ARCTIC OZONE:

The Sensitivity of the Ozone Layer to Chemical Depletion and Climate Change

by
A. Fergusson and D.I. Wardle

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The Cover
Front: An aerial view of the Eureka Stratospheric Ozone Observatory, Ellesmere Island *(John Bird)*.
Back: An observer records weather data at Alert, Ellesmere Island *(Brent Colpitts)*.
Back (insert): Launching a weather balloon at Resolute Bay, Cornwallis Island.

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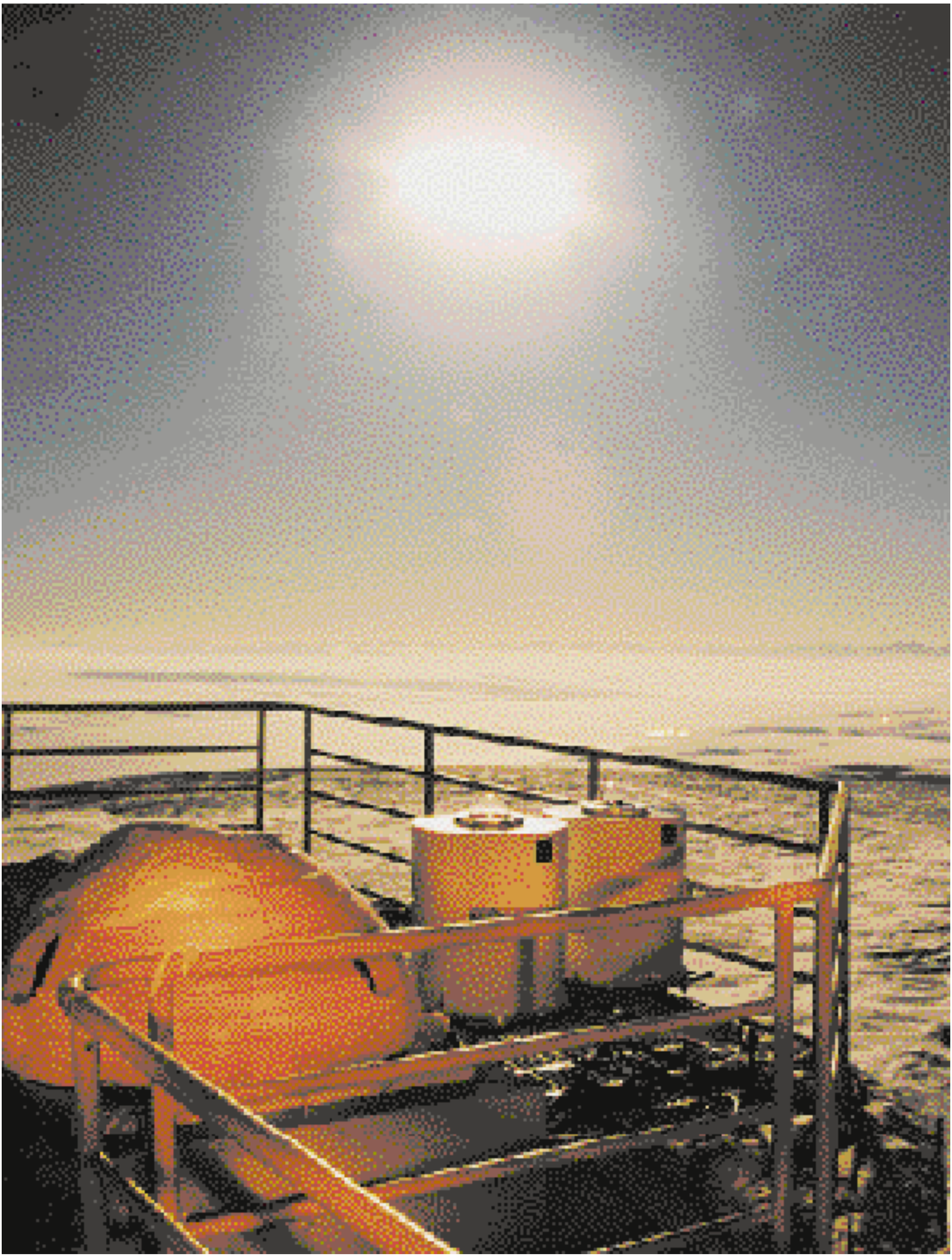
TABLE OF CONTENTS



SUMMARY

Extensive ozone losses have occurred over the Arctic in the 1990s, and there is some concern that serious depletion episodes could become even more frequent over the next 10–20 years. Concentrations of ozone-depleting chemicals will be at or near peak levels during that time, and changes to the Arctic stratosphere arising from global warming could create more favourable conditions for depletion processes.

Large increases in ultraviolet radiation at the earth's surface as a result of deep ozone depletion could be highly damaging to sensitive Arctic life forms. Ozone losses over the Arctic could also reduce ozone amounts over the middle latitudes as a result of the mixing of air masses.

Deep ozone losses over both the Arctic and Antarctic are the result of special conditions that occur over polar regions in the winter and early spring. As winter arrives in each hemisphere, a vortex of winds develops around the pole and isolates the polar stratosphere. Without milder air flowing in from the lower latitudes and in the absence of sunlight, air within the vortex becomes very cold. At temperatures of –80°C or less, clouds made up of ice, nitric acid, and sulphuric acid begin to form in the stratosphere. These are called polar stratospheric clouds (PSCs), and they give rise to a series of chemical reactions that destroy ozone far more effectively than the reactions that take place in warmer air. The destruction of ozone begins with the return of sunlight in the spring and continues rapidly until the vortex dissipates and warmer temperatures prevent the formation of PSCs.

Over the Antarctic, these processes commonly lead to the formation of a massive ozone hole. Over the Arctic, however, ozone amounts have not yet fallen to the very low levels observed in Antarctica. This is partly because the Arctic has more ozone to start with, but it is also a result of the more variable atmospheric circulation of the Northern Hemisphere, which makes the Arctic vortex less stable. As a result, incursions of air from the south often keep the Arctic stratosphere too warm for PSC formation.

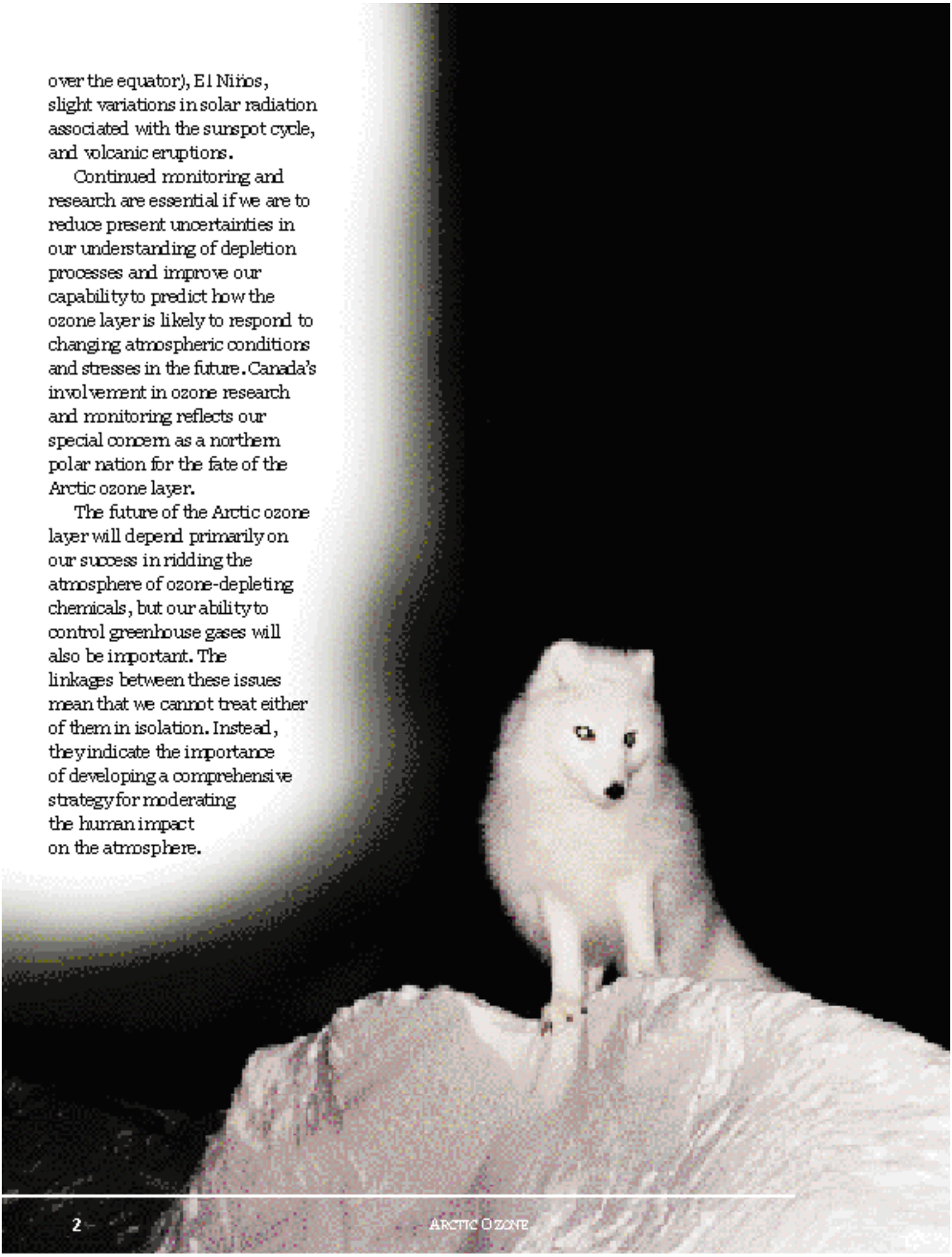
Arctic ozone depletion could be further enhanced over the next few decades, however, as a result of climatic changes caused by increasing accumulations of greenhouse gases such as CO_2 in the atmosphere. Although the build-up of these gases causes warming at the earth's surface, it also contributes to cooling in the stratosphere. Since temperatures in the Arctic stratosphere often come within a few degrees of the threshold for PSC formation, further cooling of the stratosphere could cause PSCs to form more frequently and increase the severity of ozone losses. Preliminary studies with atmospheric models suggest that this effect could delay a recovery of the Arctic ozone layer by a decade or more.

A number of natural phenomena also affect Arctic ozone levels over time periods ranging from days to years. These include weather systems, the quasi-biennial oscillation (a periodic reversal of the direction of stratospheric winds

over the equator), El Niños, slight variations in solar radiation associated with the sunspot cycle, and volcanic eruptions.

Continued monitoring and research are essential if we are to reduce present uncertainties in our understanding of depletion processes and improve our capability to predict how the ozone layer is likely to respond to changing atmospheric conditions and stresses in the future. Canada's involvement in ozone research and monitoring reflects our special concern as a northern polar nation for the fate of the Arctic ozone layer.

