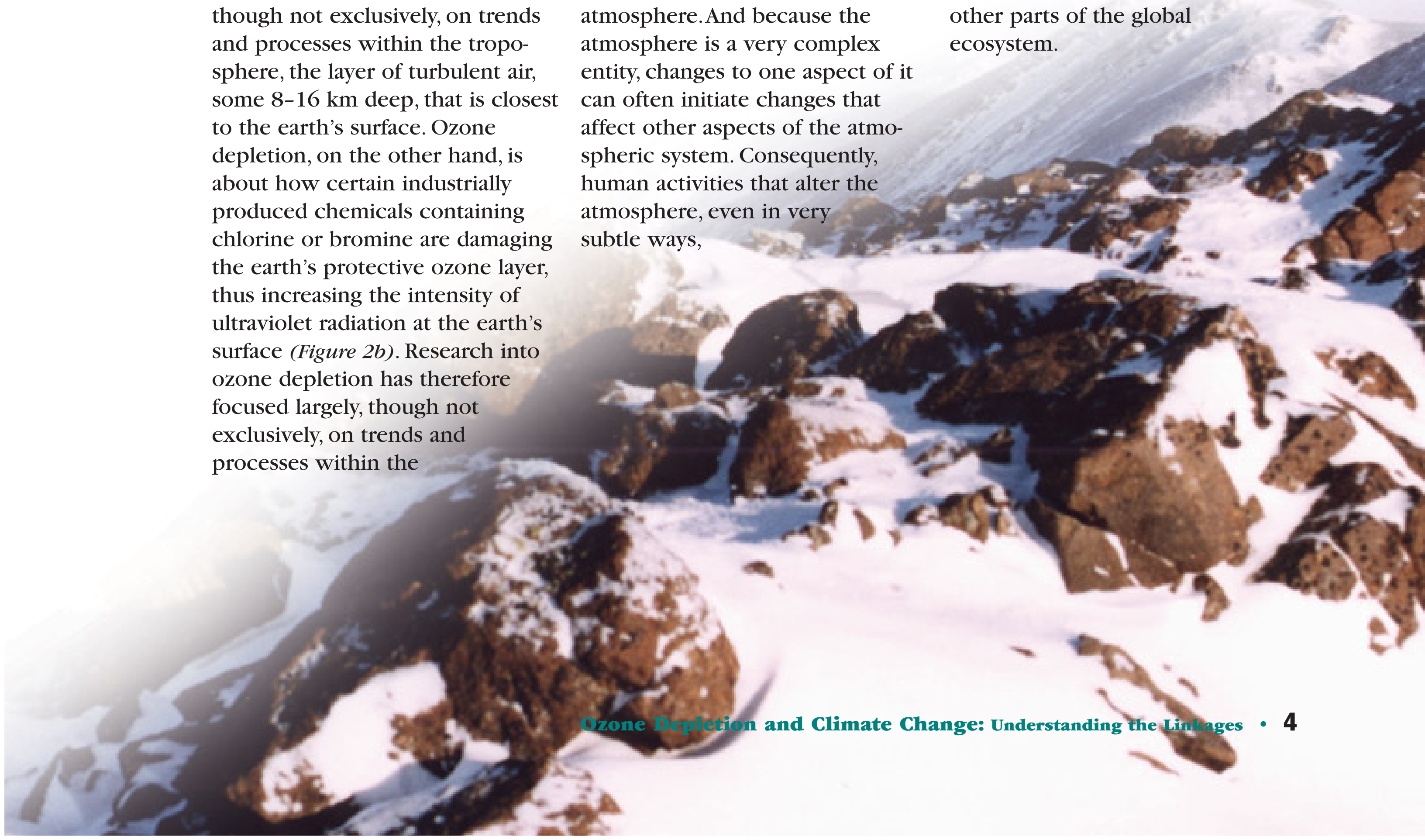
Introduction

Climate change and the depletion of the stratospheric ozone layer have been leading environmental issues for more than a quarter of a century. For much of that time, they have been treated as separate and distinct problems, with researchers setting up separate programs to investigate the underlying scientific questions and governments establishing separate international arrangements to coordinate control measures.

In many ways, of course, these issues are quite distinct. Climate change is concerned with how carbon dioxide, methane, and other greenhouse gases emitted by human activities are altering the climate system *(Figure 2a)*. Consequently, research into climate change has focused largely, though not exclusively, on trends and processes within the troposphere, the layer of turbulent air, some 8–16 km deep, that is closest to the earth's surface. Ozone depletion, on the other hand, is about how certain industrially produced chemicals containing chlorine or bromine are damaging the earth's protective ozone layer, thus increasing the intensity of ultraviolet radiation at the earth's surface *(Figure 2b)*. Research into ozone depletion has therefore focused largely, though not exclusively, on trends and processes within the stratosphere, the layer of stratified, relatively stable air that houses the ozone layer and extends from the top of the troposphere to an altitude of about 50 km. Yet, as scientists have come to understand more about these issues and the complex physical and chemical processes that drive them, they have also become increasingly aware of a number of important connections between them.

Recognition of these connections parallels a growing awareness among scientists and policy makers that atmospheric issues cannot be dealt with in isolation from each other. The human activities that contribute to climate change and ozone depletion, or to any other air pollution problem for that matter, affect the same atmosphere. And because the atmosphere is a very complex entity, changes to one aspect of it can often initiate changes that affect other aspects of the atmospheric system. Consequently, human activities that alter the atmosphere, even in very subtle ways, can have important and surprising results. To take account of the many complicated interactions that occur in the atmosphere, scientists and policy makers are increasingly taking a more holistic approach to atmospheric issues.

The most obvious linkage between ozone depletion and climate change is the fact that ozone itself and some of the more important ozone-depleting substances such as chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs) are also powerful greenhouse gases. But ozone depletion and climate change are linked in many other ways as well, particularly through their effects on physical and chemical processes in the atmosphere and on interactions between the atmosphere and other parts of the global ecosystem.



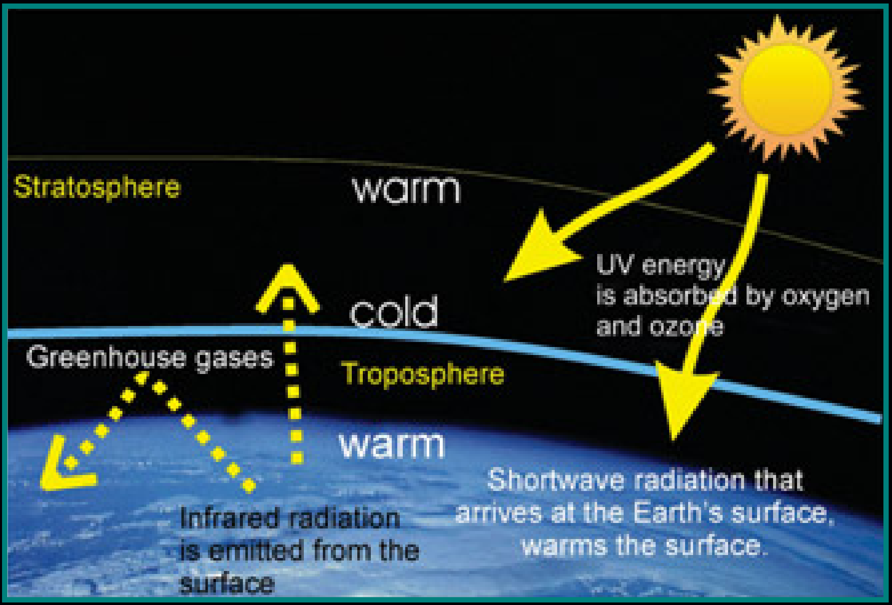
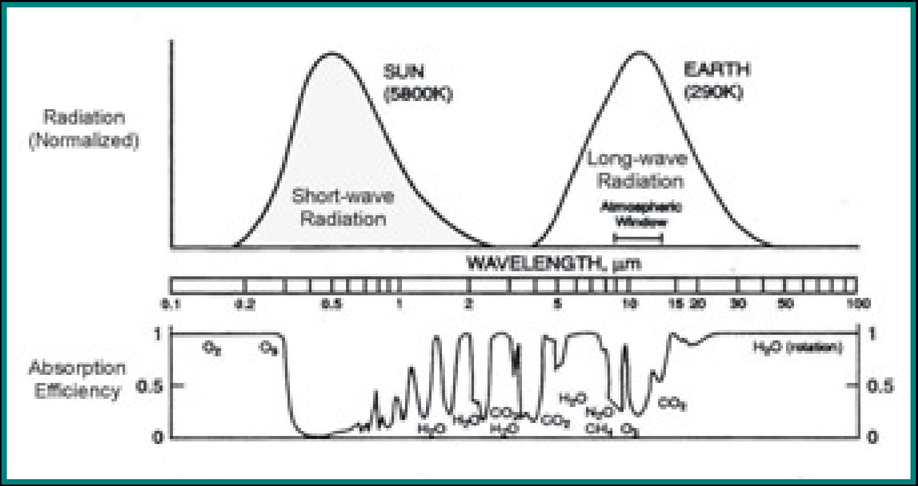


Figure 3

Figure 3. The contrasting temperature patterns in the troposphere and stratosphere are the result of differences in the way radiative energy is transferred to the atmosphere. The stratosphere is heated from the top down as intense ultraviolet radiation is absorbed by oxygen and ozone. The troposphere is heated from the bottom up as the earth's surface warmed by incoming sunlight, emits longwave infrared radiation, which is then absorbed and re-emitted by greenhouse gases in the air above. A small amount of heat is also transferred directly to the air by direct contact with the surface and by the evaporation and condensation of moisture. Because the troposphere generally becomes cooler with altitude, the warmer and lighter surface air rises easily. As a result, the air in the troposphere is often turbulent and well mixed. The stratosphere, on the other hand, tends to be quite stable because the increase of temperature with altitude inhibits vertical mixing of the air.

