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The Arctic Ozone Layer

*How the Arctic Ozone Layer is Responding to
Ozone-Depleting Chemicals and Climate Change*



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Catalogue No.: En164-18/2010E
ISBN: 978-1-100-10787-5

Aussi disponible en français


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by Angus Fergusson



Acknowledgements



The author wishes to thank David Wardle, Ted Shepherd, Norm McFarlane, Nathan Gillett, John Scinocca, Darrell Piekarz, Ed Hare, Elizabeth Bush, Jacinthe Lacroix and Hans Fast for their valuable advice and assistance during the preparation of this manuscript.



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*Looking north over
Ellesmere Island, Nunavut*



Summary

The report *Arctic Ozone: The Sensitivity of the Ozone Layer to Chemical Depletion and Climate Change* was published in 1998, based on research carried out from the 1960s to the mid-1990s. Over the last 10 years, significant advances have been made in ozone depletion science, namely in monitoring and observation, analysis and computer modelling. This report updates the science, looking into how the Arctic ozone layer has evolved since 1998. The most recent information is based on work reported in the World Meteorological Organization's *Scientific Assessment of Ozone Depletion: 2006*, the United Nation Environment Programme's 2006 *Environmental Effects of Ozone Depletion and its Interactions with Climate Change*, the 2005 *Arctic Climate Impact Assessment* and the special March 2008 issue of *Atmosphere-Ocean*: "Ozone Science in 2007: A Canadian Perspective on Ozone in the Changing Atmosphere."

During the 1990s when the Arctic atmosphere was unusually cold, scientists observed extensive ozone losses over the Arctic and were concerned that episodes of serious ozone depletion could become even more frequent. There was also unease among scientists that ozone losses over the Arctic could reduce ozone amounts over the middle latitudes as a result of the mixing of air masses. The concern was that concentrations of ozone-depleting chemicals containing chlorine or bromine atoms would be near peak levels at the end of the 20th century, and the cooling of the Arctic stratosphere resulting from increases in the concentration of carbon dioxide in the atmosphere could create more favourable conditions for ozone depletion than had previously existed. In other words, at the end of the 20th century, the Arctic was expected to be vulnerable to significant ozone depletion for the subsequent 20 years.

Since 2000, however, scientists have observed changes in the total ozone and temperatures in the atmosphere of the Northern Hemisphere. The

total ozone values in the Northern Hemisphere reversed their downward trend starting in about 2000 and increased at a rate that was higher than what had been expected from the change in the concentration of ozone-depletion substances in the atmosphere. Over the same time period, the serious Arctic ozone depletion episodes continued to occur during abnormally cold years, but the intensity of the cold years diminished (Fioletov 2008). Even though ozone depletion is still occurring in the Arctic atmosphere, it has not been in the same proportions since 2000. This may be due to a strengthening of the stratospheric circulation increasing the abundance of stratospheric ozone in the Arctic and warming the Arctic stratosphere. This change could be partly due to increased energy driving of the stratosphere, an expected response to greenhouse gas increases, or partly due to natural variability.

Research has shown that large increases in ultraviolet radiation at the earth's surface as a result of severe ozone depletion are highly damaging to sensitive Arctic life forms. In abnormally cold years, Arctic ozone levels have been 30 to 60 percent below normal in the spring, which produced a corresponding but slightly larger increase in ultraviolet radiation at the earth's surface. Although ultraviolet radiation levels are generally very low in the Arctic in spring, the increase in ultraviolet radiation has caused concern about human and environmental impacts, such as increased incidence of sunburns and snow blindness that had not been previously observed. The warming of the northern climate has accompanied a decrease in the extent of ice and snow cover in polar and sub-polar areas. Since ice and snow strongly attenuate the penetration of ultraviolet radiation into the water column, the extreme decrease in the sea ice and snow cover that occurred in the late summer of 2007 and in 2008 altered the exposure of aquatic ecosystems to solar ultraviolet radiation. An increase in ultraviolet

radiation has been shown to damage organisms that live near the surface of the water during their early stages of life.

Severe losses of ozone over both the Arctic and Antarctic are the result of special meteorological 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 poles 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 -78°C or less, clouds made up of ice, nitric acid and sulphuric acid begin to form in the stratosphere. Called polar stratospheric clouds (PSCs), they give rise to a series of chemical reactions that destroy ozone far more effectively than the reactions that take place in warmer air. Once PSCs are created, the destruction of ozone begins with the return of sunlight in the spring. This starts a series of chemical reactions to free chlorine through photolysis. The destruction continues rapidly until all the available ozone is depleted. As the atmosphere slowly warms in the spring, the vortex dissipates and warmer temperatures prevent further PSCs from being formed.

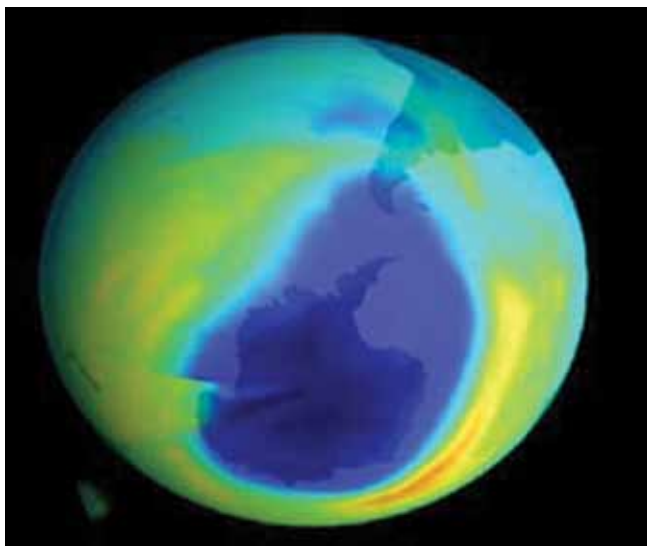


Figure 1. The Antarctic ozone hole reached a maximum size of 27 million km^2 in October 2000. Source: National Aeronautics and Space Administration

Over the Antarctic, these processes commonly lead to the formation of a massive ozone hole

every spring, as shown in Figure 1. Over the Arctic, similar processes occur, but ozone amounts have not fallen to the very low levels observed in Antarctica. This is partly because the Arctic has a higher concentration of ozone in the late winter and spring. It is also a result of the variable atmospheric circulation of the northern hemisphere, which makes the Arctic circulation vortex less stable. As a result, incursions of air from the south often keep the Arctic stratosphere too warm for PSCs to be formed.

Arctic ozone depletion will continue to be of concern in the coming decades as a result of the high concentration of anthropogenic ozone-depleting substances in the atmosphere and the variability of Arctic meteorological conditions. Controls are in place under the Montreal Protocol on Substances that Deplete the Ozone Layer to phase-out the production of ozone-depleting substances from the atmosphere. Eliminating these chemicals from the atmosphere will take between 50 to 100 years, since ozone-depleting substances break down and are removed only very slowly from the atmosphere. There is uncertainty about the severity of the impact of climatic changes caused by increasing accumulations in the atmosphere of greenhouse gases, such as carbon dioxide, methane, nitric oxides and halocarbons. Changes from radiative and chemical mechanisms brought on by increases in these gases will affect stratospheric ozone. In addition, the wind circulation in the stratosphere is changing due to alterations in the troposphere climate (Shepherd 2008), with implications for ozone and ultraviolet radiation. Although the buildup of these gases causes warming in the earth's lower atmosphere, carbon dioxide also contributes to cooling in the upper stratosphere, through more efficient radiative cooling. 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. Studies with atmospheric models suggest that this effect could either delay or accelerate a recovery of the Arctic ozone layer.



Muskoxen on Ellesmere Island, Nunavut.

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 (the periodic reversal of the direction of stratospheric winds over the equator), the El Niño southern oscillation, the solar cycle (slight variations in solar radiation associated with the sunspot cycle) and volcanic eruptions.



Instrumentation and scientist on top of the Polar Environment Atmospheric Research Laboratory.

Continued monitoring of, and research on, stratospheric ozone are necessary to improve our understanding of depletion processes and strengthen our capability to predict how the ozone layer may respond to changing atmospheric conditions and stresses. Canada's involvement in ozone research and monitoring reflects our special concern as a northern polar nation over the fate of the Arctic ozone layer.

The manner in which the Arctic ozone layer evolves in the future will depend not only on the elimination of ozone-depleting chemicals, but also on the control of greenhouse gases and other pollutants. These issues are linked and it makes scientific sense to address them through a comprehensive and integrated approach.



Sunset from the Polar Environment Atmospheric Research Laboratory, Eureka, Nunavut.



*Sunset over the Brewer
spectrophotometer,
Eureka, Nunavut*

Introduction

Since the 1980s, the depletion of the Arctic ozone layer has been of great concern, due to the sensitivity of human health and the environment to increased ultraviolet radiation (UV): elevated levels of ultraviolet radiation will have an impact on people living in the Arctic and on Arctic ecosystems (Arctic Climate Impact Assessment 2005).