The future of the Arctic ozone layer will depend primarily on our success in ridding the atmosphere of ozone-depleting chemicals, but our ability to control greenhouse gases will also be important. The linkages between these issues mean that we cannot treat either of them in isolation. Instead, they indicate the importance of developing a comprehensive strategy for moderating the human impact on the atmosphere.



INTRODUCTION

The Arctic ozone layer has suffered unusually high rates of depletion during the 1990s, and scientific considerations suggest that it could become even more vulnerable during the next 10 to 20 years. Depletion rates have not been as high as in the Antarctic, where massive ozone holes have formed almost every spring since 1982, but they have been significantly higher than in the middle latitudes *(Figure 1)*, and losses as high as 45% have occurred.

Concentrations of known ozone-depleting substances in the atmosphere have either peaked very recently or will do so shortly, but they will remain close to their peak levels for the next few decades. What is more disturbing, however, is that climatic changes stemming from the build up of greenhouse gases may be altering the Arctic stratosphere in ways that could make deep ozone depletion events increasingly frequent.

Ecologists have serious concerns about the possible effects of major ozone losses on Arctic plants and animals. Because Arctic life has evolved in an environment where ultraviolet radiation levels are normally very low, it may be extremely sensitive to the much increased radiation that reaches the earth's surface during periods of serious ozone depletion. Large Arctic depletions could also have repercussions for ozone levels elsewhere, as a result of ozone-poor Arctic air mixing with and diluting the ozone content of air further south. Indeed, the polar regions, with their unique atmospheric processes, may hold the key to how much ozone depletion will eventually occur globally.

Canada, with its vast northern territories, is especially concerned about the future of the Arctic ozone layer and has conducted an extensive program of monitoring and research to measure trends and changes in the Arctic

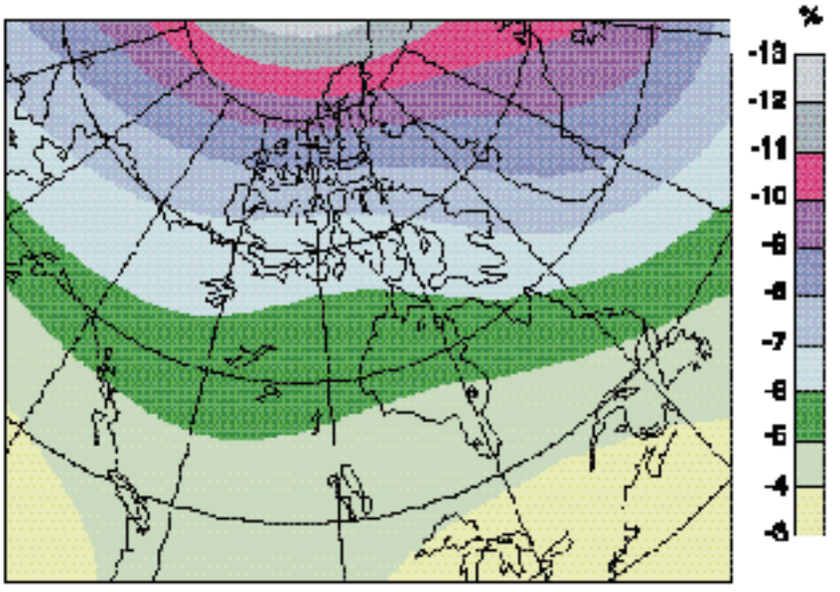


Figure 1
Percentage differences in average January–June ozone amounts over Canada between 1987 and 1997. Ozone losses have been substantially higher over the Arctic than over the southern part of the country.

stratosphere. Canadian scientists have also placed a high priority on collaborating with their counterparts around the world to improve our scientific understanding of processes affecting Arctic ozone as well as global ozone generally.

This publication summarizes what we know at the present time about the state of the Arctic ozone layer and the processes that affect it. Some of these processes are natural and contribute to normal daily, seasonal, and annual variations in ozone amounts. Others are the result of ozone-destroying pollutants released by human activities and result in longer-term changes to the ozone layer. There are also potentially crucial linkages between Arctic ozone destruction and changes occurring in the stratosphere as a result of climate change. Present controls on ozone-depleting substances should eventually undo much of the damage that has been done to the ozone layer, but whether Arctic ozone depletion will become much worse before it gets better will ultimately depend on the complex interaction of all these elements.

THE NATURAL OZONE REGIME AND THE ARCTIC

Ozone is formed in the stratosphere (the atmospheric layer that lies between about 10 and 50 km above the earth's surface) when powerful ultraviolet rays in sunlight break up oxygen molecules (O_2), liberating oxygen atoms (O) that then combine with intact oxygen molecules to form ozone (O_3). Most of the stratosphere's ozone is produced over the tropics, where these ultraviolet rays penetrate most deeply into the atmosphere, but stratospheric winds distribute this ozone over the rest of the world. Eventually the ozone is destroyed by sunlight or by reactions involving chlorine, water vapour, nitrogen oxides, and other substances in the air, but in an undisturbed natural system there is always enough new ozone coming in from the tropics to replenish these losses. This does not mean that the amount of ozone in the stratosphere is always constant. It, in fact, varies noticeably from day to day, season to season, year to year, and place to place, but at any given place average natural ozone levels tend to be much the same from one decade to another.

Ozone amounts above a point on the earth's surface are commonly measured in Dobson Units (DU), with 100 DU corresponding to 1 mm of ozone at ordinary surface temperature and pressure. Most of this ozone is in the stratospheric ozone layer, but a small amount is also present near the earth's surface, where it has been brought down by air currents from the stratosphere or created by chemical reactions involving air pollutants. Average yearly ozone values range from a low of 260 DU in the tropics to as much as 380 DU in the Arctic. In early spring, ozone amounts over parts of the Arctic commonly exceed 500 DU on some days *(Figure 2)*.

That the highest ozone amounts in the world are found over the Arctic is, at first glance, surprising, but there are at least three good reasons why this is so. The first is the total absence of sunlight for several weeks during the Arctic winter. Without solar energy to split ozone molecules apart, the natural breakdown of ozone is slowed considerably. The second is that the flow of ozone towards the poles is generally greater in the winter. This seasonal bias appears to be related to seasonal shifts in surface weather systems and upper-level wind patterns that provide much of the energy that

drives the poleward movement of air, and therefore ozone, in the stratosphere.

The third reason is that the stratosphere is deeper over the polar latitudes than anywhere else in the world. To understand why, it is necessary to look at how the atmosphere is structured vertically. The stratosphere sits on top of the troposphere, the bottom, more turbulent layer of the atmosphere where weather activity takes place. The troposphere commonly occupies as much as the bottom 18 kilometres of the atmosphere in the tropics but only about 8 km near the poles. This difference causes the boundary between these layers, known as the tropopause, to slope from the equator to the poles, at first gradually, then more steeply, like the bottom of a swimming pool. Because the Arctic is situated at the deepest part of the stratosphere, it can hold more ozone than the tropics or midlatitudes. As for the Antarctic, ozone values there, even before any depletion, have always been lower than those in the Arctic. The difference is due to the Southern Hemisphere's stratospheric winds being less effective at transporting the ozone poleward.

Ozone accumulates gradually in the Arctic stratosphere during the winter as the rate of resupply from the tropics exceeds the natural rate of destruction. With the arrival of spring, a change in the pattern of stratospheric winds usually brings a final increase in ozone values to 450 DU or more. The reapparance of the sun, however, increases the pace of ozone destruction, while the rate at which ozone is transported from the tropics falls off considerably and remains at a low level throughout the summer. Consequently, ozone levels decline from the early spring high of approximately 450 DU to about 300 DU in October.

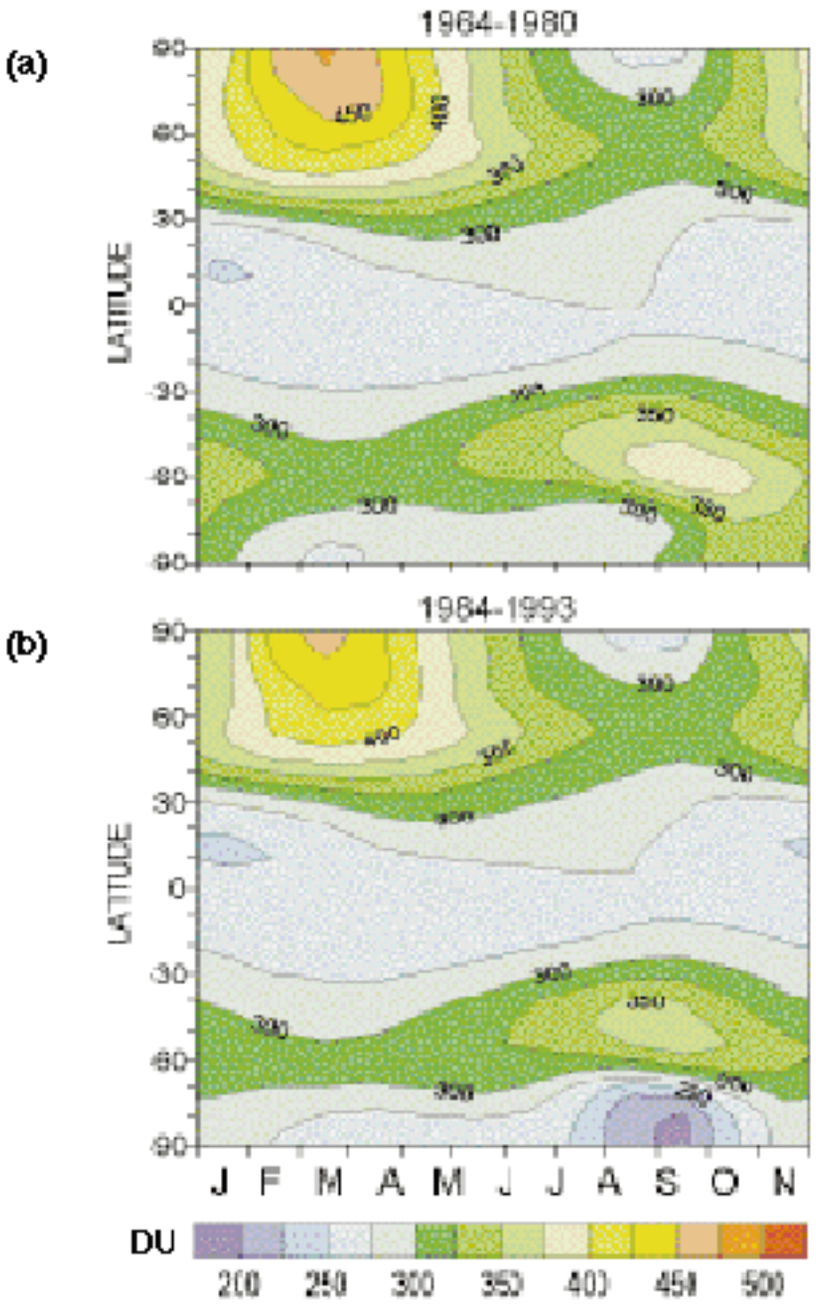


Figure 2

Average ozone amounts by latitude and season for (a) 1964–1980 and (b) 1984–1993. Both graphs show the highest ozone values occurring over the Arctic in early spring. The effects of ozone depletion are evident, however, in the later graph, which shows lower spring ozone averages over both the Arctic and Antarctic.