Figure 4. The basis of the greenhouse effect can be seen if we compare the wavelengths at which different atmospheric gases absorb radiation with the wavelengths at which radiation enters and leaves the atmosphere. The sun, because it is very hot, emits shortwave radiation, and although the shortest of these wavelengths are absorbed by oxygen and ozone, most solar radiation is not absorbed by atmospheric gases. The earth, because it is much cooler, emits longwave, infrared radiation, but most wavelengths in this part of the spectrum are readily absorbed by water vapour, carbon dioxide, methane, nitrous oxide, ozone, and other greenhouse gases. The atmosphere thus provides a very wide window through which incoming sunlight can penetrate but only a very narrow window through which infrared radiation can depart.

Figure 4
Source: adapted from Jacob, 1999



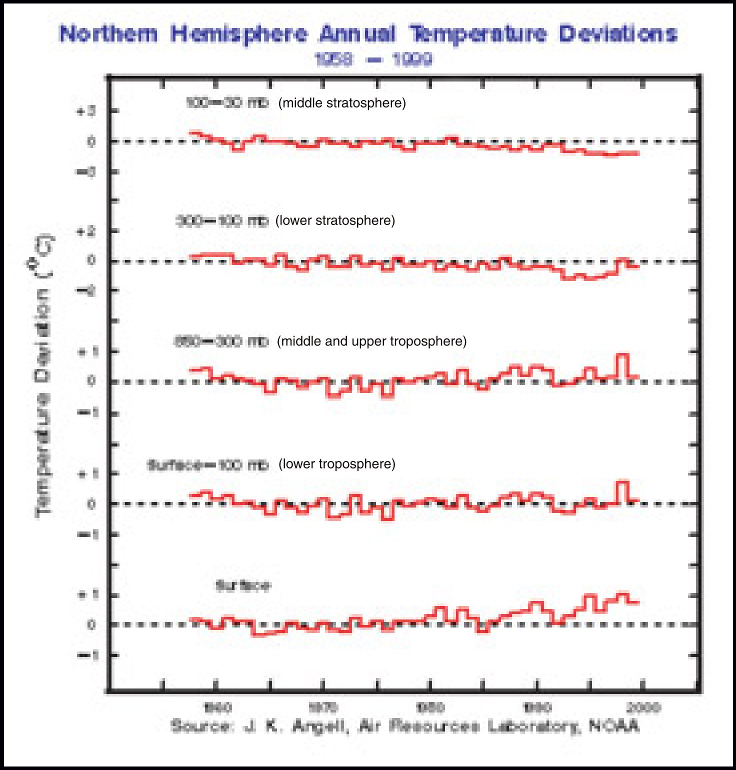
The Atmosphere and its Radiative Effects

Radiative processes have an enormous influence on the behaviour of the atmosphere because they govern the amount of energy entering and leaving the earth-atmosphere system and hence the amount of energy available to heat the air, evaporate moisture, and drive the movement of air masses. This energy initially enters the atmosphere as shortwave radiation from the sun, but it is transferred to the troposphere and stratosphere in very different ways, giving these two layers of the atmosphere very different structures and characteristics *(Figure 3)*.

The stratosphere is heated from the top down and is therefore warmer at the top than it is at the bottom. Consequently, the densest air in the stratosphere is at the bottom, there is little vertical mixing of the air, and the stratosphere is very stable. Heat is added to the stratosphere when strong ultraviolet-C (UV-C) radiation from the sun is absorbed by oxygen molecules and causes them to split. One of the results of this process is the production of ozone and the formation of the ozone layer in the stratosphere. More warming occurs when the ozone molecules intercept and are destroyed by intense but slightly less powerful ultraviolet-B (UV-B) radiation. A beneficial byproduct of these processes is that most of the ultraviolet radiation that is harmful to plant and animal life on earth is filtered out in the stratosphere and does not reach the earth's surface. Some additional heating of the stratosphere also occurs because ozone absorbs infrared radiation emitted by the earth's surface.

In the troposphere, in contrast, very little of the incoming solar radiation is absorbed directly by the atmosphere. Instead, the shortwave radiation warms the earth's surface, which then transfers heat energy to the atmosphere in a variety of ways – partly through direct contact between the surface and the air, partly through the evaporation and condensation of moisture, but mostly through the emission of longwave infrared radiation, which is absorbed by water vapour and other greenhouse gases in the air such as carbon dioxide, methane, nitrous oxide, and ozone. By re-emitting some of this longwave radiation back towards the earth's surface, these gases retain heat at the bottom of the atmosphere and help to make it warmer. As a result of this greenhouse effect, the earth's average temperature is some 33°C warmer than it would otherwise be and the planet is able to support life *(Figure 4)*.

Because it is heated in this way, air in the troposphere is generally warmest at the surface and becomes cooler with increasing altitude. Since warm air is less dense than cool air, the warm air rises and cooler air moves in at the surface to take its place. This simple convective flow is modified by the earth's rotation, by surface features, and by temperature differences between the equator and the poles. The end result is a rather turbulent layer of the atmosphere in which air circulates in complicated and variable patterns, moving energy and moisture from place to place.


Northern Hemisphere Annual Temperature Deviations
1958 — 1999

Source: J. K. Angell, Air Resources Laboratory, NOAA

Figure 5

Figure 5. The stratosphere has cooled significantly since about 1980, mostly as a result of ozone loss but also because of the accumulation of greenhouse gases in the troposphere. Over the middle latitudes of the Northern Hemisphere, the cooling trend has been noticeably greater in the middle and upper stratosphere than in the lower stratosphere.

Figure 6. Polar stratospheric clouds such as these, photographed over Sweden during the winter of 2000, form in the lower stratosphere when temperatures drop below about –80°C. These clouds support chemical reactions that change stable bromine and chlorine compounds into more active, ozone-destroying substances. Cooling of the stratosphere as a result of climate change and ozone depletion increases the possibility that these clouds will form.

Figure 6

When ozone-depleting chemicals are released into the atmosphere, however, these radiative processes are modified in a variety of ways:

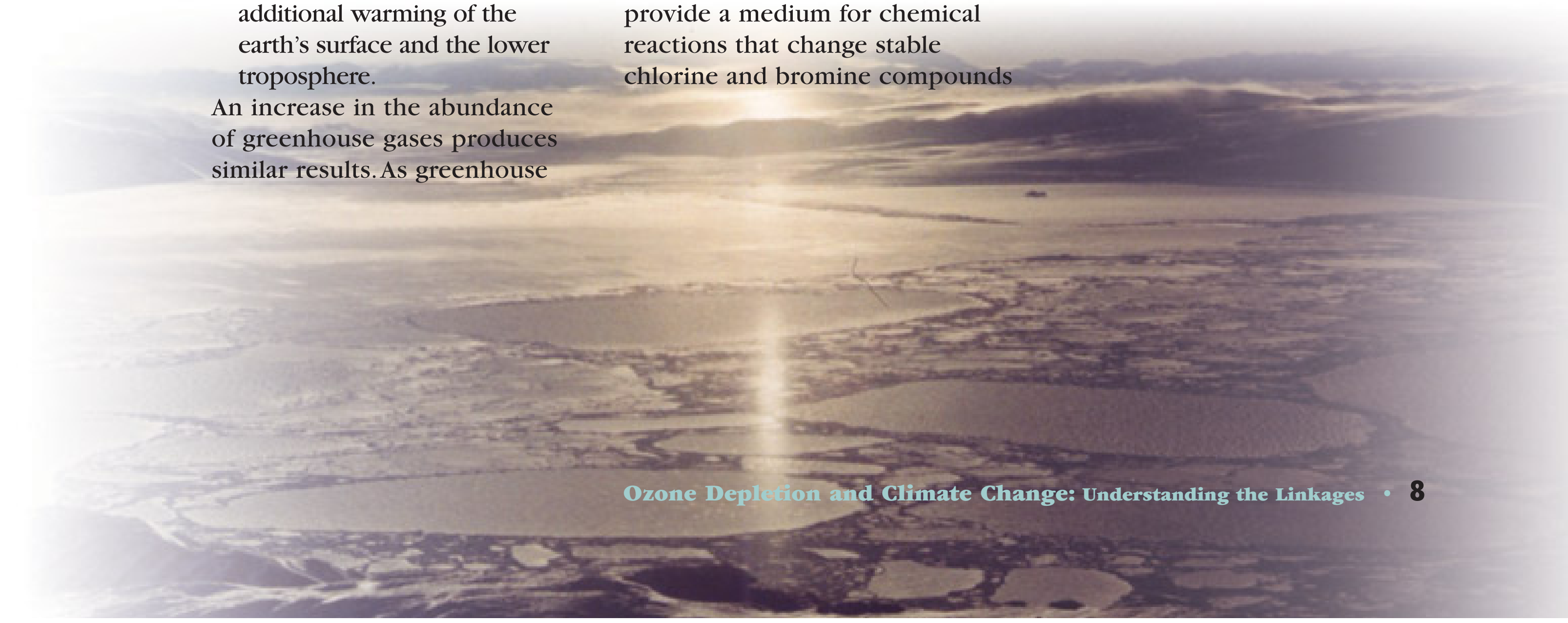
- Because the most effective ozone-destroying substances, such as CFCs and HCFCs are also strong greenhouse gases, the greenhouse effect is enhanced and the earth's surface and the lower troposphere become warmer.
- Warming by CFCs and HCFCs is partially offset, however, by the ozone losses that these chemicals cause in the lower stratosphere. Because ozone is a greenhouse gas, a loss of stratospheric ozone weakens the natural greenhouse effect and cools the stratosphere.
- Thinning of the ozone layer also means that less heat is available to the stratosphere from the absorption of UV-B radiation by ozone molecules. That also has a cooling effect on the stratosphere.
- With fewer ozone molecules available in the stratosphere to absorb UV-B radiation, more of that radiation reaches the ground. That contributes to additional warming of the earth's surface and the lower troposphere.