In 1992, Environment Canada developed the UV Index to provide Canadians with updates of the status of the ozone layer and information on the intensity of erythermal ultraviolet radiation (which causes sunburns) reaching the earth's surface. In Canada, the UV Index ranges from 0 to 11, with 11 being an extreme value of the intensity over southern Ontario in June. The UV Index is normally low in the Arctic for most of the year, reaching into the moderate range during the summer, as illustrated

in Figure 2 for Resolute Bay, Nunavut. Although the ultraviolet radiation is normally weak in the Arctic, it is reflected by snow and clouds, which increases its strength and impact. For example, its reflection from fresh snow can almost double the amount of ultraviolet radiation received, causing sun burns and affecting human vision.

The other area of great concern is the reduction of the extent and thickness of sea ice that has been observed in the summer over the past few decades. The loss of sea ice allows the ultraviolet radiation to enter the water column and alter the exposure of aquatic ecosystems to ultraviolet radiation.

Ecologists have serious concerns about the possible effects on Arctic plants and animals of major ozone losses and the corresponding increase in ultraviolet

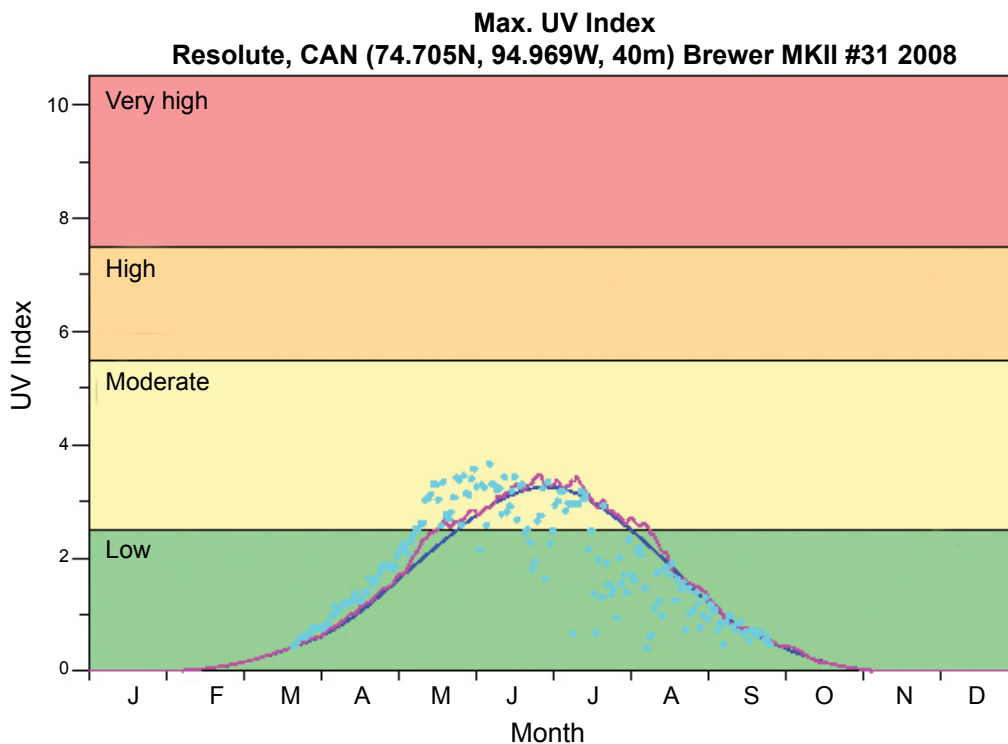


Figure 2. The daily maximum ultraviolet index for Resolute Bay, Nunavut, in 2008.
Source: Archive Preliminary

radiation. Because Arctic life has evolved in an environment in which ultraviolet radiation levels are normally low, organisms may be extremely sensitive to the increased radiation that reaches the earth's surface during periods of significant ozone depletion.

Since 1990, the Arctic ozone layer has experienced severe ozone depletion in 10 out of the last 18 years, all when the Arctic stratosphere was unusually cold. Although ozone depletion occurs as a result of the elevated concentration of ozone-depleting substances in the atmosphere, cold temperatures less than -78°C and a stable wind circulation of the Arctic atmosphere for a long period during the late winter and spring can create conditions that are right for severe depletion. A stable wind circulation limits the possibility of the incursion of warm air from the mid-latitudes known as stratospheric sudden warming. The cold conditions allow for the formation of polar stratospheric clouds that provide a surface for the conversion of stable compounds into unstable chemicals. With the energy provided by sunlight, the unstable chemicals break apart rapidly and release the chlorine and bromine atoms that destroy the ozone.

Although this pattern continues today, there has been a decrease in the intensity of very cold years since 2000. The Arctic atmosphere appears to be warming and fewer severe ozone depletion episodes are occurring. This could be due to an increase in stratosphere circulation, which is moving more air and ozone from the tropics to the pole. The air warms adiabatically as it descends through the stratosphere into the troposphere in the polar region. The result has been fewer very cold years in the Arctic and fewer years with severe ozone depletion. Scientific assessments suggest that the Arctic atmosphere will continue to be vulnerable to ozone depletion over the next 10 to 20 years during abnormally cold years. In the years when the Arctic atmosphere is warm, ozone depletion will be at levels similar to those for the middle latitudes.

Ozone depletion rates in the Arctic have not been as high as those in the Antarctic. Massive ozone holes have formed over Antarctica almost every spring

since 1982, reaching a maximum size in 2000 of 29 million km^2 . In comparison, severe ozone depletion has only occurred in the Arctic during very cold years. For example, as shown in Figure 3, severe ozone depletion occurred in the Canadian Arctic in 1997, decreasing to more than 45 percent below pre-1980 means on individual days. In Sweden in the spring of 2000, ozone loss was observed to reach 70 percent at an altitude of 20 km; ozone losses of 40 percent were estimated for southern Greenland for the first 10 days of March 2005.

Concentrations of known ozone-depleting substances in the stratosphere peaked between 1995 and 2000, but remained close to their peak levels for the subsequent decade because of their long lifetimes in the atmosphere. There are, however, other forces at work in the Arctic atmosphere. The loss of stratosphere ozone over the pole causes the stratosphere to cool, since ozone absorbs sunlight. In addition, climatic changes stemming from the buildup of greenhouse gases may be altering the Arctic stratosphere in ways that could potentially increase the intensity of ozone depletion events during abnormally cold winters. Severe ozone depletions in the Arctic also have repercussions for ozone levels elsewhere in the Northern Hemisphere. After a severe ozone depletion event, the ozone-poor Arctic air mixes with and dilutes the ozone content of air further south. Indeed, the polar regions, with their unique atmospheric processes, may influence the rate of recovery of the global ozone layer.

The Government of Canada is especially concerned about the future of the Arctic ozone layer, due to the country's vast northern territories. The Government has conducted extensive monitoring and research to measure trends and changes in the Arctic stratosphere. Canadian scientists have also placed a high priority on collaborating with their counterparts around the world to improve scientific understanding of processes affecting Arctic ozone as well as global ozone generally.

This report summarizes what is known 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 stem from ozone-destroying pollutants released by human activities, which result in long-term changes to the ozone layer. There are also crucial links between Arctic ozone destruction and changes occurring in the stratosphere as a result of climate change. Current controls under the 1987 Montreal Protocol on Substances that Deplete the Ozone Layer should eventually repair much of the damage done.

However, whether Arctic ozone depletion becomes more serious before it gets better will ultimately depend on the complex interaction of all these elements and the degree to which the Parties to the Protocol meet the control measures of the Montreal Protocol. If all the Parties are successful, and if our current understanding of the science holds true, we would expect the Arctic ozone layer to return to pre-1980 levels by the middle of this century.

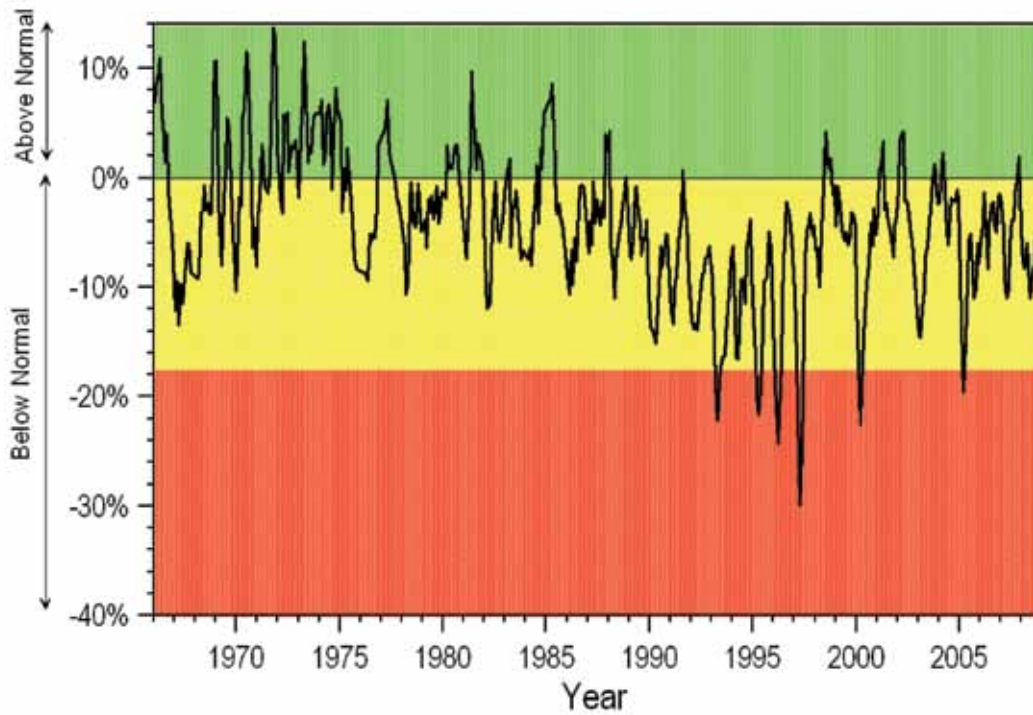


Figure 3. Deviation in total ozone changes over the Canadian Arctic from 1965 to 2009.
Source: Fioletov, 2008