Ozone-Depleting Substances and their Impact on the Arctic Ozone Layer

Depletion of the ozone layer is occurring because human activities have introduced excessive amounts of chlorine, bromine, and other ozone-destroying chemicals into the stratosphere. Chlorine is the predominant ozone-destroying substance in the stratosphere, and the surplus comes mostly from various types of chlorofluorocarbons (CFCs). These are highly versatile chemicals that have been widely used as refrigerants and spray propellants as well as in an extensive variety of industrial applications. CFCs and other ozone-destroying substances (such as halons, carbon tetrachloride, methyl chloroform, and methyl bromide) are stable compounds, and most of them can survive for many years in the atmosphere before they eventually reach the stratosphere. Once in the stratosphere, however, these compounds gradually rise above the ozone layer where they are broken down by the intense ultraviolet radiation of the upper stratosphere and their chlorine or bromine is released. As a result of the release of these chemicals, the concentration of chlorine in the stratosphere is now about four times the natural level.

Chlorine and bromine are powerful ozone destroyers because they act catalytically. That is, they take part in reactions that destroy ozone, but they are not themselves consumed in the process and are therefore free to take part in these reactions again. Consequently, a single molecule of chlorine or bromine can destroy thousands of ozone molecules before it returns to the troposphere and is removed by other chemical reactions.

Over polar regions, two additional factors make ozone destruction brutally efficient for several weeks in the spring. The first of these is the polar vortex, a nearly closed circulation system that develops over the poles with the onset of winter. Without sunlight and without warmer air flowing in from lower latitudes, the polar stratosphere becomes extremely cold, with temperatures falling to –80°C or lower. At these temperatures, the second factor comes into play – the formation of polar stratospheric clouds (PSCs), made up of ice, nitric acid, and sulphuric acid. In the absence of PSCs, most of the chlorine and bromine in the stratosphere is locked up in compounds that under ordinary conditions would be quite stable and therefore harmless to the ozone layer. PSCs cause these compounds to break

down, however, leaving the chlorine and bromine atoms in less stable compounds. When sunlight returns in the spring, these compounds are broken apart by solar radiation, and chlorine and bromine are released. Ordinarily, the reactions that destroy ozone require relatively strong sunlight. However, with the cold temperatures and the especially high concentrations of chlorine that are present in the vicinity of PSCs, an entirely different set of reactions takes place that is actually far more effective in destroying ozone. With the resupply of fresh ozone from lower latitudes blocked by the vortex, ozone amounts drop rapidly and deeply as these reactions proceed *(Figure 3)*. In some layers of the stratosphere, the ozone may be almost completely destroyed.

Over the Antarctic, these processes commonly lead to the formation of a massive ozone hole (defined as an area in which total ozone amounts are less than 220 DU). These do not fill in until the winter vortex dissipates (allowing the return of ozone-rich air from the tropics) and warmer temperatures prevent the formation of PSCs. Over the Arctic, the same processes intensify depletion but, at least so far, they have not done so to the same degree as in the Antarctic. Why the difference? A major factor is that the greater variability of the atmospheric circulation in the Northern Hemisphere makes the Arctic vortex much less stable than its

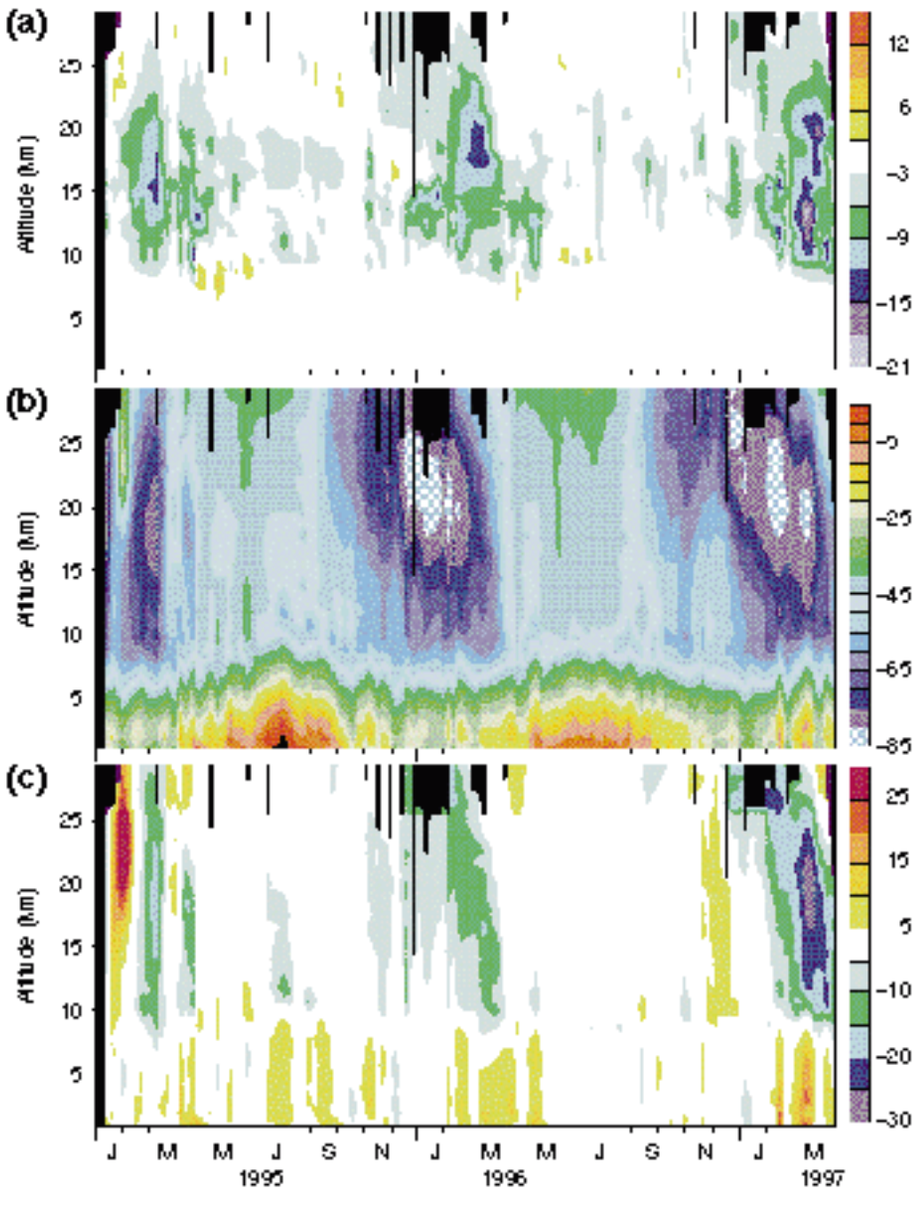


Figure 3

(a) Ozone deviations from normal in DU/km; (b) temperature in °C; and (c) temperature deviations from normal in °C over the Arctic research station at Alert, January 1995 to April 1997. The graphs indicate a close correlation between extensive ozone depletion (the light blue, dark blue, and purple areas in a) and stratospheric temperatures below –80°C (the purple and grey areas in b).

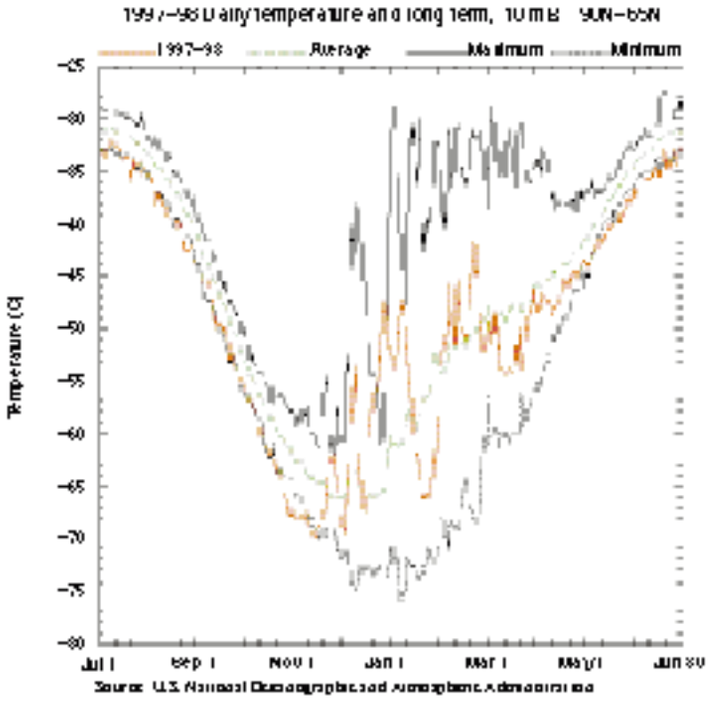


Figure 4

Daily temperatures in the Arctic stratosphere between 65°N and the North Pole, July 1, 1997, to June 30, 1998, and long-term averages. Frequent warming of the Arctic stratosphere, which is clearly evident in the winter of 1997–1998, inhibits the formation of polar stratospheric clouds and the chemical processes that result in severe ozone depletion.

southern counterpart. As a result, it is frequently penetrated by stratospheric winds bringing ozone and warmer air from the south. Because of these events, known as sudden stratospheric warmings, the Arctic stratosphere is often too warm for PSC formation *(Figure 4)*. Consequently, PSCs do not form as often in the Arctic nor do they last as long as they do over the South Pole. For that reason, there have been no massive ozone holes over the Arctic. Nevertheless, any PSC formation can greatly accelerate the pace of ozone depletion.

Other Factors Affecting Arctic Ozone Depletion

Although ozone-depleting chemicals and the unique depletion processes of the polar stratosphere have the most dramatic impact on Arctic ozone, several other factors can also affect ozone amounts. For example, day-to-day changes are often associated with the movement of weather systems and pressure patterns in the troposphere and with changes in the height of the tropopause. Longer-term changes have been linked to a variety of other natural processes, of which the most significant are the periodic reversal of stratospheric winds over the equator (the quasi-biennial oscillation), El Niños, the solar or sunspot cycle, and volcanic eruptions *(Figure 5)*.