An increase in the abundance of greenhouse gases produces similar results. As greenhouse gas concentrations increase, the downward flow of longwave radiation increases and the upward flow diminishes, thus exerting a warming force on the troposphere and a cooling force on the stratosphere *(Figure 5)*. Although all greenhouse gases contribute to warming in the troposphere, the effect of individual greenhouse gases on the stratosphere can vary considerably, depending on whether they cause a greater reduction in upward emissions at the bottom of the stratosphere or at the top. Carbon dioxide has the greatest cooling effect on the stratosphere, while CFCs actually have a warming effect on it. Nevertheless, the net result of an increase in concentrations of all greenhouse gases is a cooler stratosphere.

Cooling of the stratosphere has important consequences for ozone depletion, because it contributes to the formation of polar stratospheric clouds (PSCs). These clouds *(Figure 6)*, which form only at extremely low temperatures in the lower stratosphere during the sunless polar winter, provide a medium for chemical reactions that change stable chlorine and bromine compounds into much more active chemicals. It is these chemicals that cause rapid ozone destruction when sunlight returns to the polar regions in the spring. PSCs are a key factor in the severe ozone-depletion that occurs over polar regions in the spring.

The different heating and cooling forces that arise as a result of ozone layer depletion and increasing concentrations of greenhouse gases have been measured globally and studied using computer models. These studies indicate that the net result of all of these contending forces is a warming at the surface (due mainly to increased concentrations of greenhouse gases), a slight or negligible temperature increase in the middle to upper troposphere, and a cooling of the stratosphere (due mainly to the loss of ozone).

However, the effects of greenhouse gases and ozone depletion on the radiative balance are very complex and many uncertainties still remain. A number of research efforts are now under way in an attempt to resolve these uncertainties.



The Dynamics of the Atmosphere

As greenhouse gases accumulate in the atmosphere, they alter temperature differences between different parts of the globe and different levels of the atmosphere and in this way change atmospheric circulation patterns. There is good reason to believe that these circulation changes may be enhancing ozone depletion over the poles by weakening some of the warming forces that act on the polar stratosphere.

One of these forces is known as dynamical heating, and it is associated with a slow general circulation pattern in the stratosphere in which air gradually rises in the tropics, moves towards the poles, and then slowly sinks over the poles *(Figure 7)*. The compression of the air as it descends over the poles causes it to become warmer. The energy that drives this circulation comes from atmospheric waves that penetrate upward from the troposphere. These waves are caused by large-scale atmospheric disturbances that are a result of differences in the way that land and water and different types of land surfaces affect the heating and movement of the air. They tend to be stronger in the Northern Hemisphere because of its greater land area, and thus cause the stratosphere to be warmer on average over the Arctic than it is over the Antarctic.

Atmospheric waves also affect the stability of a feature known as the polar vortex. This is a wind system that circles around each of the poles in winter and isolates the polar stratosphere, preventing the influx of warmer air and ozone from the lower latitudes. Because of this isolation, the area inside the vortex becomes an extremely favourable environment for the formation of PSCs and rapid ozone depletion. Before it finally dissipates in the spring, however, the vortex may occasionally be broken down by the action of strong atmospheric waves, thus allowing a temporary incursion of warmer air that makes conditions less favourable for the rapid destruction of ozone. Because atmospheric wave action is stronger in the Northern Hemisphere, the Arctic vortex tends to be less stable than the Antarctic vortex. Consequently, massive ozone holes, such as those that form regularly over the Antarctic in spring, have not yet occurred in the Arctic.

There is evidence from climate model studies, however, that the warming of the atmosphere near the earth's surface and the

Figure 7. Air in the stratosphere flows poleward from the equator, its movement driven largely by the force of waves created by storms in the troposphere. Air enters the stratosphere at the equator, where the hot surface generates strong upward currents and thunderstorms. The tropopause, the boundary between the two layers, disappears over the poles in winter, allowing stratospheric air to sink back into the troposphere. Although the tropopause tends to block the movement of air between the troposphere and stratosphere, air exchanges in both directions also occur in the mid-latitudes and the polar regions as a result of the actions of planetary waves. The breakup of these waves in the lower stratosphere creates a "surf zone" where some mixing of air occurs.

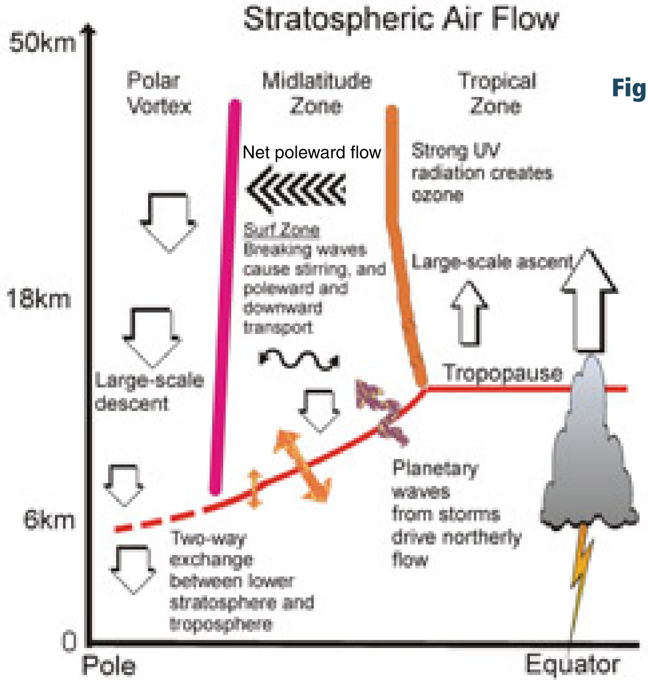


Figure 7

circulation changes resulting from it may be weakening these planetary wave motions and thus their warming effect on the polar stratosphere. If so, this would have the effect of enhancing ozone depletion over both poles, but especially over the Arctic. Such a development would slow the recovery of the ozone layer that should occur over the coming decades as concentrations of ozone-depleting compounds in the stratosphere decline.

Research is also revealing mechanisms through which changes in the composition of the stratosphere can affect the movement of air in the troposphere. Meteorologists have long known that atmospheric pressure patterns at the earth's surface vary with the solar sunspot cycle, but they have had trouble explaining the connection, since the sun's total energy output varies by only about 0.1% across the entire cycle. Recent studies have shown, however, that the variation in solar energy is much greater in the UV-C portion of the spectrum, where the sun's output can vary by as much as 10% during the cycle. This is enough to have a noticeable effect on ozone amounts in the stratosphere, which have been shown to be about 1.5% greater at the solar maximum (when the number of sunspots is greatest) than at the solar minimum (when the number of sunspots is least). These changes in ozone amounts cause corresponding changes in the temperature of the stratosphere, which in turn result in changes in air pressure and wind flow.

Recent computer simulations at NASA's Goddard Institute for Space Studies have shown that changes in stratospheric airflow also affect the flow of energy downward into the troposphere, where it can have an impact on pressure and circulation patterns. Such changes may affect the position of the jet stream, which controls the path of weather systems in the troposphere. A small change in the path of the jet stream can cause very noticeable changes in regional climates. Initial studies with models, for example, suggest that increases in stratospheric ozone could have the effect of directing more storms into Canada. Further study is needed, however, to determine how long-term depletion of the ozone layer is affecting surface weather patterns.

Smog over the lower Fraser Valley

The Chemistry of the Atmosphere

Ozone depletion is largely a matter of atmospheric chemistry, but chemical processes play an important part in climate change as well, particularly in the generation and breakdown of some greenhouse gases. The chemistry of ozone depletion and that associated with climate change interact significantly in at least two ways.

One way is through photochemistry – chemical processes that are driven by energy from the sun. Many reactions in the atmosphere are of this kind, and the amount of ozone in the stratosphere affects the rate at which these reactions occur, because it determines how much of the sun's high-energy UV-B radiation reaches the atmosphere near the ground. This has important consequences for climate change, because ground-level or tropospheric ozone, a significant greenhouse gas and a major constituent of smog, is photochemically produced *(Figure 8)*. As the ozone layer thins and more ultraviolet radiation reaches the earth's surface, the photochemical reactions that produce ground-level ozone can proceed more vigorously. Average ozone amounts over Canada are now about 6% below pre-1980 values. Scientists estimate that this decrease has resulted in a corresponding increase of about 7% in the amount of UV-B radiation reaching the earth's surface. Recent computer model research indicates that an increase in UV radiation will result in an increase in ground level ozone in polluted urban areas where there are high concentrations of nitrogen oxides, carbon monoxide, and hydrocarbons.

The other linkage involves a short-lived, highly reactive molecule known as the hydroxyl radical (OH), which is produced by the photochemical breakdown of ozone in the presence of water vapour. OH is an atmospheric scavenger that reacts with many pollutants and removes them from the atmosphere. These include the greenhouse gas methane as well as ozone-depleting methyl chloroform and gases such as hydrochlorofluorocarbons (HCFCs) and hydrofluorocarbons (HFCs) that are both ozone depleters and greenhouse gases. In addition, OH reacts with a host of other pollutants, including carbon monoxide, volatile organic compounds, and various oxides of nitrogen. There is some concern that the demands on the hydroxyl radical in a heavily polluted atmosphere may lead to a decline in OH concentrations and thus a reduction in the efficiency with which methane and various ozone-depleting compounds are removed from the atmosphere. Slower removal of these compounds would intensify the process of climate change and slow the recovery of the ozone layer. Although global hydroxyl amounts cannot be estimated with a high degree of certainty, some recent evidence suggests that a significant decline in hydroxyl concentrations has taken place during the 1990s and that further declines can be expected in the coming decade.