Iqaluit, Nunavut, March 2007

The Natural Ozone Regime and the Arctic

Ozone forms 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 ultraviolet rays penetrate deeply into the atmosphere. Stratospheric winds distribute the ozone over the rest of the world. Eventually, sunlight destroys the ozone in reactions involving chlorine, bromine, water vapour, nitrogen oxides and other substances in the air. 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. The amount, in fact, varies considerably from day to day, season to season, year to year, and place to place, as shown

in Figure 4, but in 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 standard temperature (0°C) and pressure (1013.25 millibars or one atmosphere or "atm"). Most of this ozone is in the stratospheric ozone layer, but a small amount (about 10 percent) is also present near the earth's surface, brought down by air currents from the stratosphere, created by chemical reactions involving air pollutants or present naturally. Average yearly ozone values range from a low of 260 DU in the tropics to a high of 380 DU in the Arctic. In early spring, ozone levels over parts of the Arctic commonly exceed 500 DU on some days, as shown in Figure 5.

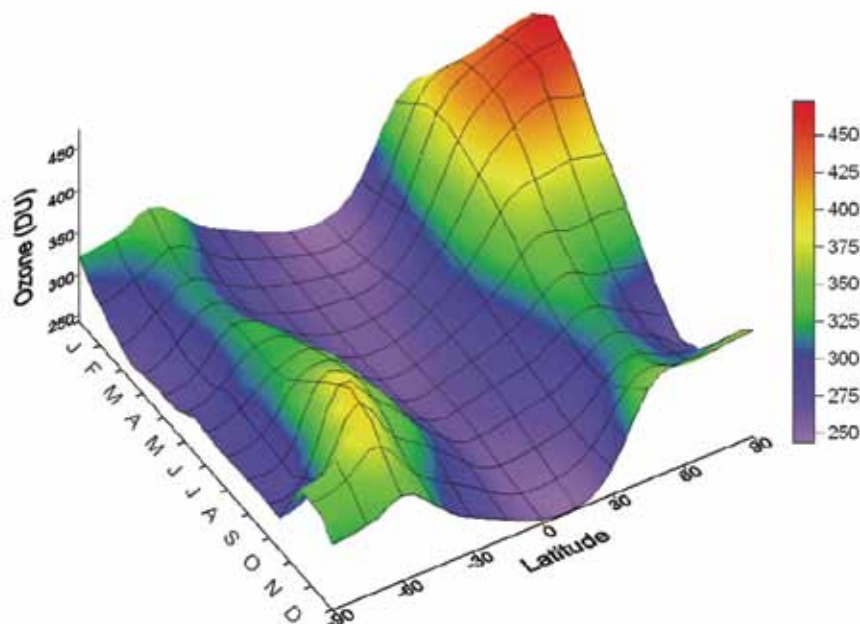


Figure 4. Surface plot of zonal mean total ozone as a function of latitude and month, estimated from ground based data for the period from 1964 to 1980.

Source: Fioletov 2008

Mean total ozone (DU), 2008/03/01-2008/03/10

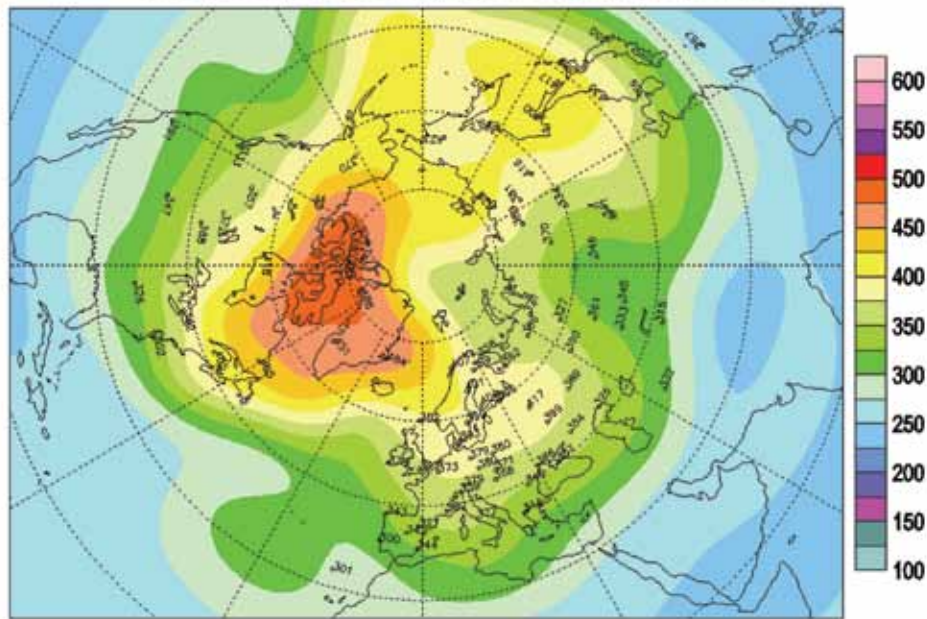


Figure 5. Mean total ozone over the northern hemisphere for the period from March 1 to 10, 2008.
Source: WOUDC

The fact that the highest ozone levels 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. First, the total absence of sunlight for several weeks to months during the Arctic winter slows down the destruction of ozone. Without solar energy to split ozone molecules apart, the natural breakdown of ozone slows considerably. Second, the flow of ozone towards the pole is generally greater in the winter than at other times of the year. This seasonal bias appears to be related to seasonal shifts in upper-level wind patterns that provide much of the energy that drives the air and, therefore, ozone in the stratosphere toward the pole. Third, the stratosphere is deeper over the polar latitudes than anywhere else in the world. To understand why, it is necessary to look at the atmosphere's vertical structure (see Figure 6). The stratosphere sits on top of the troposphere, which is the lower, more turbulent layer of the atmosphere where weather activity takes place. The troposphere commonly occupies as much as the bottom 18 km 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, similar to the slope of the bottom of a swimming pool. Because the deepest part of the stratosphere is over the Arctic, it can hold more ozone than can the stratosphere over the tropics or



The High Arctic Weather Station at Eureka.

middle latitudes. 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 geography and meteorology of the southern hemisphere, which influence the stratospheric wind circulation from the tropics to the south pole. In the stratosphere, the vertical and north-south component of the wind circulation—rising in the tropics, moving towards the pole in middle latitudes and descending in the polar regions—is known as the Brewer-Dobson circulation.

Ozone accumulates gradually in the Arctic stratosphere during the winter as the rate of supply from the tropics exceeds the natural rate of destruction. With the arrival of spring, ozone values reach to 450 DU or more. The reappearance of the sun increases the pace of ozone destruction, however, while the rate at which ozone is transported from the tropics falls off considerably and remains low throughout the summer. Consequently, ozone levels decline from the late spring high of approximately 450 DU to about 300 DU in October.

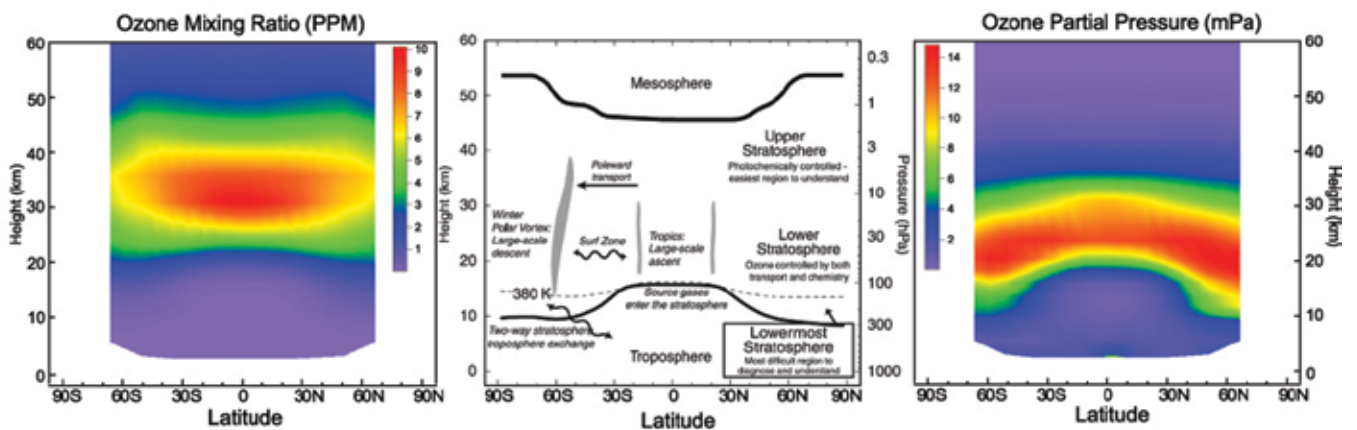


Figure 6. Left panel: Annual mean ozone mixing ratio (the fractional concentration of ozone as the number of ozone molecules per million air molecules). Middle panel: A schematic diagram showing the structure and circulation of ozone from the tropics towards the poles in the atmosphere. Right panel: The mean pressure that ozone alone creates in the atmosphere illustrating ozone structure and concentration.