The quasi-biennial oscillation

Over the equator, stratospheric winds circle the globe in either an easterly or a westerly direction. Every 20–30 months the direction is reversed. This phenomenon is known as the quasi-biennial oscillation (QBO). Its ultimate cause is not fully understood, but it is known to influence a variety of atmospheric phenomena, including ozone amounts over the middle and high latitudes. When the QBO is in its westerly phase, polar stratospheric temperatures are generally lower, the poleward transport of ozone is reduced, and ozone depletion tends to be greater. In 1993, 1995, and 1997, for example, the QBO was in its westerly phase and large ozone losses were recorded in the Arctic. In 1994, 1996, and 1998, it was in its easterly phase. Depletion was minimal, as expected, in 1994 and 1998, but losses as high as 30% occurred in 1996. These unexpected results suggest that factors other than the QBO had a more substantial effect on ozone levels that year.

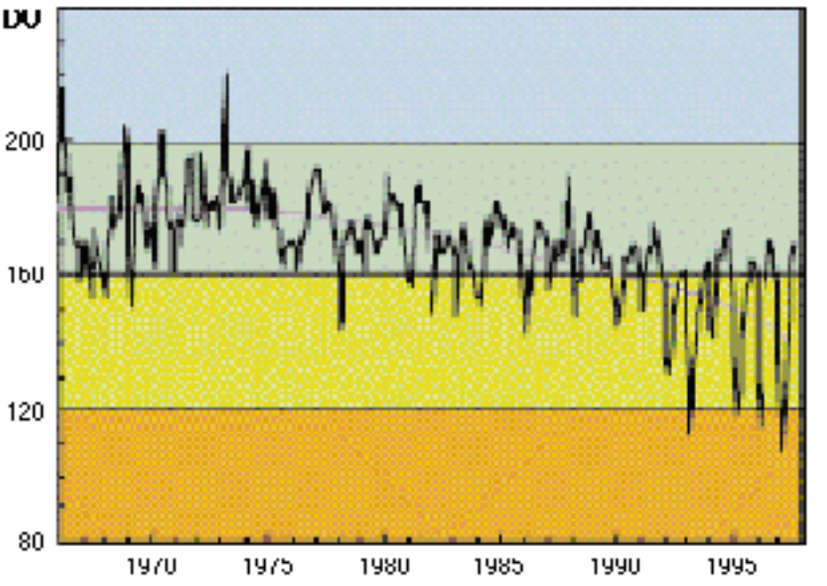


Figure 5
Ozone amounts in the lower stratosphere (10–20 km) over the Canadian Arctic. The graph shows a downward trend beginning in the late 1970s. The extensive year-to-year variability reflects the influence of factors such as the quasi-biennial oscillation, El Niños, the solar cycle, and volcanic eruptions.

El Niño Southern Oscillation

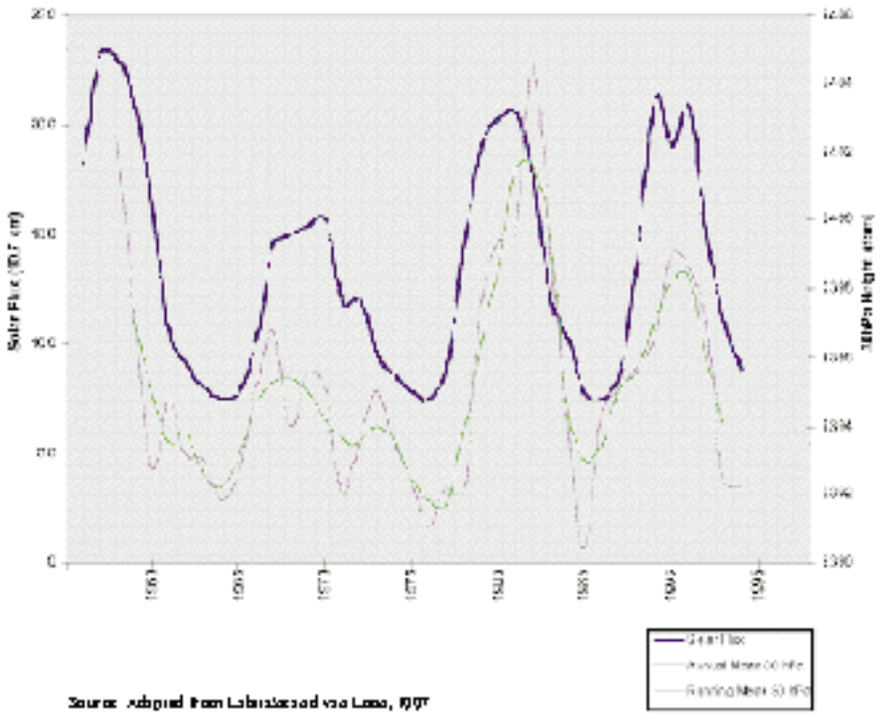
El Niños are periodic abnormal warmings of the eastern equatorial Pacific. Occurring roughly every three to seven years, they are accompanied by a reversal of normal pressure patterns over the Southern Hemisphere (a phenomenon known as the Southern Oscillation) and result in disturbances of prevailing weather patterns in much of the world. Because El Niños also change normal pressure patterns in the upper troposphere, they can alter the height of the tropopause, affect the poleward transport of ozone, and cause changes in ozone amounts over many parts of the world.

One of the consequences of the strong El Niño of 1997-1998 was a deepening of the Aleutian Low, a large quasi-permanent low pressure area over the northeastern Pacific Ocean. It is an important feature in the large-scale circulation of the atmosphere, and its strengthening may well have made the Arctic vortex less stable and more subject to the sudden stratospheric warmings that moderated temperatures within the vortex during the winter of 1998. By making conditions less favourable for PSC formation, the El Niño may have made a significant contribution to the comparatively low rate of Arctic ozone depletion that was observed in the spring.

The solar cycle

Over a period of approximately 11 years, the energy output of the sun varies by only about 0.1%, changing with the growth and decay of sunspots on the solar surface. When the number of sunspots is greatest, the sun produces more energy than when the number of sunspots is least. Although the change in energy is quite small, much of it is concentrated in the ultraviolet range. Since ozone is created as a result of the breaking of oxygen molecules by the sun's ultraviolet radiation, more ozone will be produced in years when the solar cycle is at its maximum. The observed variation in ozone amounts over the cycle is approximately 1–2%.

Recent studies have linked the solar cycle maximum to a slight warming of the winter stratosphere (thus making conditions less favourable for PSC formation) and a strengthening of the poleward transport of ozone *(Figure 6)*. Both of these conditions tend to diminish the extent of ozone depletion in the Arctic. Other factors being equal, ozone depletion over the Arctic is therefore likely to be lower in years when the solar cycle is at a maximum (as it was in 1968, 1979, and 1990 and will be again in about 2001).



Source: Adapted from Labitzke and van Loon, 1997

Figure 6

The solar cycle and average annual air pressure patterns in the stratosphere, 30°N, 150°W. The two light curves show variations in the annual average height at which a pressure of 30 hPa occurs. They closely match the changes in solar radiation (shown by the dark curve) that occur during the 11-year sunspot cycle. Such pressure variations affect the poleward transport of ozone, with more ozone being carried into the Arctic when the incoming solar radiation is greatest.

Volcanoes

Major volcanic eruptions can have a significant impact on ozone depletion over a one- or two-year period. That is because chemical reactions similar to those that take place on PSCs can also take place on the surfaces of sulphate aerosols (fine droplets or particles) that have formed in the stratosphere as a result of the eruptions. These aerosols may also stimulate the formation of PSCs by various indirect processes.

The eruption of Mt. Pinatubo in the Philippines in 1991, for example, put about 120 million tonnes of sulphur dioxide into the stratosphere, and within a week or two the gas was converted to sulphate aerosols by atmospheric reactions. During the next two years, severe ozone depletion was observed both in the midlatitudes and at the poles. Over Canada, ozone amounts in the spring of 1993 were 10–17% below normal, the largest decrease observed until then. At the same time, in the high Arctic, ozone amounts in the lower stratosphere (between 10 and 20 km) fell to about 110 DU, a low value not seen again until 1997.

Because the timing and magnitude of volcanic eruptions are unpredictable, volcanoes function as a kind of wild card in estimates of future ozone depletion.

The Effects of Climate Change

Ozone depletion and climate change are usually seen as independent issues. They involve different atmospheric processes, they have different impacts, and they are the subject of separate international negotiations and treaties. Yet both of these problems affect the same atmosphere, and given the complex array of interactions and feedbacks that characterize atmospheric behaviour it is not surprising that there are some important linkages between them.

Climate change has become a very serious concern in recent years because human activities are causing concentrations of greenhouse gases, like carbon dioxide, methane, and nitrous oxide, to rise well above natural levels. These gases affect the world's climate by retaining heat in the troposphere, thus raising the average temperature of the planet and altering global circulation and precipitation patterns *(Figure 7)*. Carbon dioxide, released by the burning of fossil fuels, is the most abundant of the greenhouse gases associated with human activities,