Figure 8

Source: Ontario Ministry of the Environment (ozone) and Environment Canada (UV Index)

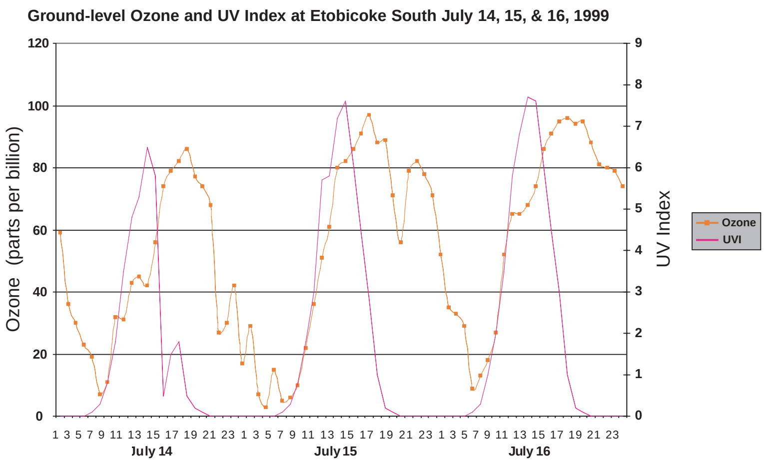


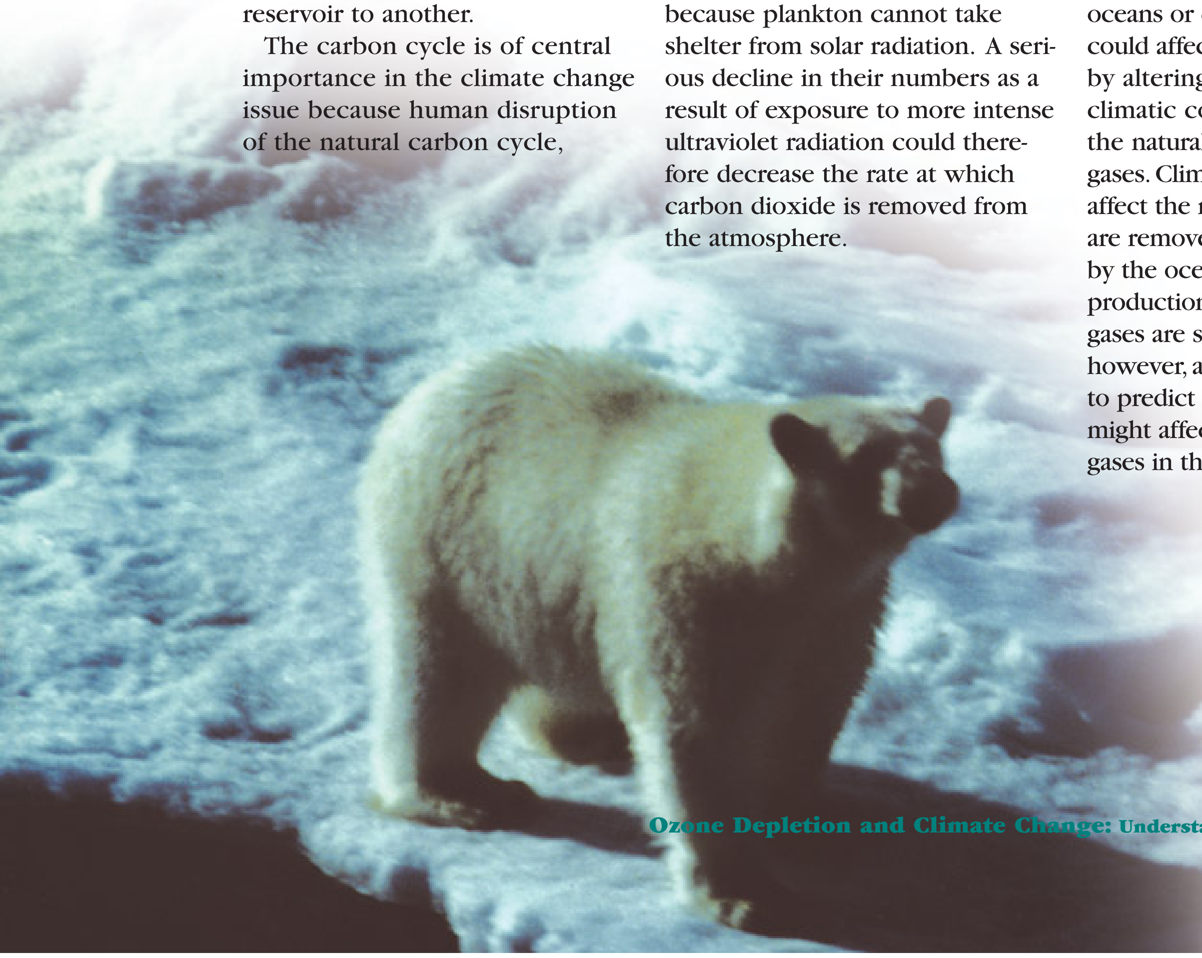
Figure 8. Ultraviolet-B radiation provides the energy for the chemical reactions that lead to the formation of ground-level ozone, which is both a major component of smog and a greenhouse gas. Measurements taken during a smog episode in Toronto in July 1999 show a close relationship between UV levels and ground-level ozone concentrations. Computer models suggest that higher levels of UV-B could lead to an increase in ground-level ozone formation in highly polluted areas. Such an increase would not only make smog problems worse but would also add to warming from greenhouse gases.

Biogeochemical Linkages:
The Impact of Increased UV Radiation

Changes in climate and changes in the intensity of ultraviolet radiation can both have substantial impacts on the biological, geological, chemical, and physical processes that control the exchange of matter and energy between the major components of the environment – the atmosphere, the biosphere, the hydrosphere, and the lithosphere. Probably the most familiar of these exchanges is the carbon cycle, in which carbon is transferred continuously between the atmosphere, the oceans, living things, and the rocks and soils, changing from an almost purely elemental form, as in charcoal or anthracite, to a simple gas like carbon dioxide, or to one of numerous organic compounds as it moves from one environmental reservoir to another.

The carbon cycle is of central importance in the climate change issue because human disruption of the natural carbon cycle, through the burning of fossil fuels and the clearing of forests, is largely responsible for the modern increase in atmospheric concentrations of carbon dioxide, the most abundant anthropogenic greenhouse gas. One of the more important links in the carbon cycle from an atmospheric perspective is the so-called "marine biological pump." This is a process in which plankton, the microscopic plants and animals that live near the surface of the oceans and freshwater lakes, remove carbon from the air and then transfer it to the ocean bottoms and lakebeds when they die. Ozone depletion, particularly severe episodes such as the spring ozone holes in the Antarctic, present a potentially serious threat to this process, because plankton cannot take shelter from solar radiation. A serious decline in their numbers as a result of exposure to more intense ultraviolet radiation could therefore decrease the rate at which carbon dioxide is removed from the atmosphere.

Similarly, biological changes initiated by changes in climate might have some effect on ozone depletion. Methyl chloride and methyl bromide, for example, are two ozone-depleting compounds whose production and use are now being phased out under the Montreal Protocol. However, because natural sources of these gases are larger than the human industrial sources, anything affecting the ecosystems and natural processes that produce these gases could also have consequences for the ozone layer. Much has yet to be learned about these natural sources, but coastal marshes appear to be important contributors. Fungi, crops such as rapeseed, and soils rich in organic matter are also thought to be substantial sources. Warming of the atmosphere and oceans or changes in sea level could affect all of these sources by altering the ecosystems and climatic conditions that support the natural production of these gases. Climate change could also affect the rate at which these gases are removed from the atmosphere by the oceans. Studies of the natural production and removal of these gases are still in their early stages, however, and it is not yet possible to predict how climate change might affect the quantities of these gases in the atmosphere.



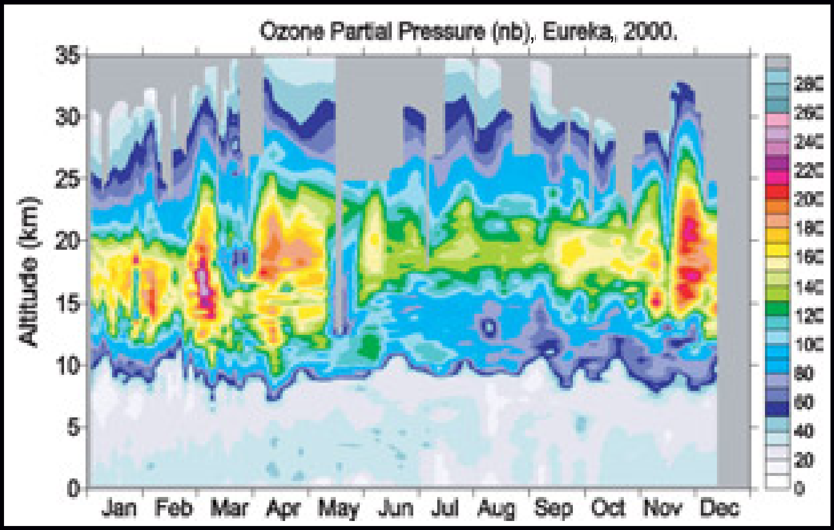


Figure 9

Figure 9. Ozonesonde data collected over Eureka in 2000 show the annual ozone cycle, with highest levels occurring in the winter and early spring and lowest levels in summer. The plot also shows unusually low levels of ozone in late March and early April between about 15 and 20 km. This depleted area is believed to be the result of high levels of chlorine and bromine in a very cold Arctic stratosphere.

Figure 10. At Environment Canada's observatory at Alert on Ellesmere Island in the High Arctic, background concentrations of greenhouse gases, ozone-depleting substances, and aerosols are monitored daily.

Figure 10

Canadian Research and Monitoring

Through its Experimental Studies Division, Environment Canada's Air Quality Research Branch is involved in a number of activities that are contributing to a better understanding of ozone depletion and its interactions with climate change. Some of these activities are research projects designed to provide new knowledge about atmospheric constituents and processes. Others are long-term monitoring programs whose function is to provide a long and continuous record of atmospheric conditions that can be used as a reliable basis for identifying trends and changes in the atmosphere's composition and behaviour. These activities, which also assist in evaluating the effectiveness of controls under the Montreal Protocol and help to set strategies for the future, are carried out through the following key facilities and programs.