Source: Fioletov, 2008



*Baffin Island in the
Canadian Arctic, March 2007*

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

The ozone layer was created over the earth some two billion years ago and is believed to have been relatively stable ever since. In the mid-1970s, scientists discovered that industrial chemicals such as chlorofluorocarbons were changing the chemical balance in the upper atmosphere, causing stratospheric ozone to be destroyed at a faster-than-normal rate. Depletion of the ozone layer is occurring because human activities have increased the natural abundance of ozone-depleting substances in the stratosphere, causing an increase in the rate of destruction of stratospheric ozone that exceeds the natural rate of replenishment. Ozone-depleting substances are stable chemicals in the lower atmosphere but degrade under intense ultraviolet radiation in the upper stratosphere and release their chlorine or bromine atoms. Man-made ozone-depleting substances include chlorofluorocarbons, hydrochlorofluorocarbons, carbon tetrachloride, methyl chloroform, methyl chloride and methyl bromide. Of these chemicals, only methyl chloride and methyl bromide are found naturally in the environment as well as being industrial chemicals.

Chlorofluorocarbons are highly versatile chemicals that have been widely used as refrigerants, foams and spray propellants as well as in an extensive variety of industrial applications. They are also the predominant ozone-destroying substances in the stratosphere, responsible for the largest percentage increase of chlorine in the atmosphere. Halons and methyl bromide are also major ozone-depleting substances that contain the bromine atom and whose concentrations have been growing in the atmosphere in recent years. The bromine atom is about 60 times more effective at destroying ozone in the stratosphere than the chlorine atom but is found in much smaller concentrations. Halons were used mostly in fire extinguishers, while methyl bromide is still used as a fumigant and pesticide.

Most of these ozone-depleting chemicals can survive for many years, becoming horizontally and vertically well mixed in the lower atmosphere. The chemicals are eventually carried up to the tropopause by air motion or convection, where they ascend into the stratosphere in association with the Brewer-Dobson circulation or other dynamics. Once there, these compounds gradually rise above the ozone layer to be broken down by the sun's intense ultraviolet radiation, which releases their chlorine or bromine atoms. Chlorine and bromine are powerful ozone destroyers because they act catalytically—that is, they are part of reactions that destroy ozone but are not themselves consumed, so they are free to be part of more of these reactions. Consequently, a single atom of chlorine or bromine can destroy hundreds of thousands of ozone molecules before it returns to the troposphere and is removed by other chemical reactions. It is estimated that the burden of chlorine in the atmosphere rose from a natural state of 0.5 parts per billion before the invention of chlorofluorocarbons to 3.5 parts per billion by 1994.

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 closed natural circular wind circulation system that develops around the poles with the onset of winter, isolating the polar air from middle latitude air. Without sunlight and warmer air flowing in from lower latitudes, the polar stratosphere becomes extremely cold, with temperatures falling to -78°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 would be quite stable and therefore harmless to the ozone layer under ordinary circumstances. However,

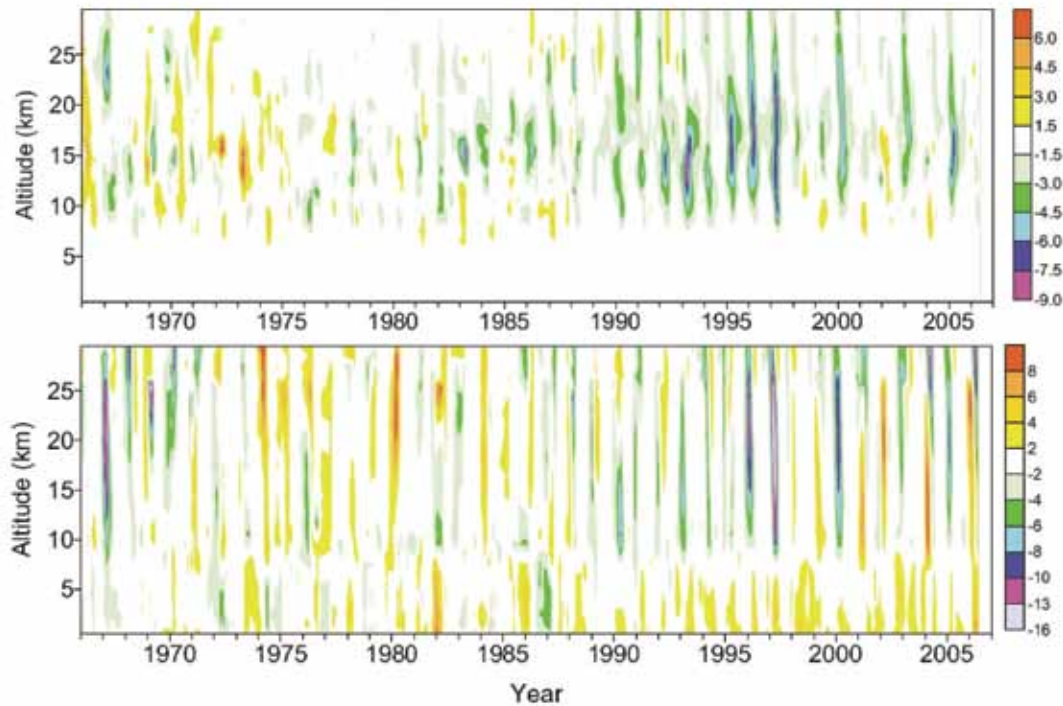


Figure 7. Ozone deviations from normal in Dobson units per kilometer (top panel) and temperature deviations from normal in degrees Celsius over the Resolute, Eureka and Alert, Nunavut (bottom panel): three-month running mean values. The panels indicate the close correlation between extensive ozone depletion (dark blue in top panel) and cold stratospheric temperatures below -78°C .

Source: Fioletov 2008

PSCs provide a surface on which these compounds can break down, leaving the chlorine and bromine atoms in less stable compounds. When sunlight returns in the spring, solar radiation breaks these compounds apart, releasing the chlorine and bromine atoms. Ordinarily, the reactions that destroy ozone require strong sunlight. However, with the cold temperatures and the especially high concentrations of chlorine present in the vicinity of PSCs, the reactions that do take place in the spring sunshine are actually far more effective at destroying ozone in comparison to those at middle latitudes. Without the flow of fresh ozone from lower latitudes, which is blocked by the vortex, ozone amounts drop rapidly and deeply as these reactions proceed, as shown in Figure 7. 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). This hole does 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; however, research indicates that conditions will not develop to thin the ozone layer to anywhere near to the same extent 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 southern counterpart. As a result, it is frequently penetrated by stratospheric flow patterns that bring ozone and warmer air from the south, as illustrated in Figure 8. This figure depicts the zonal mean temperature, which is the mean temperature component along the local parallel of latitude. Because of these events, known as stratospheric sudden warmings, the Arctic stratosphere becomes too warm for PSC formation. Consequently, PSCs do not form as often in the Arctic nor do they last as long as they do over the Antarctic. For that reason, no single massive ozone hole has ever developed over the Arctic.