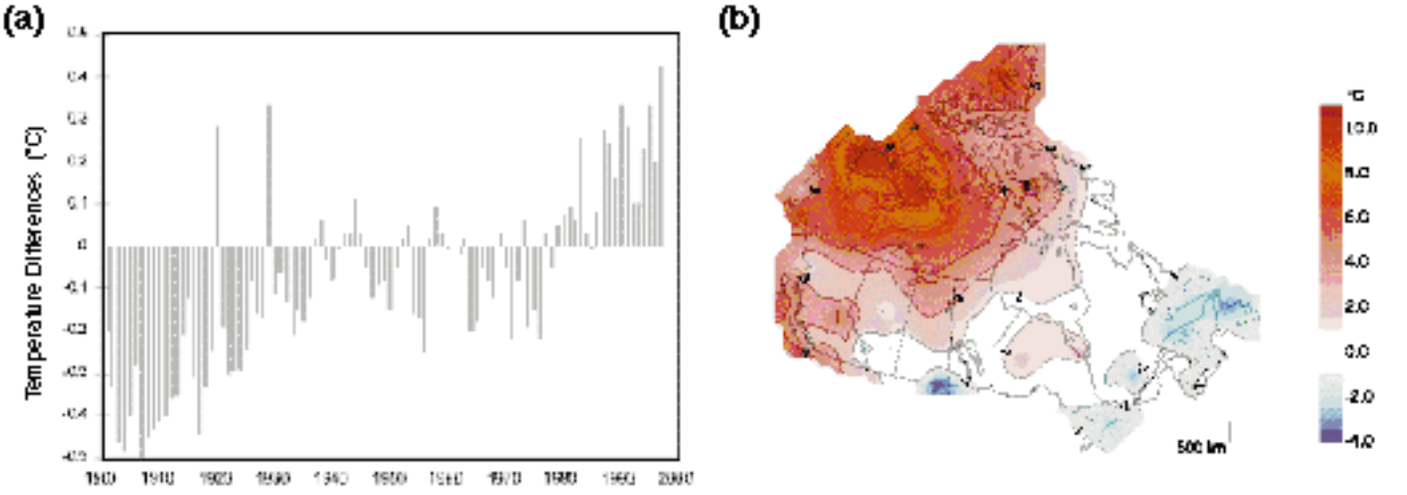


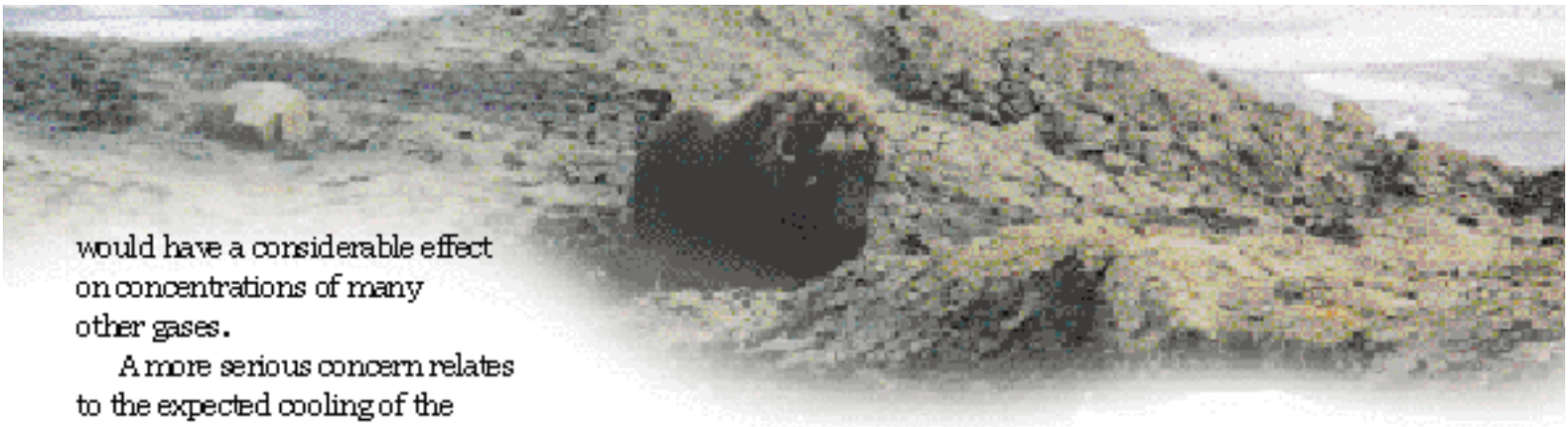
Figure 7

(a) Differences between annual average global surface temperatures and the 1961–1990 average, and (b) accumulated temperature changes in Canada from 1993 to 1997 relative to the 1951–1980 average. Over the past century the earth as a whole has warmed by 0.3–0.6°C. In Canada, most of the Arctic has experienced unusually warm conditions during the mid-1990s. Experiments with climate models suggest that the earth's average temperature could rise by an additional 1.0–3.5°C over the next century as greenhouse gas concentrations continue to rise. Climate models also predict a cooling of the stratosphere as surface temperatures become warmer. Current observations indicate a downward trend in lower stratospheric temperatures of about 0.6°C per decade between 1979 and 1994. A cooler stratosphere could lead to the more frequent formation of polar stratospheric clouds and more extensive ozone loss over the Arctic.

but CFCs, the major players in ozone depletion, are also powerful greenhouse gases. In addition, ozone itself has a considerable effect on the earth's heat budget. Not only does it add heat to the stratosphere when it absorbs ultraviolet radiation from the sun, but it also acts as a greenhouse gas. Ozone losses in the lower stratosphere lead to cooling of both the stratosphere and troposphere, thus offsetting some, though not all, of the direct warming caused by CFCs. Near the earth's surface, however, ozone amounts have increased substantially during the twentieth century as a result of air pollution. This increase has contributed significantly to global warming, although not as much as increases in carbon dioxide have.

The state of the atmosphere at any given time is the result of a constantly adjusting balance among a wide array of processes. By altering some of these processes, ozone-depleting substances and greenhouse gases trigger a series of readjustments that affect other parts of this balance. Some of these readjustments are almost certain to have an important effect on ozone depletion.

There is a possibility that rising concentrations of methane, for example, will raise the water vapour content of the stratosphere, since water vapour is produced when methane reacts with the hydroxyl radical, a short-lived, highly reactive compound of hydrogen and oxygen. With more water vapour in the stratosphere, more PSCs could form (when temperatures are right) and ozone depletion would be enhanced. The consumption of the hydroxyl radical in this reaction (which occurs in the troposphere as well) would also have important effects, since it is one of the atmosphere's greatest scavengers of pollutants and a key participant in a wide range of atmospheric chemical reactions. Reducing the hydroxyl abundance in the atmosphere

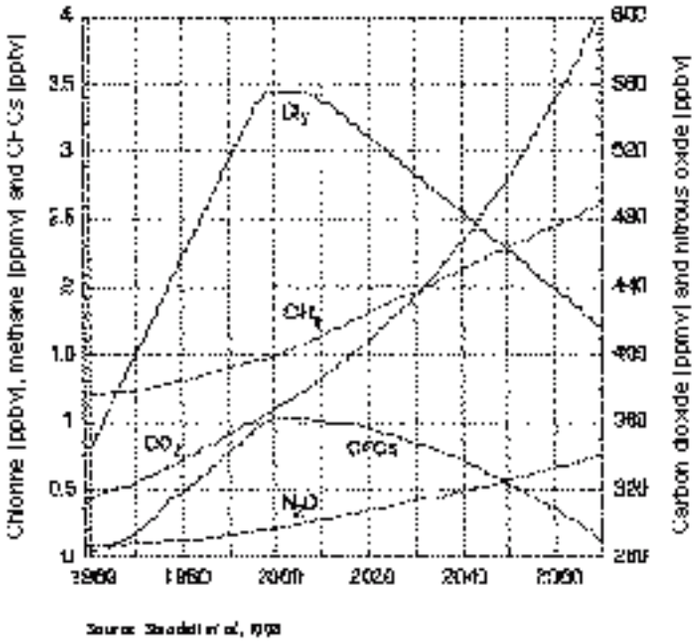


would have a considerable effect on concentrations of many other gases.

A more serious concern relates to the expected cooling of the stratosphere due to the buildup of greenhouse gases. The same changes in the atmosphere's infrared radiation that cause warming in the lower atmosphere tend to make the stratosphere colder. This cooling (which is in addition to that already caused by the loss of ozone) would greatly increase the probability of PSC formation over the Arctic, where the stratospheric temperature often comes within only a few degrees of the threshold for PSC formation. With PSCs forming more frequently over the Arctic, the rate of ozone destruction would rise considerably.

The interactions between greenhouse warming and ozone depletion can be explored with computer models of the global climate system that incorporate not only the warming effects of greenhouse gases but also the reactions that determine the chemical composition of the atmosphere. Such models, however, do not yet give reasonably accurate values for present temperatures in the winter stratosphere unless they are adjusted by the addition of special constraints. Since these constraints override some aspects of the known physics of the atmosphere, they can correct only the starting values but may not prevent additional errors when the model is run. Thus, although a model may predict a plausible change in temperature in the stratosphere, it is very difficult to know what degree of error is involved in such a prediction.

While recognizing these problems, a team at NASA's Goddard Institute for Space Studies and Center for Climate Systems in the United States recently reported results of a model simulation of the combined effects of increases in greenhouse gases and decreases in ozone-depleting chemicals that are expected in the next few decades *(Figure 8)*. When the model was run, global temperatures and wind patterns changed as greenhouse gas concentrations were gradually increased, and the frequency of sudden stratospheric warmings in the Northern Hemisphere was seen to diminish. With a more stable vortex over the Arctic and colder temperatures in the lower stratosphere, the



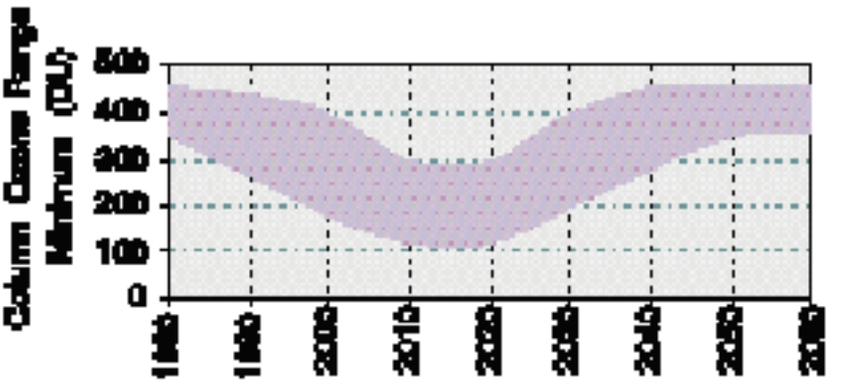
Source: Stordal et al., 1993

Figure 8

Emission assumptions used in the Goddard Institute (GISS) model. The combination of rising greenhouse gas concentrations and continuing high levels of ozone-depleting substances over the next few decades could intensify Arctic ozone depletion.

severity and duration of ozone depletion episodes increased, reaching a peak between 2010 and 2020, about 10–20 years later than expected if only the concentrations of ozone-depleting substances had been taken into account *(Figure 9)*. Within this general pattern, however, the model showed considerable variation from one year to another, which is consistent with the current behaviour of the Arctic stratosphere.

The simulation therefore reinforces the basis for concern that climate change caused by greenhouse gases will worsen ozone depletion over the Arctic in the next few decades. However, before we can be more certain about these conclusions, the results from this model need to be studied and compared with results from other models that incorporate more thorough representations of the physical and chemical processes that are involved.



Source: Adapted from Shindell *et al.*, 1998

Figure 9

Range of lowest spring ozone levels as simulated by the GISS model, 1980–2060. The inclusion of greenhouse gases causes maximum ozone depletion to occur about 10–20 years later than would be expected if concentrations of ozone-depleting substances alone had been considered.

RESEARCH AND OBSERVATION: THE STATE OF THE ARCTIC OZONE LAYER

OBSERVATION AND MONITORING

Canadian scientists have been active in stratospheric ozone research since the late 1920s, but continuous monitoring of ozone levels over Canada did not begin until the late 1950s. The present Canadian observation network consists of a dozen stations, of which three are located in the Arctic *(Figure 10)*. One of these, at Resolute Bay, has observations dating back to 1957. Observations at the other two, Alert and Eureka, began in 1987 and 1992 respectively.