Ground-based ozone monitoring and ozonesondes

Canadian scientists have been using ground-based instruments to measure total ozone amounts since the 1950s. These measurements are now taken at 12 sites across Canada, using the Canadian-developed Brewer ozone spectrophotometer. Three of the instruments are in the High Arctic, at Resolute Bay, Eureka, and Alert. The Brewer network is a fundamental source of information about changes in the state of the stratosphere. At a more practical level, it also provides data for use in producing UV Index reports and forecasts.

These ground-based measurements are supplemented by data gathered by small balloon-borne sensors known as ozonesondes. Weighing about 3 kg, these instrument packages provide continuous measurements of ozone concentrations up to an altitude of about 20 km *(Figure 9)*.

Arctic observatories

In 1992 Environment Canada built the High Arctic stratospheric ozone observatory near the Eureka weather station on Ellesmere Island. The observatory is the main centre for atmospheric research in the Arctic and is also a primary component of the international Network for the Detection of Stratospheric Change, a series of high quality, ground-based stations that measure the physical and chemical state of the stratsphere. The Eureka observatory operates instruments that measure ozone, nitrogen dioxide, and other substances important to atmospheric chemistry. Canada also maintains an observatory at Alert on Ellesmere Island *(Figure 10)* that provides continuous monitoring of background concentrations of greenhouse gases, ozone-depleting substances, and aerosols (atmospheric particles). Analysis of this data provides information about the long-term variability of these substances and furthers understanding of the impact of human activities on the atmosphere.

The Alert observatory is an official baseline station for the World Meteorological Organization's Global Atmosphere Watch (GAW) program and is one of about 20 such stations around the world. The objective of the GAW program is to make available ongoing background concentration measurements of selected atmospheric constituents and related physical conditions for every major region of the globe. The Canadian Baseline Program began at Alert in 1975 with simple measurements of carbon dioxide. By 1998, the program had expanded to include measurements for other greenhouse gases, such as methane, ozone, and chlorofluorocarbons.

Radiation studies (Bratt's Lake Observatory)

The Bratt's Lake Observatory, located about 20 km south of Regina, is the Canadian link in the World Climate Research Programme's Baseline Solar Radiation Network. This is a network of approximately 40 stations, spread across all seven continents that take very accurate measurements of solar and infrared radiation *(Figure 11)*. Since shortwave radiation from the sun and the longwave infrared radiation emitted by the earth's surface and atmosphere provide the energy that drive the earth's climate system, this information can provide evidence of how changes in radiative energy flows are affecting regional and global climate change. The Bratt's Lake

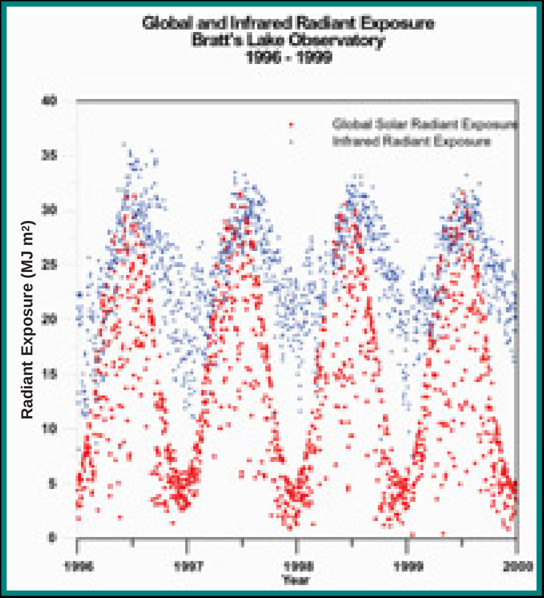


Figure 11
Source: B. Arthur, Environment Canada

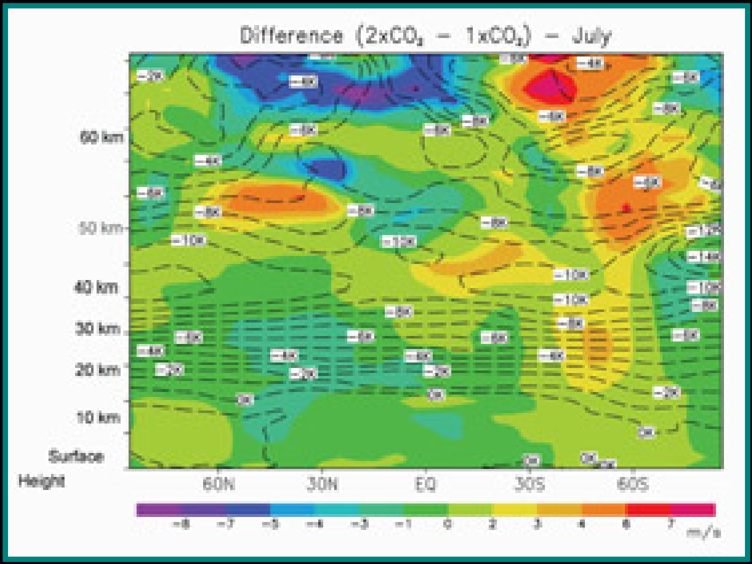


Figure 12
Source: de Grandpré 2001

Figure 11. Measurements of daily amounts of solar and infrared radiation reaching the earth's surface should allow the detection of trends over time. The four-year plot shown here indicates little change in either solar or infrared radiation from one summer to another. Over the four winters, however, solar radiation has declined and infrared radiation has increased. These changes may be the result of increased cloud cover during the winters. Many more years of data will be needed, however, before it can be determined whether this pattern is part of a longer-term trend or simply a result of the climate's natural short-term variability.

Figure 12. While increasing concentrations of greenhouse gases lead to warming at the earth's surface, they cause cooling in the stratosphere. The plot shown here shows the potential effects of a doubling of atmospheric carbon dioxide concentrations on summer temperatures and winds in the stratosphere, as estimated by the Canadian Middle Atmosphere Model. Temperature changes are indicated by the dashed lines in degrees Kelvin (1°K is the same as 1°C, but the Kelvin scale starts at absolute zero or –273°C). Wind speed changes are shown by the coloured areas. The model shows the greatest cooling occurring near the top of the stratosphere, with temperatures in the upper stratosphere over the Antarctic cooling by as much as 14ºK.

Figure 13. The graph shows the average daily amount of ultraviolet-B radiation received at Toronto, Edmonton, and Churchill for each year since 1965. Values from the late 1980s on are derived from actual measurements. Earlier values are estimates derived from related meteorological information by a statistical model. UV-B amounts begin to increase noticeably at all locations in the early 1980s, shortly after the thinning of the ozone layer is believed to have started. The increase at Churchill, however, has been greater than at the other two locations. This is thought to be due to climatic factors, although it is as yet unclear whether these are related to long-term climate change.

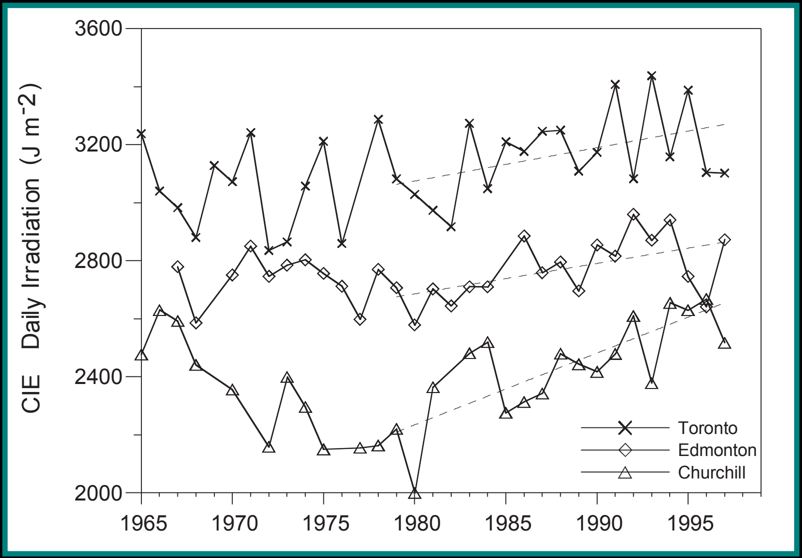


Figure 13
Source: V. Fioletov,
Environment Canada

Observatory, which has been operational since the mid-1990s, provides researchers with a relatively non-polluted environment in an area where the climate is expected to change significantly as greenhouse gases increase.

Balloon-based ozone research

Over the past 20 years, Environment Canada has worked with the Canadian Space Agency and partners in the universities and industry to collect data about reactive nitrogen compounds, chlorine and bromine compounds, ozone, aerosols, and other substances that play a critical role in the chemistry of the upper troposphere and the stratosphere. This work is coordinated under the Middle Atmosphere Nitrogen Trend Assessment program or MANTRA. To collect the data, researchers use large polyethylene balloons, about 20 stories high, that carry instruments to altitudes of, typically, 30–40 km. The instruments scan the earth's horizon at various altitudes and record the spectra produced by scattered sunlight. At the end of the flight, the instrument payload is separated from the balloon and descends to earth by parachute, where it can be recovered. Analysis of the recorded data then provides information about the chemical composition of the atmosphere at different altitudes. Information from the MANTRA flights not only contributes to a better understanding of stratospheric processes but also helps governments determine the effectiveness of controls on ozone-depleting substances under the Montreal Protocol.