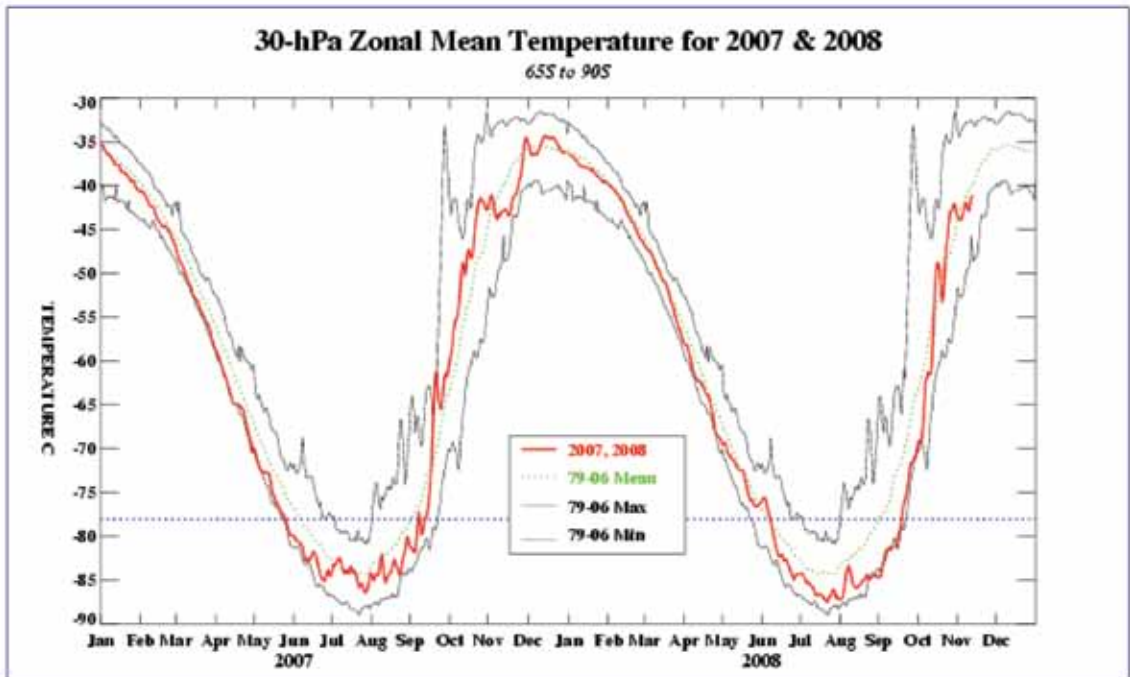
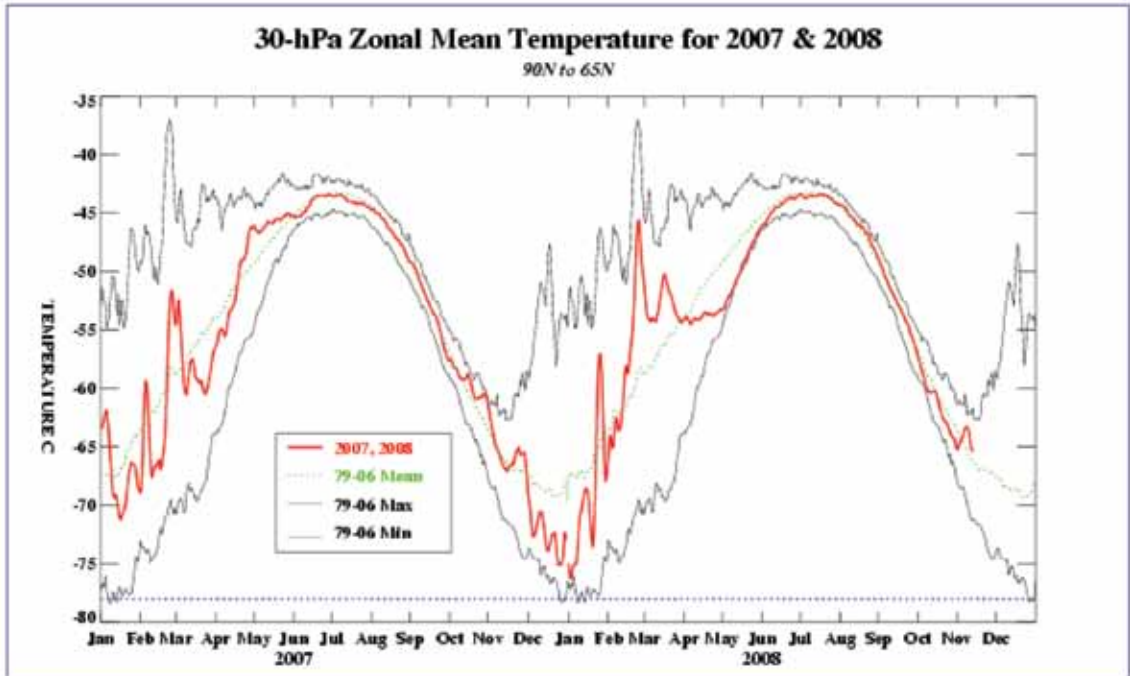
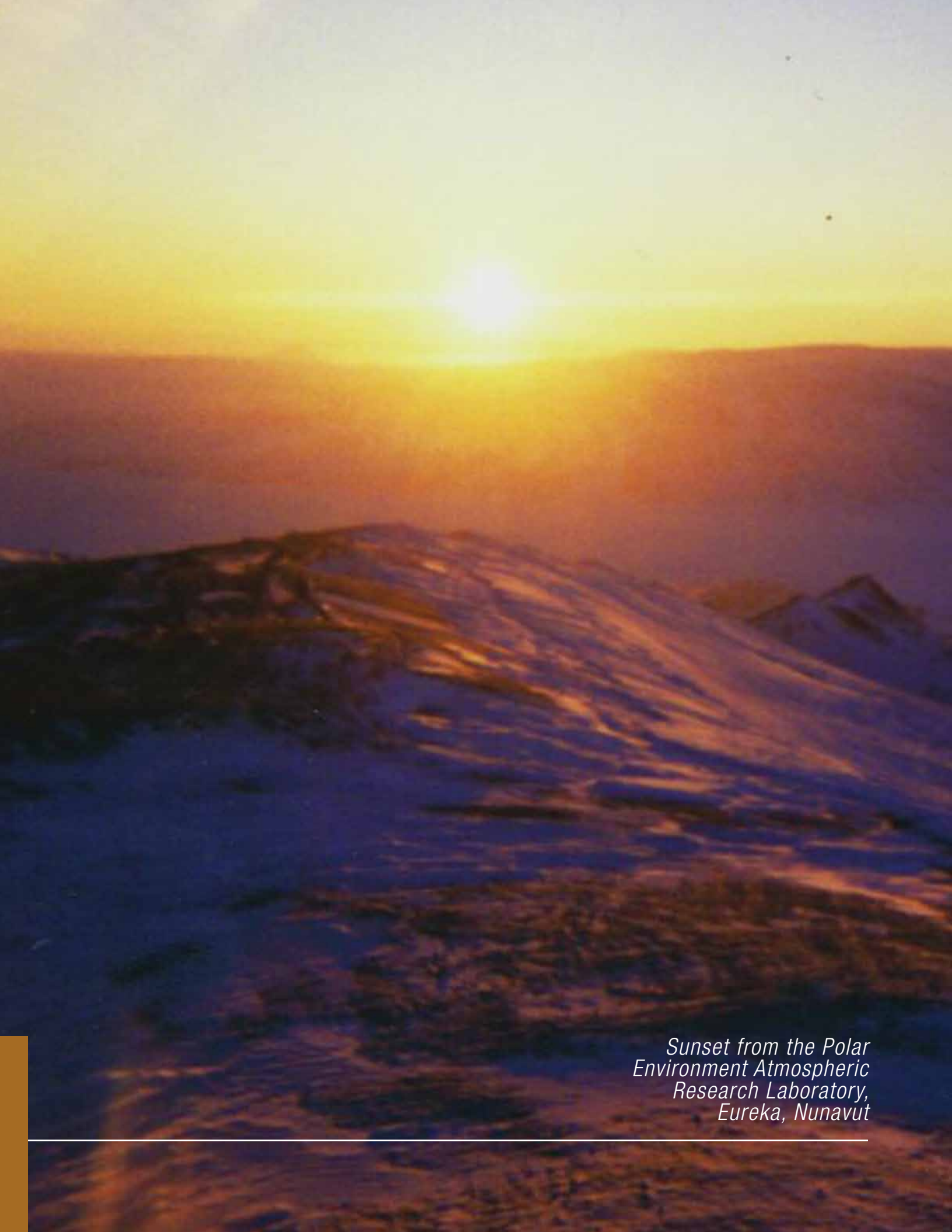


Figure 8. Zonal minimum temperatures for 2007 and 2008 for the Arctic (top panel) and the Antarctic (bottom panel). The warming of the Arctic stratosphere is clearly evident in late February 2008. In comparison, the stratosphere over the Antarctic in 2008 was colder than average, and the warming occurred in late spring as the vortex dissipated.

Source: Climate Prediction Center, National Oceanic and Atmospheric Administration



*Sunset from the Polar
Environment Atmospheric
Research Laboratory,
Eureka, Nunavut*

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 affect ozone levels. For example, day-to-day changes as large as 25 percent of the mean total ozone are often associated with the movement of weather systems and pressure patterns in the troposphere, and with changes in the height of the tropopause. Long-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 Niño southern oscillation, the solar or sunspot cycle, and volcanic eruptions. Many of these processes affect the flow of ozone directly or do so indirectly through other processes. For example, the solar cycle affects atmospheric pressure and wind circulation, thereby affecting the flow of ozone in the stratosphere. Variations in solar UV associated with the solar cycle directly affect the production of ozone in the upper stratosphere, which in turn influences ozone in the lower stratosphere.

The Quasi-Biennial Oscillation

Over the equator, the stratospheric winds circle the globe in either an easterly or a westerly direction. Every 20 to 30 months the direction reverses, starting from the top of the stratosphere and working down. This phenomenon is known as the quasi-biennial oscillation (QBO). Its ultimate cause is not fully understood, but it is thought to be created by the upward propagation of energy in atmospheric waves from the troposphere. The QBO is known to influence a variety of atmospheric phenomena, including stratospheric ozone amounts over the middle and high latitudes. When the QBO is in its westerly phase, polar stratospheric temperatures tend to be lower, the Arctic vortex stronger, the transport of ozone toward the pole reduced and ozone depletion greater. In 1993, 1995, 1997 and

2000, for example, the QBO was predominantly in its westerly phase and large ozone losses were recorded in the Arctic. In 1994, 1996, 1998, 2005 and 2006, it was in its easterly phase. Depletion was minimal, as expected, in 1994, 1998 and 2006, but losses as high as 30 percent and 45 percent occurred in 1996 and 2005, respectively. These unexpected results suggest that factors other than the QBO had a substantial effect on ozone levels in those years.