Ozone at all Canadian stations is measured with ground-based instruments. The Dobson ozone spectrophotometer, devised in the 1920s by the pioneer British ozone researcher G.M.B. Dobson, was used for these measurements until 1988. It was then replaced by the Canadian-developed Brewer ozone spectrophotometer, an automated instrument that is now the standard apparatus for ground-based ozone measurements worldwide. In addition, some 300 ozonesondes, which are instrument packages carried aloft by balloons, are launched throughout the year from half a dozen Canadian locations, including all three Arctic sites, to provide direct measurements of ozone concentrations at different altitudes. Ozonesondes have been launched from Resolute Bay since 1966 and from Alert and Eureka since 1987 and 1992 respectively.

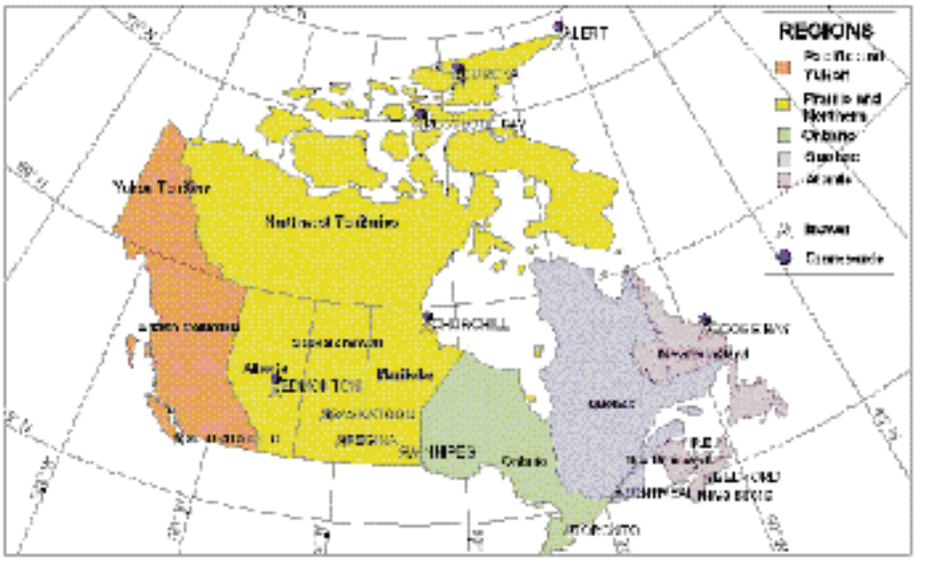


Figure 10
The Canadian ozone observation network.

The downward trend in the ozone content of the lower stratosphere can be seen to begin in the late 1970s, and by the 1990s severe depletion episodes were being observed in some years *(Figure 5)*. The longest record, from Resolute Bay, provides a particularly striking illustration of seasonal and annual trends in the Arctic ozone layer over the past 40 years. Figure 11 shows the seasonal pattern, with ozone amounts peaking in February and March and reaching a minimum in August and September. The general downward movement of ozone levels in the 1990s during all seasons is also abundantly

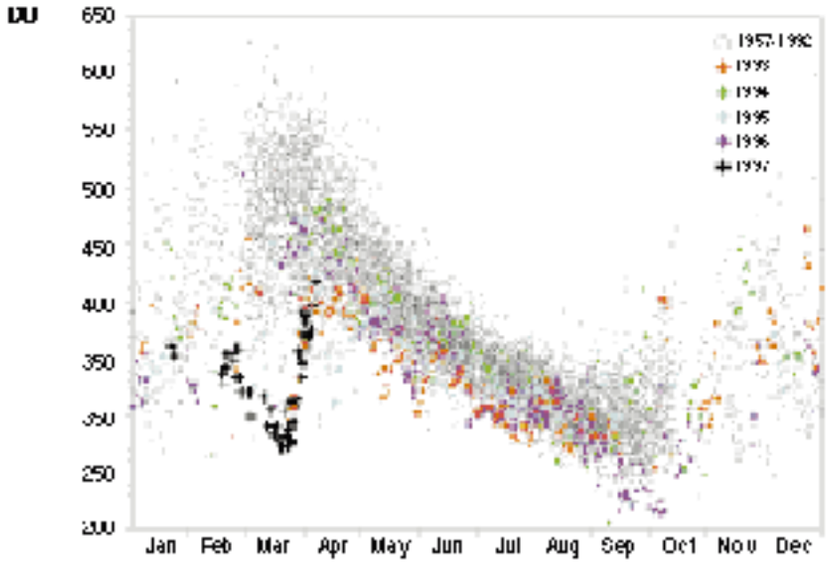


Figure 11

Total ozone over Resolute Bay, 1957–1997. The graph shows both the annual cycle of ozone values in the Arctic and the general downward trend of ozone values in the 1990s. The severe depletion in the spring of 1997 is particularly evident.

clear, with springtime values below 300 DU occurring more frequently after 1993. Before 1993, springtime values below 300 DU were occasionally recorded at Resolute Bay, but they were relatively infrequent and lasted for only a few days.

During March 1996, ozone values over the high Arctic were as much as 30% below normal, while in March 1997 they dropped to as much as 45% below the normal values. During the 1997 episode, ozone values remained below 300 DU for much of March and remained significantly below normal minimum values until the middle of April *(Figure 12)*. Although this depletion was very large by Arctic standards, ozone amounts were still well above those in the Antarctic, where values of 100 DU or less have commonly been recorded during ozone hole episodes.

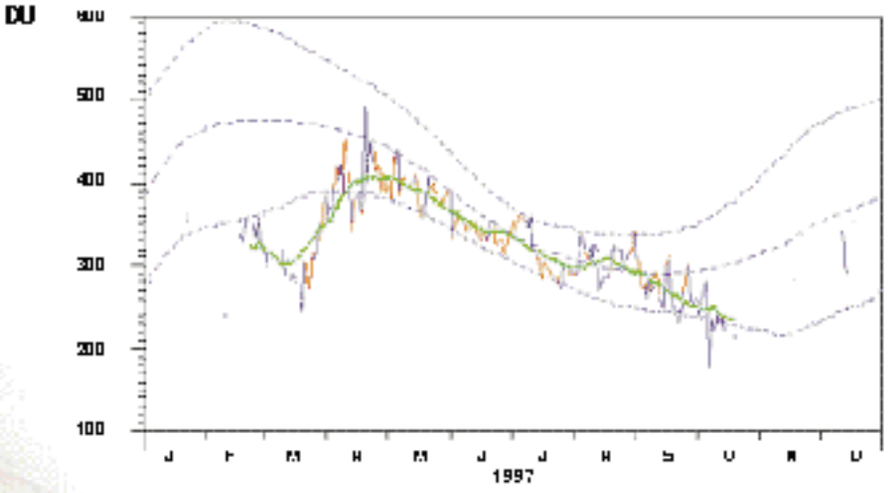


Figure 12

Total ozone over Resolute Bay, February–October 1997. The centre dashed line shows average ozone values, while the upper and lower dashed lines show average maximum and minimum values. After severe depletion in the spring, the ozone layer recovered, but values remained below the long-term average for most of the summer.

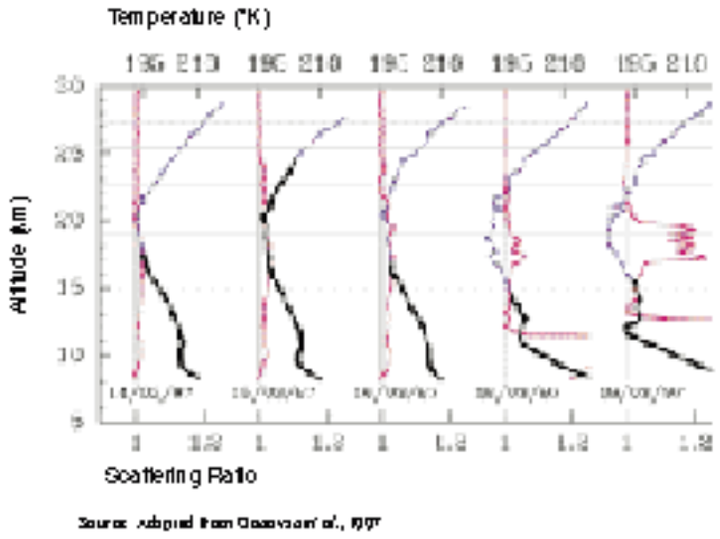
Figure 13
The Eureka Stratospheric Ozone Laboratory on Ellesmere Island in the Canadian Arctic.

Arctic Ozone Research

Arctic ozone research received a boost in 1992 with the opening of the Eureka Stratospheric Ozone Observatory on Ellesmere Island *(Figure 13)*. The observatory is a primary component of the Network for the Detection of Stratospheric Change, an international group of high quality, ground-based research stations for investigating the physical and chemical processes of the stratosphere. The Eureka observatory is used by university and government researchers from Canada, Japan, and the United States.

Total ozone amounts over Eureka are measured year-round by a Brewer spectrophotometer, which uses the absorption of ultraviolet radiation in sunlight and moonlight to determine how much ozone is in the atmosphere. In addition, ozonesondes are launched weekly to provide vertical profiles of ozone and temperature. From early December to March an instrument known as a lidar is used to obtain vertical profiles of ozone and temperature. The lidar, which measures the reflection of laser pulses much as a radar measures reflected radio waves, can also be used to determine atmospheric concentrations of fine sulphate particles associated with volcanic eruptions, polar stratospheric clouds, and Arctic haze (a kind of smog that is transported into the Arctic during the winter from industrial regions to the south). Because the lidar works best in total darkness, it is shut down as Arctic summer approaches and the nights get shorter. Overlapping measurements from these instruments not only provide an accuracy check on total ozone amounts but can also be used to detect the atmospheric temperatures and light-scattering patterns that indicate the presence of polar stratospheric clouds *(Figure 14)*.

Another instrument, known as a Fourier Transform Infrared Spectrometer (FTIR), can be used to measure the chemical content of the stratosphere. One of the



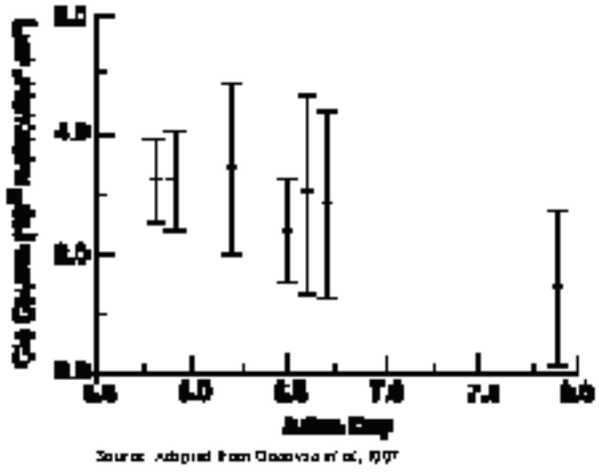
Source: Adapted from Donovan et al., 1997

Figure 14

Temperature and light scattering in the Arctic stratosphere, March 14–19, 1997. The vertical temperature profile is shown in black (lidar measurements) and blue (ozonesonde measurements). The straight vertical lines denote a temperature of 193°K (–80°C), the threshold for PSC formation. The red line indicates the amount of light scattering and shows the presence of PSCs on the 18th and 19th.

activities closely with those of other nations. Since 1991, for example, it has participated in the Match ozonesonde program, which coordinates the launches of ozonesondes in Europe and Canada to probe the same air mass at different points as it travels around the Arctic vortex. By analyzing the differences between measurements taken at different times and places within this air mass, it is possible to determine the amount of ozone loss that is due to chemical processes alone and to avoid any distortions caused by ozone brought in by other air masses. Among other things, data from the Match program, clearly reveal the crucial role of sunlight in ozone destruction *(Figure 16)*.