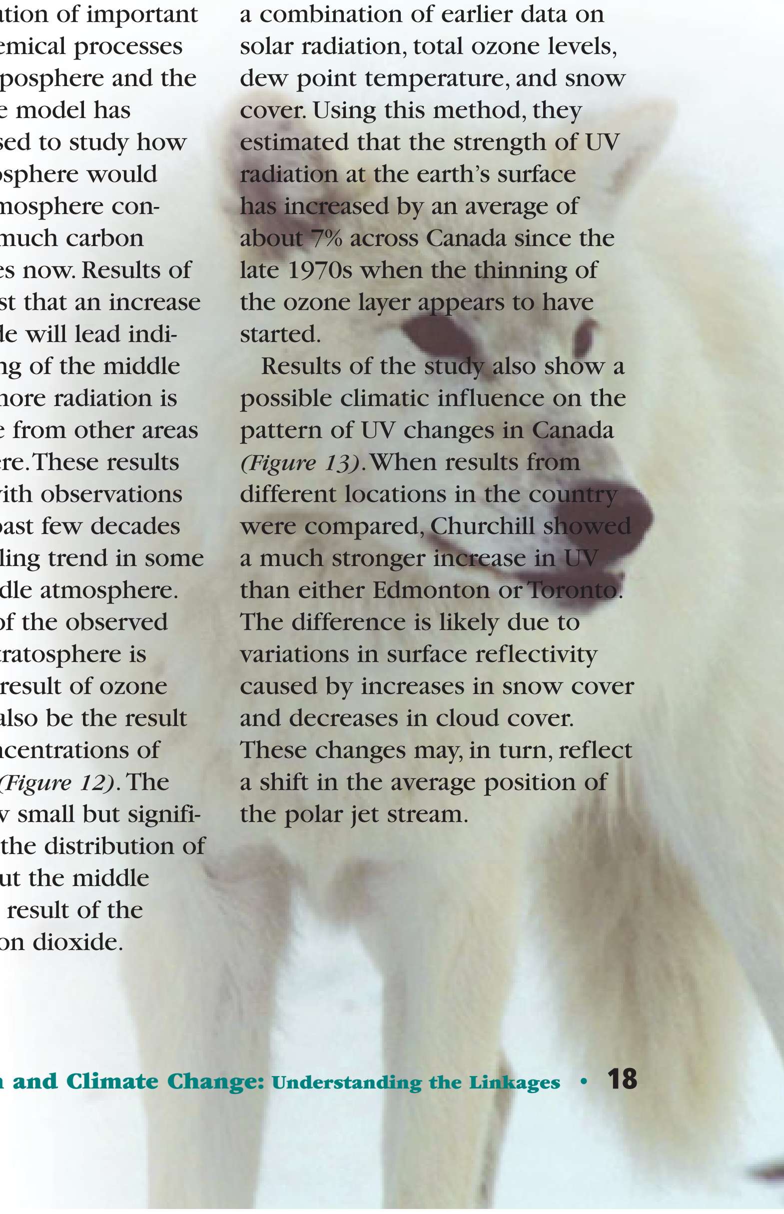
The Canadian Middle Atmosphere Model

Computer modelling is an important tool that helps researchers improve their understanding of atmospheric processes, study the impact of natural and human-induced changes in the atmosphere, and make long-term predictions about atmospheric change. The Canadian Middle Atmosphere Model (CMAM), developed jointly by scientists from Environment Canada and the universities, provides a sophisticated representation of important physical and chemical processes in the upper troposphere and the stratosphere. The model has recently been used to study how the middle atmosphere would change if the atmosphere contained twice as much carbon dioxide as it does now. Results of this study suggest that an increase in carbon dioxide will lead indirectly to a cooling of the middle atmosphere as more radiation is emitted to space from other areas of the atmosphere. These results are consistent with observations taken over the past few decades that show a cooling trend in some parts of the middle atmosphere. Although most of the observed cooling of the stratosphere is thought to be a result of ozone loss, part could also be the result of increased concentrations of carbon dioxide *(Figure 12)*. The results also show small but significant changes in the distribution of ozone throughout the middle atmosphere as a result of the increase in carbon dioxide.

UV Climatology and Research

Measurements of the strength of UV radiation at the earth's surface were not taken on a regular basis in Canada until the introduction of the Brewer spectrophotometer in the late 1980s. When Environment Canada researchers set out a decade later to estimate long-term trends in UV radiation, the length of the data record was still too short to yield reliable results. To overcome this problem, they developed statistical models that estimated the UV irradiance from a combination of earlier data on solar radiation, total ozone levels, dew point temperature, and snow cover. Using this method, they estimated that the strength of UV radiation at the earth's surface has increased by an average of about 7% across Canada since the late 1970s when the thinning of the ozone layer appears to have started.

Results of the study also show a possible climatic influence on the pattern of UV changes in Canada *(Figure 13)*. When results from different locations in the country were compared, Churchill showed a much stronger increase in UV than either Edmonton or Toronto. The difference is likely due to variations in surface reflectivity caused by increases in snow cover and decreases in cloud cover. These changes may, in turn, reflect a shift in the average position of the polar jet stream.



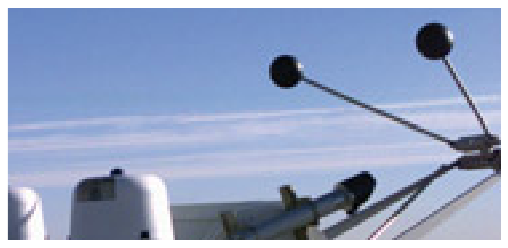
Implications for Policy

Thanks to the Montreal Protocol of 1987 and the various amendments made to it in subsequent years, concentrations of CFCs, halons, and other major ozone-depleting substances in the atmosphere are now decreasing. As these concentrations decline further over the rest of century, the effects of stratospheric ozone depletion on climate change can be expected to diminish gradually. Full compliance with the Protocol would see concentrations of ozone-depleting substances fall by the end of the century to the point where they would no longer be a significant threat to the ozone layer. However, it is unlikely that full compliance will be achieved; therefore, recovery of the ozone layer will almost certainly take longer. The effects of ozone depletion on climate change will also continue longer if CFCs are replaced by substitutes such as hydrofluorocarbons (HFCs), which are also potent greenhouse gases. The greenhouse effect of these gases, moreover, would be in addition to that of older ozone-depleting substances that remain in the atmosphere.

While atmospheric concentrations of ozone-depleting substances are declining, concentrations of important greenhouse gases, such as carbon dioxide and methane, that have no direct connection with ozone depletion, continue to increase. Higher concentrations of these gases may have the effect of prolonging the recovery of the ozone layer, mainly through their effects on stratospheric cooling and the formation of polar stratospheric clouds. Recent computer simulations support this notion and suggest that expected increases in greenhouse gas concentrations could cause severe polar ozone depletion to continue for about 10–20 years longer than it would if concentrations of greenhouse gases had remained at earlier levels. These studies are very preliminary, however, and further investigation with more refined models is needed.

From a policy perspective, it is clear that actions to mitigate global warming can have positive effects on ozone depletion and vice versa. However, care must be taken to avoid solutions to one problem that make the other worse. Policy makers and scientists are now wrestling with this difficulty as they look for long-term alternatives to CFCs, halons, and other ozone-depleting substances whose use has been phased out under the Montreal Protocol. Current restrictions on HCFCs, which have a lower ozone-depleting potential than CFCs but are strong greenhouse gases, illustrate acceptance of the need to consider the implications for both issues.

But further problems remain. What, in particular, should we do about HFCs and any other greenhouse gases now being promoted as alternatives to CFCs and HCFCs? Although concentrations of these gases in the atmosphere are as yet fairly low, they are expected to increase significantly over time if the use of these substances is not controlled. Canada has adopted the position that the use of HFCs should be restricted to the replacement of ozone-depleting substances. Canada also wants emissions of HFCs controlled through mandatory recovery and recycling, safe disposal, and the use of other emission control measures. At the tenth meeting of the Parties to the Montreal Protocol and the Fourth Conference of the Parties to the Climate Convention, the technical and scientific authorities of each body were asked to provide guidance on limiting emissions of HFCs and other greenhouse gases that might be used as CFC replacements. Their investigation of the options is now under way.

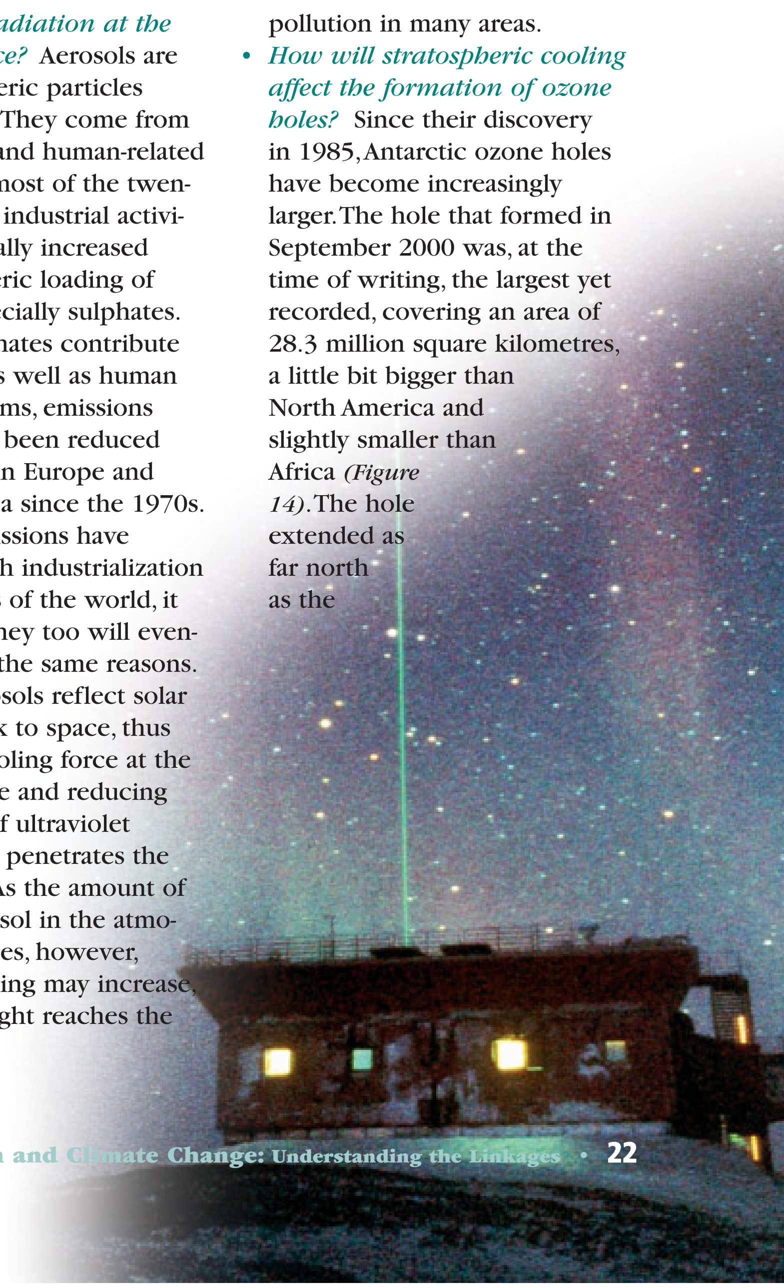


At the Bratt Lake Observatory, the Brewer spectrophotometer in the foreground measures ultraviolet radiation and the depth of the ozone layer while the solar trackers in the background measure diffuse solar radiation.