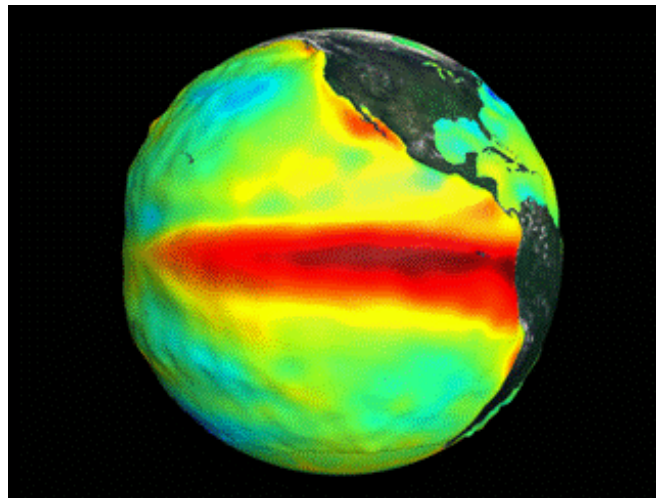


Figure 9. Warming (red area) of the tropical Pacific Ocean due to El Niño.

Source: NASA

El Niño Southern Oscillation

As shown in Figure 9, El Niño is a periodic warming of the eastern equatorial Pacific Ocean. Occurring roughly every three to seven years, it is accompanied by a reversal of normal pressure patterns over the Southern Hemisphere (a phenomenon known as the southern oscillation), which results in disturbances of prevailing weather patterns in much of the world. Because El Niños also change normal pressure patterns in the upper troposphere, they alter the height of the tropopause, affect the transport of ozone toward the poles, and cause changes in ozone levels over many parts of the world.

One of the strongest observed El Niños occurred in 1997 and 1998, the consequence of which was a deepening of the Aleutian Low, a large, semi-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 stratospheric sudden 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 of that year. Since the El Niño of 1997 and 1998, the others that have followed in 2002, 2004 and 2006 have been generally weak.

The Solar Cycle

Over a period of approximately 11 years, the total energy output of the sun varies by only about 0.1 percent, changing with the growth and decay of sunspots on the solar surface, which are shown in Figure 10. When the number of sunspots is greatest, the sun produces more energy than when the number of sunspots is at its lowest. Although the change in energy output is quite small, much of it is concentrated in the ultraviolet range. Since ozone is created as a result of the breaking down of oxygen molecules by the sun's ultraviolet radiation, more ozone will be produced in years when the solar cycle is at its maximum and correspondingly less ultraviolet radiation reaches the earth's surface. The observed variation in ozone amounts over the cycle is approximately one to two percent.

Studies have linked the solar cycle maximum to a slight warming of the winter stratosphere (thus making conditions less favourable for PSC formation) and to a strengthening of the transport of ozone toward the poles. 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 at the peak of the solar cycle (as it was in 1968, 1979, 1990 and 2001, and will be again in about 2012).

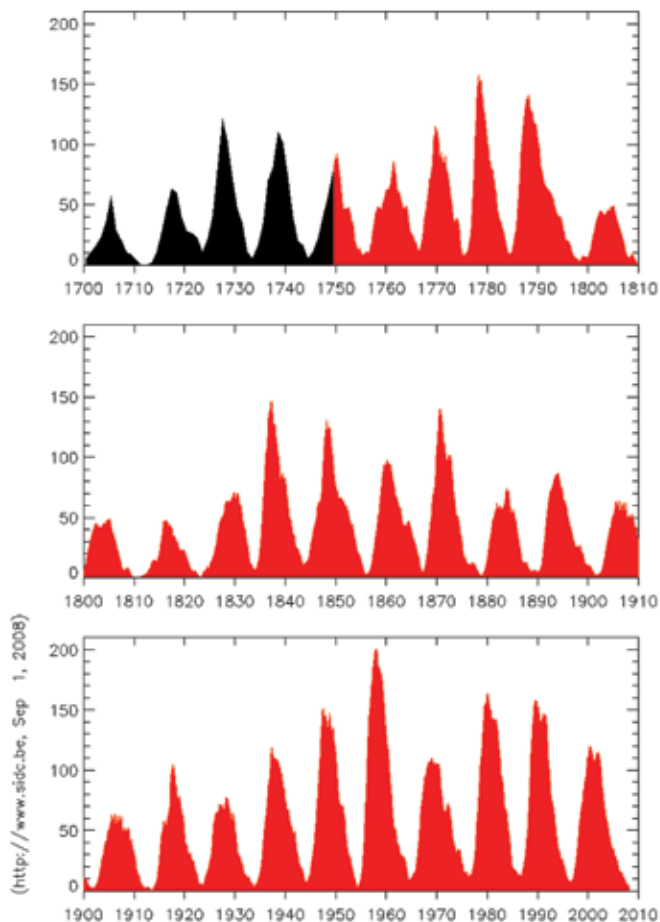


Figure 10. The solar cycle is a 11-year sunspot cycle. The number of sunspots on the surface of the sun has varied between 50 and 200 since the 1750s. The solar cycle affects the production of ozone and the average annual air pressure patterns in the stratosphere. Such pressure variations affect transport of ozone towards the poles, with more ozone being carried into the Arctic when the incoming solar radiation is greatest. Source: Solar Influences Data Analysis Centre, 2008

Volcanoes

Major volcanic eruptions can have a significant impact on stratospheric temperatures and ozone depletion over a one- or two-year period, as shown in Figure 11. 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 form in the stratosphere as a result of volcanic eruptions. These aerosols may also stimulate the formation of PSCs by various indirect processes.

The eruption of Mount Pinatubo in the Philippines in 1991, for example, put about 120 million tonnes of sulphur dioxide into the stratosphere; within a week or two, atmospheric reactions converted the gas into sulphate aerosols. During the next two years, severe ozone depletion was observed over northern mid-latitudes. Over Canada, ozone amounts in the spring of 1993 were 10 to 17 percent below normal, the largest decrease that had been observed up until that time. During the same

period, ozone amounts in the lower stratosphere in the high Arctic (between 10 and 20 km) fell to about 110 DU, a low value not seen again until 1997 during an episode of severe ozone depletion.

Volcanoes function as a kind of wild card when estimating future ozone depletion because the timing and magnitude of eruptions are unpredictable.

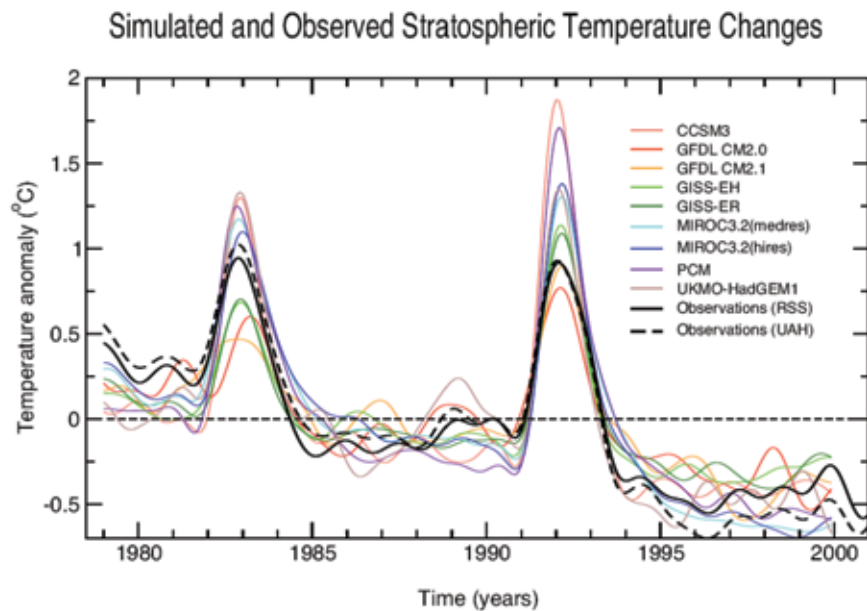


Figure 11. Globally averaged temperature variations in the lower stratosphere from a range of climate models and observations. The eruptions of El Chichón in 1982 and Mount Pinatubo in 1991 sent sulfate aerosols and ash into the stratosphere causing temperatures in the stratosphere to rise initially by about 1°C. They also caused tropospheric cooling for several years afterwards since the volcanic aerosols absorbed or reflected the solar radiation.

Source: World Meteorological Organization 2007



*Arctic flowers bloom
in the short summer season
at Eureka, Nunavut*

The Linkages between Climate Change and the Ozone Layer

Ozone depletion and climate change are often considered to be independent concerns. They involve different atmospheric processes from one another, have different impacts and are the subject of separate international negotiations and treaties. Yet both affect the same atmosphere, and, given the complex array of interactions and feedback that characterize atmospheric behaviour, it is not surprising that there are important linkages between them.

Some of these linkages are very direct. For example, the halocarbons that cause ozone depletion are also a greenhouse gas that contributes to warming in the lower atmosphere. Carbon dioxide, a powerful greenhouse gas warming the lower atmosphere, is also causing a net radiative cooling of the stratosphere, which may affect the evolution of the ozone layer in the polar regions.