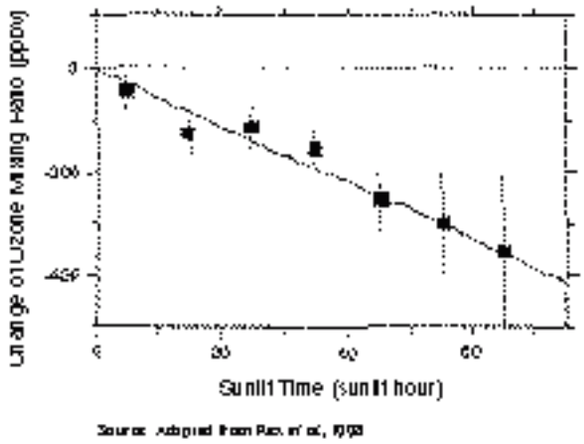
Canada has also collaborated closely with the U.S. National Aeronautics and Space Administration (NASA) in Project Polaris, a campaign to



Source: Adapted from Donovan et al., 1997

Figure 15

Average daily chlorine monoxide amounts over Eureka after polar sunrise in 1997. The elevated chlorine monoxide amounts between days 55 and 70 indicate that ozone depletion is taking place.



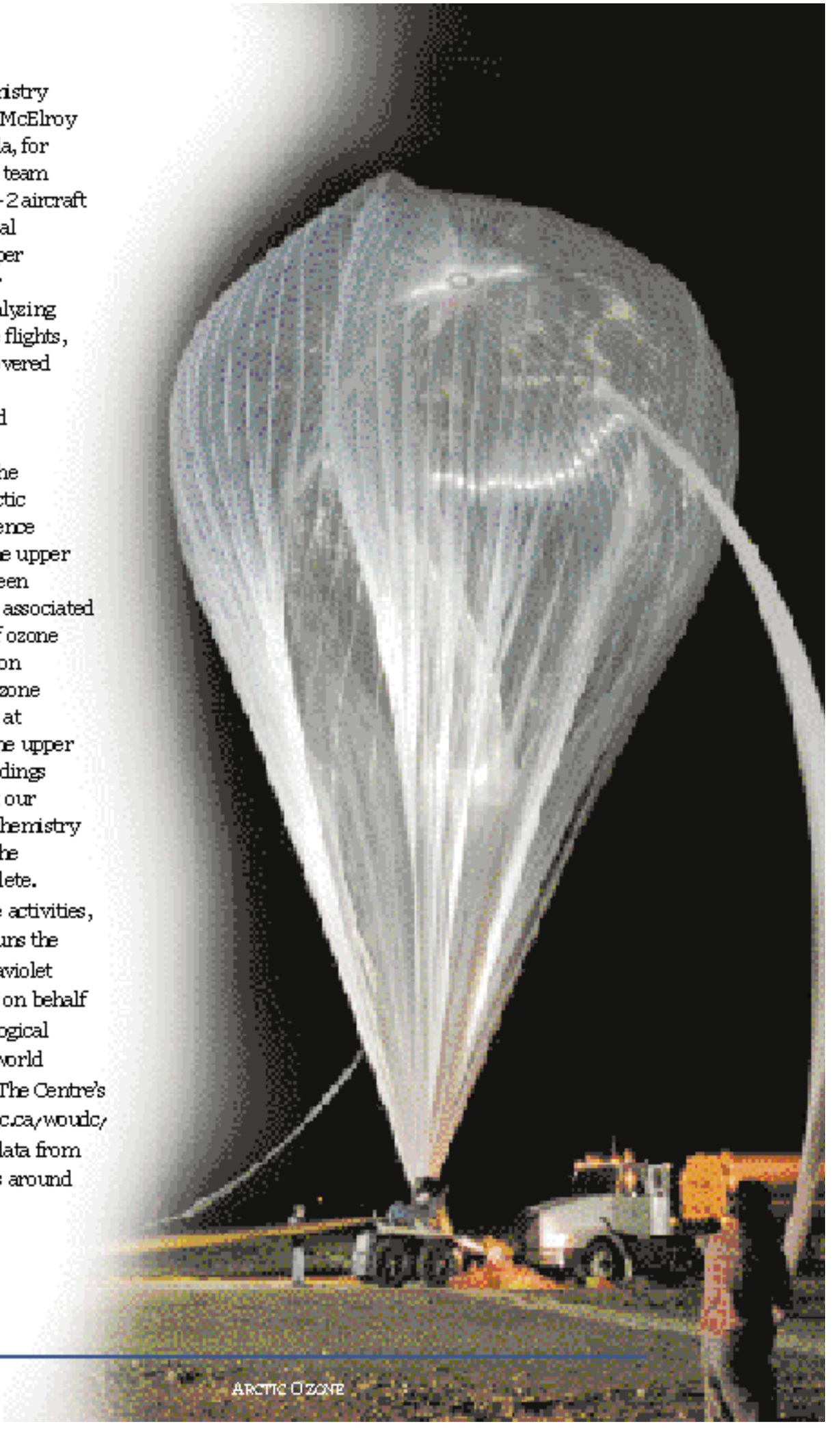
Source: Adapted from Rex et al., 1998

Figure 16

Change in ozone concentrations with exposure to sunlight, January 4 to February 9, 1992. Measurements of a single air mass as it moves around the Arctic vortex show a steady decrease in ozone concentrations as accumulated exposure to sunlight increases.

investigate ozone chemistry in the Arctic. Dr. Tom McElroy of Environment Canada, for example, works with a team using a high-flying ER-2 aircraft to measure the chemical composition of the upper troposphere and lower stratosphere. After analyzing data collected by these flights, McElroy recently discovered evidence that bromine monoxide, a compound associated with ozone destruction, exists in the higher levels of the Arctic troposphere. The presence of this compound in the upper troposphere had not been expected. Because it is associated with the destruction of ozone by bromine, its detection suggests that further ozone depletion is occurring, at least occasionally, in the upper troposphere. These findings emphasize as well that our understanding of the chemistry of ozone depletion in the troposphere is incomplete.

In addition to these activities, Environment Canada runs the World Ozone and Ultraviolet Radiation Data Centre on behalf of the World Meteorological Organization and the world scientific community. The Centre's web site (www.tor.ec.gc.ca/woudc/woudc.htm) contains data from more than 150 stations around the world.



The Future of the Arctic Ozone Layer

The Montreal Protocol of 1987 and later amendments to it were intended to phase out the use of ozone-depleting chemicals for all nonessential purposes and restore the ozone layer to its former healthy state. As a result of these agreements, atmospheric concentrations of some ozone-depleting substances, such as CFC-11, have begun to decline and concentrations of others will follow suit over the next decade *(Figure 17)*. Because of the time taken for ozone-depleting chemicals to reach the stratosphere and break down, the decline in stratospheric levels of chlorine and bromine will lag any decrease in concentrations of CFCs and other ozone-depleting substances by a few years. It is expected, for example, that the amount of chlorine in the stratosphere, currently at a level of 3.5 parts per billion (ppb), will peak by about 2003 and decrease thereafter. By 2050 it should have fallen to 2.0 ppb, the level at which the Antarctic ozone hole was first detected. One should therefore expect a substantial degree of recovery in ozone values by 2050. These expectations, of course, assume that the gaps in our understanding of ozone-depletion processes turn out not to be important and that present international agreements will be strictly adhered to. If either of these assumptions is incorrect, the time for recovery will be longer.

The recovery of the ozone layer could be delayed further if ozone-depleting substances that are not covered by the present agreements begin to be released into the atmosphere in substantial quantities. This possibility could become a reality by the middle of the twenty-first century as a result of the development of supersonic transport aircraft that would fly in the lower stratosphere. A fleet of 500 to 1000 of these aircraft would release large quantities of nitrogen oxides, water vapour, and sulphates, all of which have the potential to increase ozone

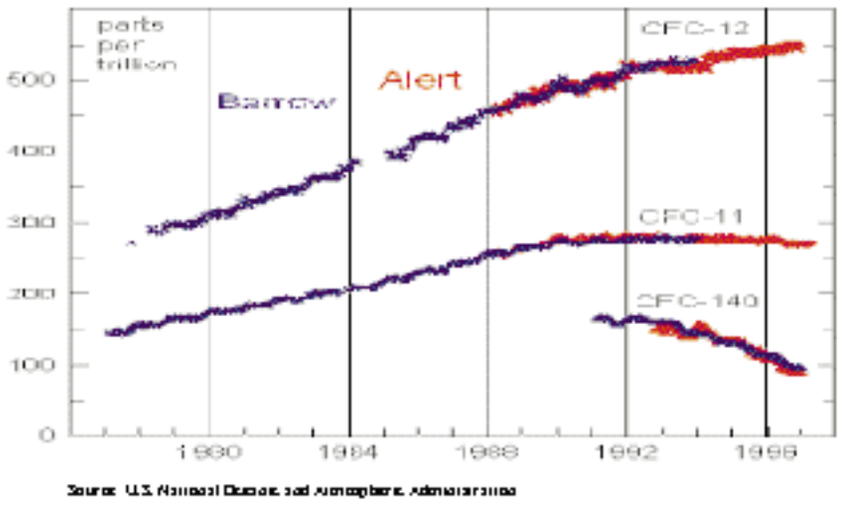


Figure 17

Concentrations of ozone-depleting substances in the Arctic troposphere. CFCs are highly stable in the troposphere and only break up when exposed to the intense ultraviolet radiation of the upper stratosphere. The chlorine they contain eventually returns to the troposphere, but the cycle takes about 50 years for CFC-11 and about 100 years for CFC-12.