The Research Agenda

On the research side, more needs to be known about how the troposphere and the stratosphere interact. The following are some of the more important questions now being pursued.

- *What are the major coupling mechanisms between the troposphere and the stratosphere and how do they affect climate?* We know, for example, that the vertical temperature structure of the troposphere is sensitive to changes in the vertical temperature structure of the stratosphere. We also know that waves propagating upwards from the troposphere reach into the stratosphere and affect temperatures and circulation there. Similarly, waves generated in the stratosphere can penetrate downwards and affect weather in the troposphere. Further study of such mechanisms will improve our understanding of how conditions in the stratosphere affect climate in the troposphere and vice versa.
- *How do changes in the vertical temperature structure of the troposphere and stratosphere affect climate?* During the past three decades, researchers have measured a cooling of the stratosphere and a warming of the lower troposphere. These changes could affect the height of the tropopause, the boundary between the troposphere and the stratosphere. Such a change could, in turn, affect the height of convection currents within the troposphere, such as those associated with thunderstorms, and could possibly affect the intensity of those storms. It might also alter the positions of the planet's jet streams and thus the movement of weather systems.
- *How will changes in tropospheric aerosol concentrations affect solar radiation at the earth's surface?* Aerosols are tiny atmospheric particles and droplets. They come from both natural and human-related sources. For most of the twentieth century, industrial activities substantially increased the atmospheric loading of aerosols, especially sulphates. Because sulphates contribute to acid rain as well as human health problems, emissions of them have been reduced substantially in Europe and North America since the 1970s. Although emissions have increased with industrialization in other parts of the world, it is expected they too will eventually fall for the same reasons. Sulphate aerosols reflect solar radiation back to space, thus exerting a cooling force at the earth's surface and reducing the amount of ultraviolet radiation that penetrates the atmosphere. As the amount of sulphate aerosol in the atmosphere declines, however, surface warming may increase, as more sunlight reaches the earth's surface. In addition, with more sunlight more ultraviolet radiation will also reach the earth's surface. Since ultraviolet radiation contributes to the formation of ground-level ozone, which is both a greenhouse gas and a major constituent of smog, reduction in sulphate concentrations could further intensify greenhouse warming as well as lead to more ozone pollution in many areas.
- *How will stratospheric cooling affect the formation of ozone holes?* Since their discovery in 1985, Antarctic ozone holes have become increasingly larger. The hole that formed in September 2000 was, at the time of writing, the largest yet recorded, covering an area of 28.3 million square kilometres, a little bit bigger than North America and slightly smaller than Africa *(Figure 14)*. The hole extended as far north as the



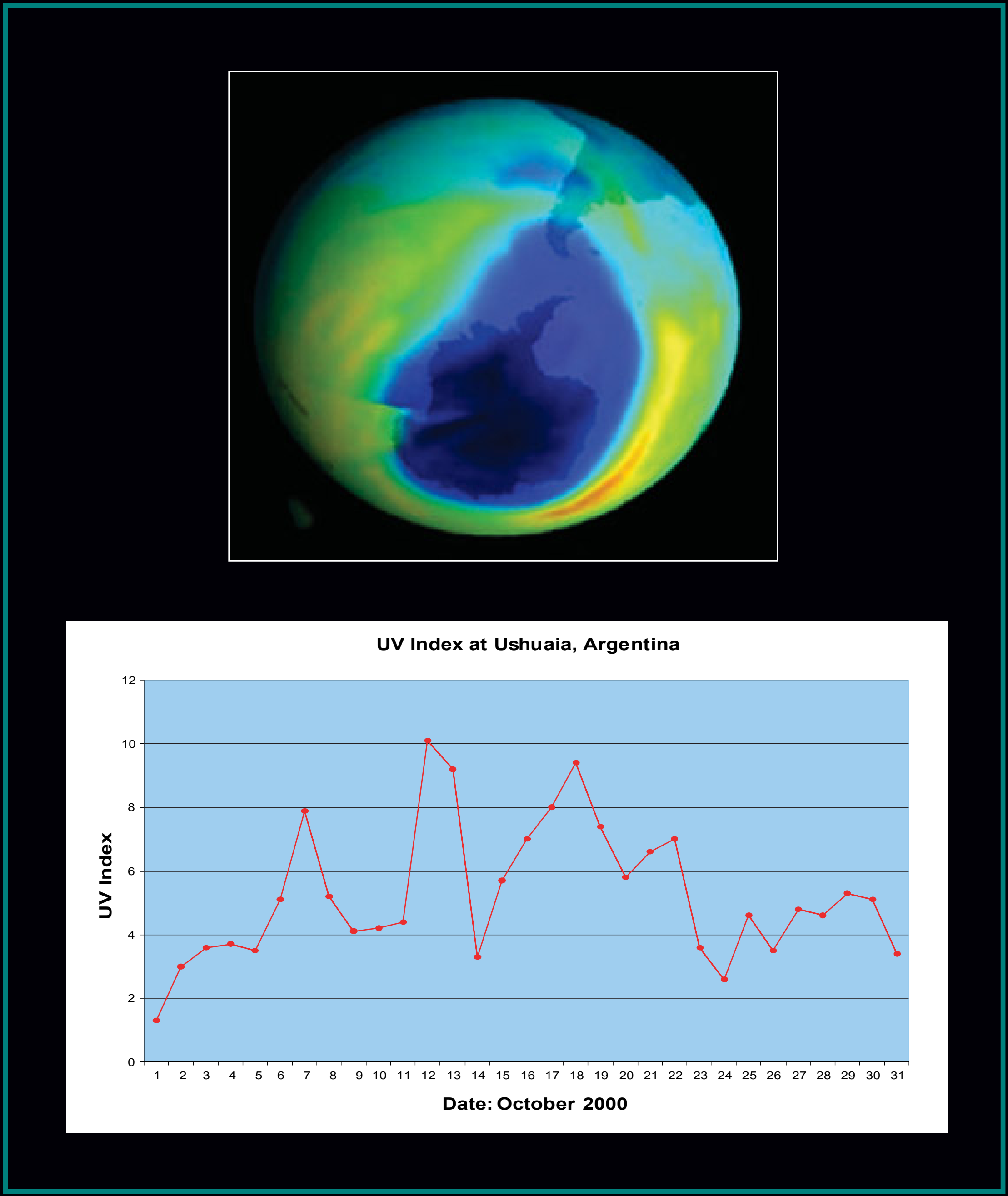


Figure 14
Source: NASA (top); Servicio Meteorológico Nacional, Argentina (bottom)

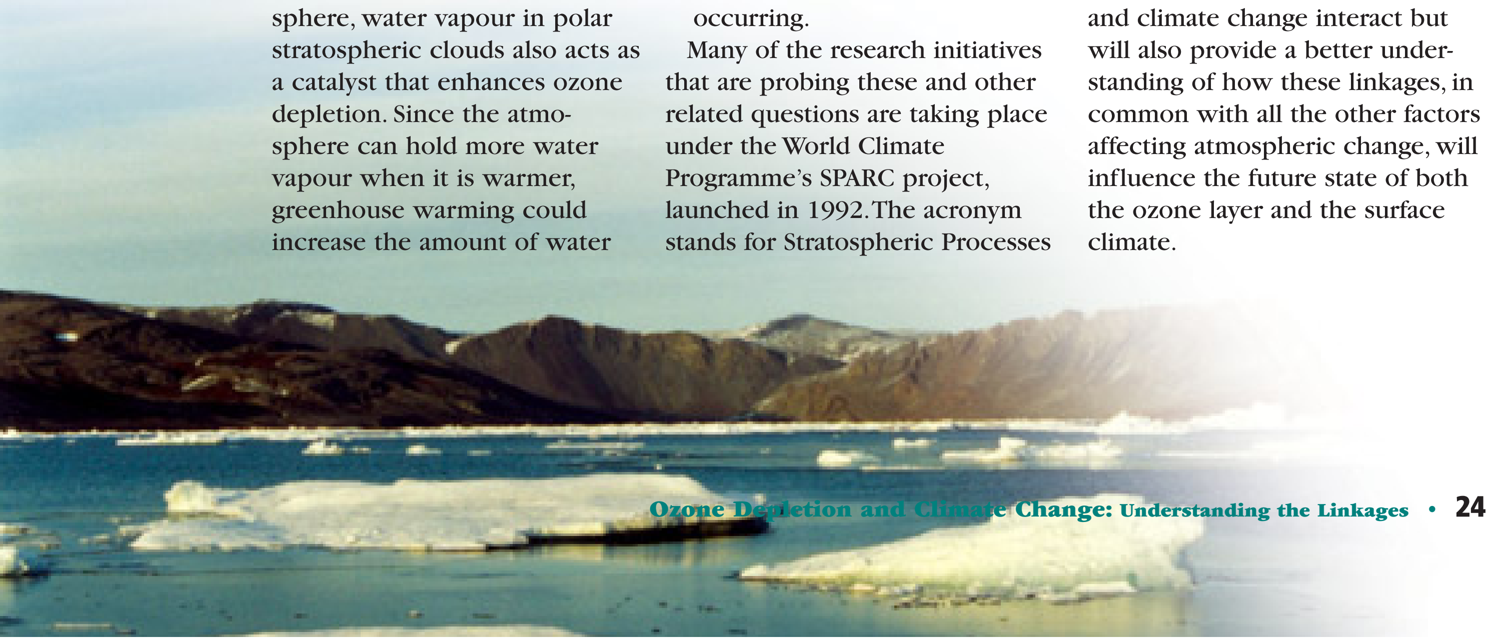
Figure 14. The Antarctic ozone hole reached its largest extent yet in October 2000, and for the first time extended over sizeable settled areas in southern South America. UV Index values in Ushuaia, Argentina, were close to or greater than 8 on five different days and reached 10.1 on October 12. UV Index values for October in Ushuaia are normally around 4. Values greater than 10 are usually found only in tropical areas.