There are many more subtle links involving changes in atmospheric circulations and chemical processes in the atmosphere. For example, changes in ocean temperatures and the energy distribution in the atmosphere as a result of the warming of the lower atmosphere may be changing the dynamics of the atmospheric circulation and the speed of chemical reactions and processes in the atmosphere. These links are very important for understanding how the atmosphere has changed, is changing and will change as a result of the addition to it of gases and chemicals.

Climate Change

Climate change has become a very serious concern in recent years because it will have adverse effects on life on earth. Human activities are causing concentrations of greenhouse gases, such as carbon dioxide, methane, nitrous oxide, ozone and halocarbons, to rise well above natural levels. It is widely accepted today that increasing the concentrations of the greenhouse gases will cause the troposphere to retain heat, raising the average surface temperature of the earth and lower atmosphere.

Figure 12 shows the trend in temperatures for Canada over the last 30 and 50 years. As shown in Figure 12b, Canada has warmed by more than 1.3°C over the past 60 years. The greatest warming (up to 2.6°C) has occurred in the last 30 years from the high Arctic to the lower Hudson Bay. In comparison, the Earth as a whole has warmed by about 0.74°C over the last 100 years (Intergovernmental Panel on Climate Change 2007).

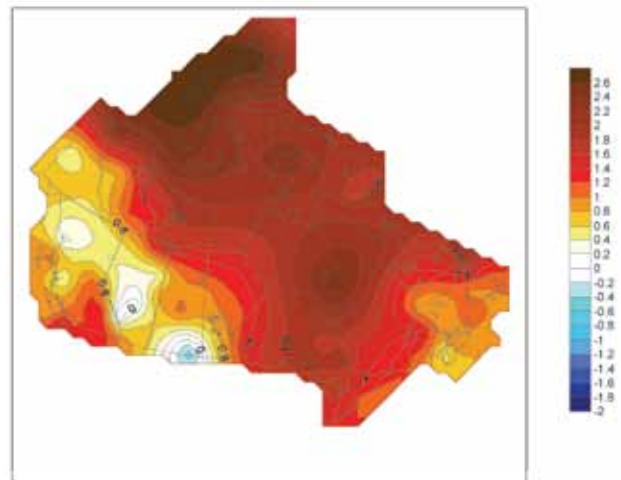
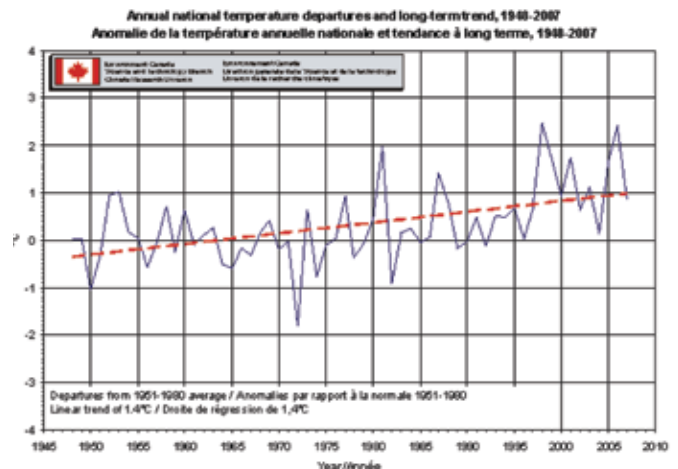


Figure 12. Above: Accumulated observed temperature trend in Canada from 1976 to 2006. Below: Departures from the annual national temperatures and the long-term average (1951–1980).

Source: Bob Whitewood, Climate Research Division, Environment Canada



Carbon dioxide, released by the burning of fossil fuels, is the most abundant of the greenhouse gases associated with human activities, but chlorofluorocarbons, the major players in ozone depletion, are also powerful greenhouse gases, with up to 10 000 times the global warming potential of carbon dioxide. In addition, ozone, itself a greenhouse gas, has a considerable effect on the earth's heat distribution. Not only does ozone add heat to the stratosphere when it absorbs ultraviolet radiation from the sun but it also absorbs long-wave radiation from the earth's surface.

The Linkages

The state of the atmosphere at any given time is the result of a constantly adjusting balance among a wide range of processes. By altering some of these processes, ozone-depleting substances and greenhouse gases trigger readjustments that affect other parts of this balance. Some of these readjustments have a significant effect on ozone depletion. There is a possibility, for example, that rising concentrations of methane will raise the water vapour content of the stratosphere, since water vapour is produced when methane reacts with two molecules of oxygen to produce two molecules of water plus carbon dioxide. Water, however, primarily flows into the stratosphere by being transported vertically across the tropical tropopause layer as part of the Brewer-Dobson circulation. Many studies have reported an increase in water vapour over various time periods. The increase can be attributed to an increase in methane or an increase in the Brewer-Dobson circulation. With more water vapour in the stratosphere, more polar stratosphere clouds could form (when temperatures are below -78°C) and ozone depletion would be enhanced.

Ozone losses in the lower stratosphere have led to cooling of the stratosphere, because with ozone depletion there is less ozone to absorb shortwave energy from the sun and longwave radiation from the earth. The cooling of the stratosphere through the loss of ozone has been shown to offset some, but not all, of the direct warming caused by the introduction of chlorofluorocarbons, a greenhouse gas,

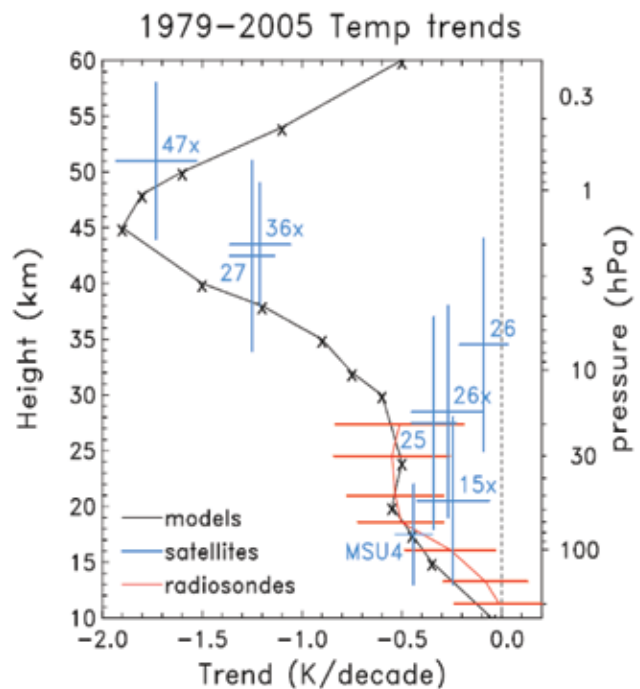


Figure 13. Vertical profile of temperature trends obtained from model, satellite and radiosonde data over 60°N to 60°S for the period from 1979 to 2005. Source: World Meteorological Organization 2007

into the troposphere. As shown in Figure 13, observations from satellites and radiosondes between 1979 and 2005 show that the lower stratosphere cooled by 0.5°C per decade. In the upper stratosphere, the cooling has been more pronounced, from 1 to 2°C per decade. Studies also indicate that ozone depletion has led to a smaller cooling of the Arctic polar vortex, which maximizes in the spring. Model studies suggest that only part of the observed cooling of the Arctic vortex can be attributed to ozone depletion.

The other significant cause of cooling in the stratosphere is the increase in carbon dioxide in the atmosphere, which increases the rate at which longwave radiation is emitted into space. With the buildup of carbon dioxide, more energy than normal is emitted into space from the top of the stratosphere as compared to the bottom of the stratosphere, resulting in an overall cooling as shown in Figure 14.

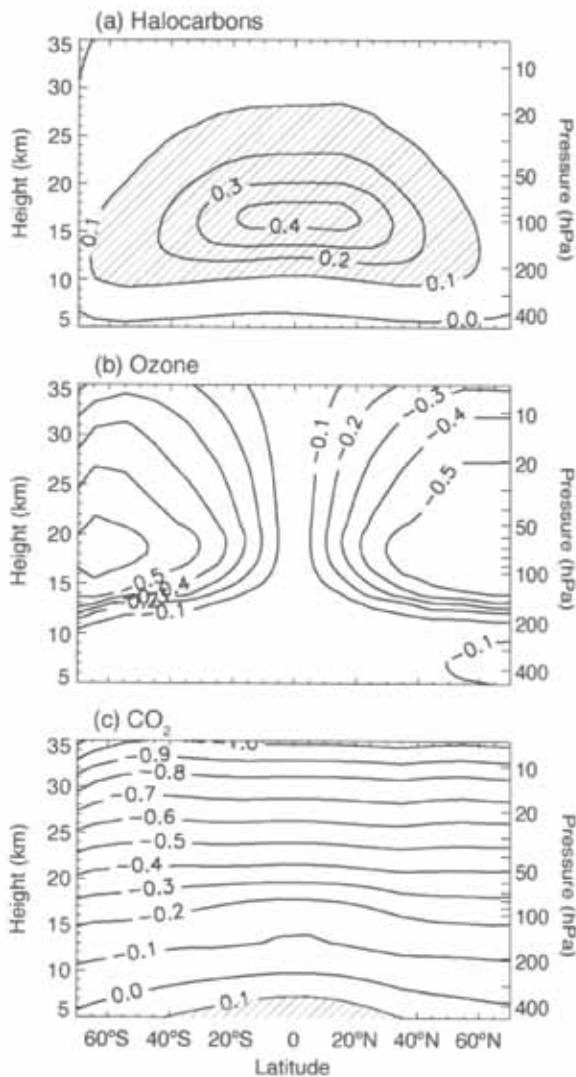


Figure 14. The annually averaged temperature change (K) for (a) total observed halocarbon change since about 1950, (b) the change in stratospheric ozone from 1979 to 1997, and (c) the 1980 to 2000 change in carbon dioxide.