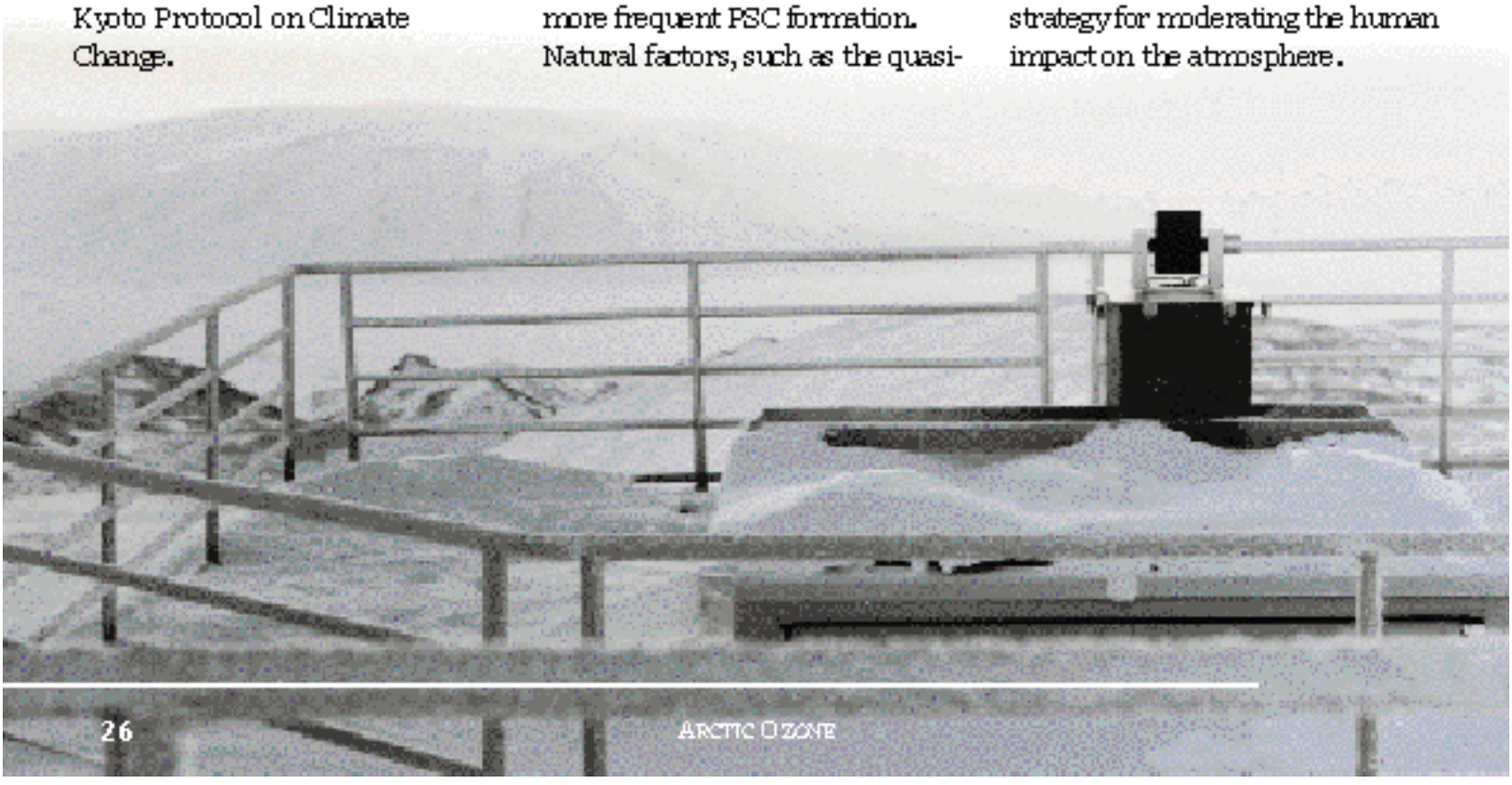
depletion. Because these substances contribute to PSC formation as well, their impact on Arctic ozone levels could be particularly harmful.

Ironically, our current efforts to rid the atmosphere of ozone-depleting substances may have a negative impact on climate change and this, in turn, could have consequences for Arctic ozone depletion in the future. Hydrochlorofluorocarbons (HCFCs) and hydrofluorocarbons (HFCs), the most widely used replacements for CFCs, are also greenhouse gases, and some of them are nearly as effective as CFCs as global warming agents. Consequently, their use will contribute to further greenhouse warming and related cooling of the stratosphere. For that reason, the consumption of HCFCs is scheduled to be phased out by 2030 under the Copenhagen Amendments to the Montreal Protocol. The usage of HFCs has been addressed under the 1997 Kyoto Protocol on Climate Change.

In dealing with all of these complex problems, research and monitoring will continue to play an important role. Continuing observations of ozone amounts as well as CFCs, chlorine, bromine, sulphates, nitrates, and other key participants in the ozone depletion process will be necessary to assess progress towards the recovery of the ozone layer. Further studies of atmospheric processes will also be essential if we are to reduce the uncertainties in our current understanding of ozone depletion and improve our capability to predict what is likely to happen to the ozone layer in the future.

The ozone layer will be particularly vulnerable over the next 20 years when atmospheric concentrations of ozone-depleting substances will be at or near their highest levels. The Arctic will be especially vulnerable during this period if continuing increases in greenhouse gases lead to further cooling of the stratosphere and more frequent PSC formation. Natural factors, such as the quasi-biennial oscillation, El Niños, and the solar cycle will also influence the severity of ozone depletion in any given year, and large volcanic eruptions could lead to particularly serious depletions in some years.

Over the much longer term, the health of the ozone layer will depend primarily on our ability to rid the atmosphere of present ozone-depleting substances and prevent the release of new ones. But it will also depend on our success in controlling greenhouse gases. These issues are linked, as we have seen, through a variety of physical and chemical interactions. They are also linked at the ecosystem level, where plants and wildlife are affected not just by ozone depletion or by climate change independently but by an entire spectrum of human-related stresses on natural systems. That means that we cannot treat any of these issues in isolation. Instead, we must deal with them as interrelated parts of a common strategy for moderating the human impact on the atmosphere.



BIBLIOGRAPHY

Austin, J., N. Butchart, and K.P. Shine, 1992. Possibility of an Arctic ozone hole in a doubled-CO_2 climate. *Nature*, **360**, 221–225.

Bojkov, R.D., and V.E. Fioletov, 1995. Estimating the global ozone characteristics during the last 30 years. *Journal of Geophysical Research*, **100**, 16,537–16,551.

Bojkov, R.D., and V.E. Fioletov, 1996. Total ozone variations in the tropical belt: an application for quality of ground-based measurements. *Meteorology and Atmospheric Physics*, **58**, 223–240.

Coy, L., E. Nash, and P. Newman, 1997. Meteorology of the polar vortex: Spring 1997. *Geophysical Research Letters*, **24**, 2693–2696.

Dameris, M., *et al.*, 1998. Assessment of the future development of the ozone layer. *Geophysical Research Letters*, **25**, 3579–3582.

Danilin, M.Y., *et al.*, 1998. Stratospheric cooling and Arctic ozone recovery. *Geophysical Research Letters*, **25**, 2141–2144.

Donovan, D.P., H. Fast, *et al.*, 1997. Ozone, column ClO, and PSC measurements made at the NDSC Eureka observatory (80°N, 86°W) during the spring of 1997. *Geophysical Research Letters*, **24**, 2709–2712.

Fioletov, V.E., *et al.*, 1997. Long-term ozone decline over the Canadian Arctic to early 1997 from ground-based and balloon observations. *Geophysical Research Letters*, **24**, 2705–2708.

Haigh, J. D., 1996. The impact of solar variability on climate. *Science*, **272**, 981–984.

Hasebe, F., 1994. Quasi-biennial oscillations of ozone and diabatic circulation in the equatorial stratosphere. *Journal of the Atmospheric Sciences*, **51**, 729–745.

Hengeveld, H., 1995. *Understanding Atmospheric Change*. SOE Report No. 95-2. Ottawa: Environment Canada.

Houghton, J.T., L.G. Meira Filho, B.A. Callander, N. Harris, A. Kattenberg, and K. Maskell, eds., 1996. Climate Change 1995: *The Science of Climate Change. Summary for Policymakers and Technical Summary of the Working Group I Report*. Geneva: Intergovernmental Panel on Climate Change.

Kerr, R.A., 1998. Deep chill triggers record ozone hole. *Science*, **282**, 391.

Labitzke, K. and H. van Loon, 1997. The signal of the 11-year sunspot cycle in the upper troposphere-lower stratosphere. *Space Science Reviews*, **80**, 393–410.

MacKay, R.M., *et al.*, 1997. An estimate of the climatic effects of stratospheric ozone losses during the 1980s. *Journal of Climate*, **10**, 774–788.

Makhijani, A. and K.R. Gurney, 1995. *Mending the Ozone Hole*. Cambridge, Massachusetts: MIT Press.

Manney, G.L., *et al.*, 1997. MLS observations of Arctic ozone loss in 1996–97. *Geophysical Research Letters*, **24**, 2697–2700.

Maruyama, T., 1997. The quasi-biennial oscillation (QBO) and equatorial waves - a historical review. *Papers in Meteorology and Geophysics*, **48**, 1–17.

McConnell, J. and J. Kaminski, 1996. *Science of Total Atmospheric Ozone*. Workshop on Atmospheric Ozone. Downsview, Ontario: Ontario Climate Advisory Committee.

McElroy, C.T., *et al.*, 1998. Evidence for the presence of BrO in the free troposphere during the Arctic polar sunrise. *Nature*, in press.

Newman, P.A., J. Gleason, et al., 1997. Anomalously low ozone over the Arctic. *Geophysical Research Letters*, **24**, 2689–2692.

Rex, M., P.P. von der Gathen, *et al.*, 1998. In situ measurements of stratospheric ozone depletion rates in the Arctic winter 1991/1992: a Lagrangian approach. *Journal of Geophysical Research*, **103**, 5843–5853.

Shindell, D.T., *et al.*, 1998. Increased polar stratospheric ozone losses and delayed eventual recovery owing to increasing greenhouse-gas concentrations. *Nature*, **392**, 589–592.

Wardle, D.I., 1997. Trends in ozone over Canada, ozone-depleting substances, and the UV-B. Pages 66–74 in *Emerging Air Issues of the 21st Century*, Proceedings of a conference held at Calgary, Alberta, September 1997. Pittsburgh: Air and Waste Management Association.

Wardle, D.I., J.B. Kerr, C.T. McElroy, and D.R. Francis. 1997. *Ozone Science: A Canadian Perspective on the Changing Ozone Layer*. Downsview, Ontario: Environment Canada.

Wennberg, P.O., et al., 1998. Hydrogen radicals, nitrogen radicals, and the production of ozone in the upper troposphere. *Science*, **279**, 49–53.

World Meteorological Organization, 1999. *Scientific Assessment of Ozone Depletion: 1998*. Geneva: World Meteorological Organization, in press.