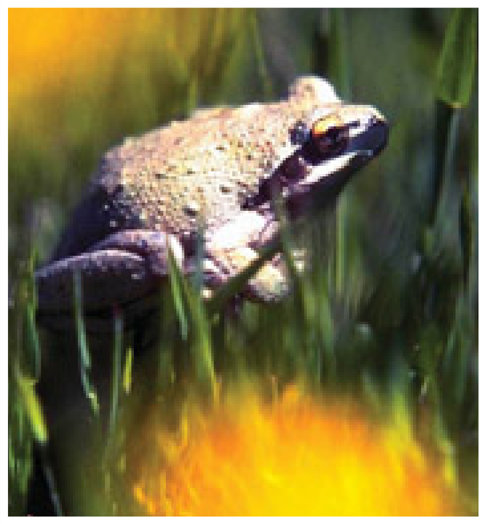
southern tip of South America, subjecting Ushuaia, Argentina and the city of Punta Arenas in Chile, with a population of over 100,000 people, to very high ultraviolet radiation levels for that time of year. Since the early 1990s, severe ozone depletion has also been detected in some years in the Arctic stratosphere. In the spring of 2000, for example, ozone levels in the Arctic were depleted by almost 60% at an altitude of 18 km. Ozone depletion over the poles should decrease as the quantity of ozone-depleting substances in the atmosphere diminishes, but researchers need to know more about how changes in greenhouse gas and stratospheric ozone concentrations will affect temperatures in the polar stratosphere before they can confidently predict future trends in ozone hole formation.

- *How will changes in the amount of water vapour in the atmosphere affect climate change and ozone depletion?* Water vapour is the most abundant greenhouse gas in the atmosphere. In the stratosphere, water vapour in polar stratospheric clouds also acts as a catalyst that enhances ozone depletion. Since the atmosphere can hold more water vapour when it is warmer, greenhouse warming could increase the amount of water vapour in the atmosphere and that could have important consequences for both climate and ozone depletion. Scientists therefore need to determine whether the amount of water vapour in the atmosphere is actually increasing and, if so, how it is distributed in different parts of the atmosphere.
- *How will decreases in the atmospheric loading of chlorine and bromine affect climate change and ozone depletion?* As the amount of chlorine and bromine in the stratosphere decreases, ozone concentrations in the stratosphere should gradually increase towards natural levels. At the same time, however, atmospheric temperatures will be affected as the cooling effect of ozone loss and the warming effect of ozone-depleting greenhouse gases diminish. Data from monitoring systems that track ozone concentrations and other important atmospheric characteristics will help to verify that expected changes are taking place and expand our understanding of other changes that may be occurring.

Many of the research initiatives that are probing these and other related questions are taking place under the World Climate Programme's SPARC project, launched in 1992. The acronym stands for Stratospheric Processes and their Role in Climate, and the project embraces a number of studies designed to improve scientific understanding of the physical, chemical, and radiative connections between the troposphere and the stratosphere and their effects on climate. SPARC's current research agenda includes such areas as stratospheric indicators of climate change, the physics and chemistry of ozone depletion, the influence of ozone changes on climate, energy and gas exchanges between the troposphere and the stratosphere, and atmospheric waves.

Another important area of activity, and one in which SPARC is heavily involved, focuses on improving the way in which computer models of the atmosphere represent important linkages between ozone depletion and climate change. These improvements include better representation of the stratosphere in the general circulation models used to study climate change and better representation of atmospheric waves. Inclusion of these refinements will give us not only greater insight into how ozone depletion and climate change interact but will also provide a better understanding of how these linkages, in common with all the other factors affecting atmospheric change, will influence the future state of both the ozone layer and the surface climate.



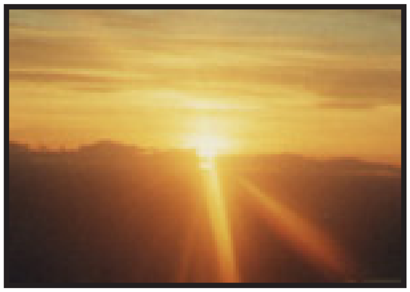


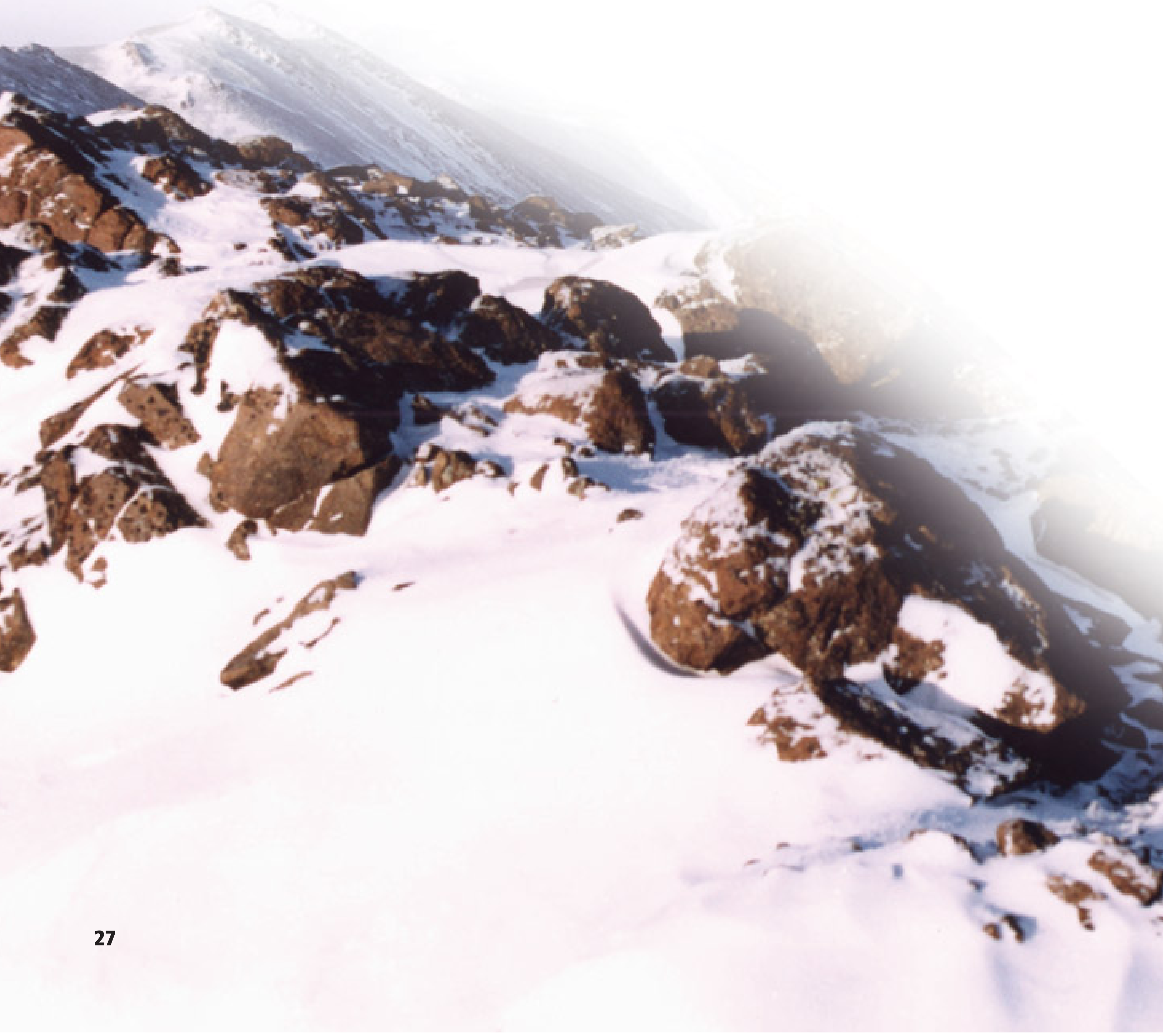
An integrated approach to atmospheric issues is also necessary because ecosystems and human health are affected not by just one of these issues but by all of them. The puzzling decline of amphibian populations, for example, may be a result of multiple stresses related to acid rain, persistent organic pollutants, and a number of other pollution issues. Increased UV levels (caused by ozone depletion) and changes in shallow water levels (caused by climate change) may also be contributing to the decline, as they make amphibian eggs more susceptible to water mould, which kills the embryos.

Making Connections

Increasingly both science and policy are being driven by the recognition that the atmosphere cannot be seen as a collection of separate compartments in which different things happen in isolation. Instead, researchers and policy makers are adopting a more comprehensive view of the atmosphere, seeing it as a single dynamic whole whose state at any given time depends on a maze of interactions not only between its different parts and processes but also with those of other parts of the ecosphere.

To take proper account of these interactions, atmospheric scientists are increasingly thinking outside the confines of their particular specialties and collaborating more closely with experts in other areas. The evolution of integrated approaches to ozone depletion and climate change – and to other atmospheric issues as well – is now enhancing our ability to understand and moderate the enormous changes that human activities have imposed on the earth's atmosphere over the past two centuries. Not only will these approaches help us deal more effectively with today's problems, but they will also give us a much better chance of anticipating and controlling any further human threats to the atmosphere that might occur in the future.





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