Source: McFarlane 2008

The cooling of the stratosphere over the middle latitudes has been shown to slow the speed of chemical reactions and, hence, ozone depletion. Over the polar regions, however, the cooling of the polar stratosphere increased the likelihood and frequency of polar stratospheric clouds, leading to an increase in polar ozone depletion in the spring. Since this ozone-depleted air is exported from the polar regions in the late spring as the polar wind circulation breaks down, the concentration of ozone in the middle latitudes is reduced.

Atmosphere dynamics play an important role in understanding and accurately describing stratospheric ozone depletion. Dynamics affect the distribution and abundance of stratospheric ozone, directly through the transport of ozone itself and indirectly through their effect on ozone chemistry via temperature and transport of other chemical species. With ozone-depleting substances decreasing in the atmosphere and with the expected impacts of climate change, the tasks for researchers are to detect when a recovery will begin and to determine the possible future states of the ozone layer.

Computer models

Chemistry–climate models have become useful tools, since they provide a consistent representation of the dynamic aspects of climate and their coupling to ozone chemistry. A new area of model research involves quantifying the combined effects by evaluating the impact of stratospheric ozone depletion and its recovery on the tropospheric climate as well as understanding the effects of climate change on the evolution of ozone itself. This, in turn, requires understanding the long-term sensitivity of the climate system to changes in the radiation budget associated with human activities and natural events, such as volcanoes and solar variability, on the composition and evolution of the atmosphere and ultimately of the effects of such events on the climate change signal throughout the active atmosphere and at the surface.

The interactions between warming due to greenhouse gases and ozone depletion can be explored using global climate system models that incorporate not only the warming effects of greenhouse gases but also the reactions that determine the chemical composition of the atmosphere. In recent years, scientists have used estimates from complex climate computer models (coupled atmospheric–ocean general circulation models and chemistry–climate models with interactive ozone) to predict the general evolution of the stratosphere. All the models indicate a cooling of the global average stratosphere similar to what is being observed.

The degree of cooling varies by model and global scenario, but the general consensus is that there is a cooling of the global average stratosphere, from 0.5 K/decade in the lower stratosphere, increasing to 2.0 K/decade in the upper stratosphere. Predictions of the rate of cooling in polar regions are much more difficult to make, due to the high degree of variability in the Arctic atmosphere.

Arctic stratospheric model simulations indicate that there will not be a major decline in ozone levels in the Arctic atmosphere in the years to come but that it will slowly improve. This will depend to a large degree on the temperatures of the Arctic stratosphere. Severe ozone depletion episodes will occur in very cold years, similar to those that occurred in 2000 and 2005. Model simulations show that the Arctic stratosphere is getting warmer with more variability and that much of the increase in ozone can be explained by changes in wind circulation rather than a reduction in chlorine or bromine in the atmosphere.

The Canadian Middle Atmosphere Model provides results similar to those of the other major and reliable chemical–climate models in the world. For example (see Figure 15), it recreated the decline in the near-global total ozone (60°S–60°N) that occurred as the halogens increased in the atmosphere and predicts a recovery, with the expected decrease in future halogen concentrations. The model also suggests a strengthening of the Brewer–Dobson circulation in the stratosphere, which may lead to a “super recovery” to levels about four percent more than pre-1980 levels as more ozone is transported from the tropics to the Arctic. With the increased circulation, the model indicates a dynamic induced warming of the Arctic stratosphere that may limit the meteorological conditions suitable for severe ozone depletion in the Arctic.

Model simulations that include climate feedback indicate that the ozone layer over the middle latitudes will return to pre-1980 levels before similar recovery takes place in the polar regions. The cold spring temperatures and the high abundance of ozone-depleting chemicals in the Antarctic

atmosphere will result in the reoccurrence of the ozone hole until about 2065. Over the Arctic, model simulations indicate severe ozone depletion episodes will be possible until the middle of the century. The models also indicate that the interactions between ozone depletion and climate change have not led to large delays in ozone recovery. It cannot be assumed, however, that the interactions will be linear or will proceed at the current rate. Some Arctic observations currently indicate that climate change is occurring faster than the rate the models predict. As a result, profound changes in the climate systems of the troposphere and stratosphere should be anticipated, with unknown interactions and impacts on the environment and human health.

As reported by the Intergovernmental Panel on Climate Change in 2007, climate models suggest that the earth’s average surface temperature could rise by another 1.5 to 4°C by 2100. The range is dependent on the emission scenario for greenhouse gases and their rise over this century. However, as the ozone layer recovers as a result of measures under the Montreal Protocol, the polar stratosphere will warm as a result of the higher concentration of ozone, the frequency of polar stratospheric clouds will decline and the strength of the westerly winds in the vortex will decrease in the spring and summer. In other words, the troposphere changes due to the ozone depletion will reverse and the full effect of climate change will be realized.



Arctic icebergs.

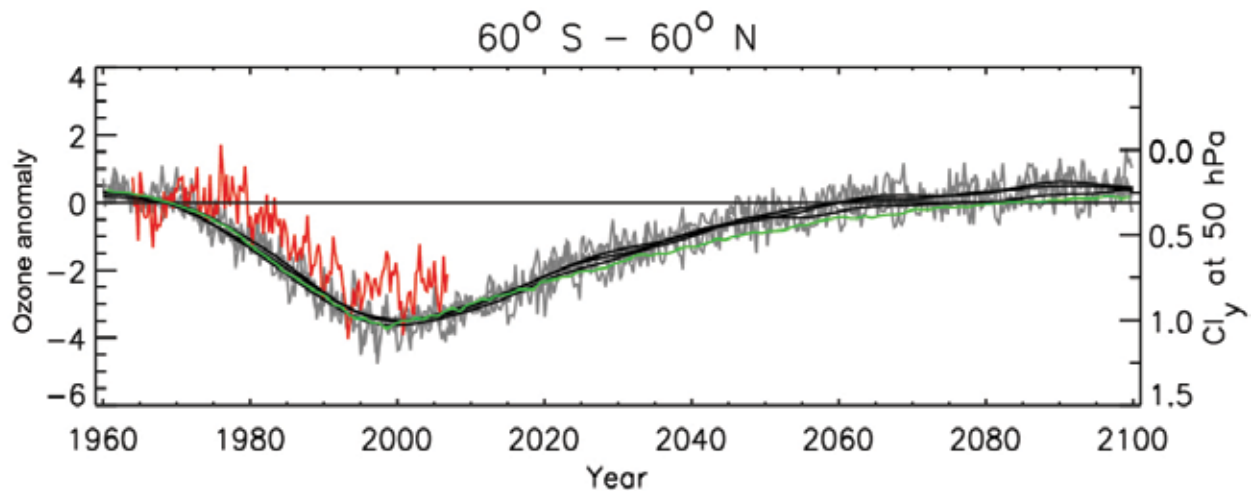


Figure 15. The grey lines show changes in near-global total ozone as projected by three Canadian Middle Atmosphere Model (CMAM) simulations for 1960 to 2100, relative to the 1960 to 1975 averages. The black lines are smoothed versions of the grey lines, and the green line shows the projected changes in inorganic chlorine in the lower stratosphere. The red line shows observed changes in ozone from 1964 to the present, relative to the 1964 to 1975 average. CMAM near-global total ozone follows the chlorine loading closely, and shows recovery to 1960 to 1975 levels occurring by 2060.

Source: Shepherd 2008



*Polar stratospheric clouds
photographed over Sweden*

Research and Observations: The State of the Arctic Ozone Layer

Observation and Monitoring

Scientists have been active in stratospheric ozone research since the late 1920s, but it was not until 1957 that Canada began, as its contribution to the International Geophysical Year, to establish a permanent network to gather data on stratospheric ozone. At this time, it was hoped that this research network would lead to improvements in weather forecasting. Monitoring stations using Dobson ozone spectrophotometers were installed at five sites between 1957 and 1964: Edmonton (1957), Resolute Bay (1957), Toronto (1960), Goose Bay (1962) and Churchill (1964). The Dobson ozone spectrophotometer, devised in the 1920s by the pioneering British ozone researcher G. M. B. Dobson, was used for these measurements until 1988 and then replaced by an automated Brewer ozone spectrophotometer developed by scientists at Environment Canada (T. McElroy, J. Kerr and D. Wardle).



Brewer spectrophotometers located on top of the Environment Canada building in Toronto.

The current Canadian observation network consists of 10 stations, 3 of which are located in the Arctic (Figure 16). Three additional sites, in Halifax, Montréal and Winnipeg, operated from the early 1990s until 2006.



Figure 16. The Canadian ozone observation network consists of 10 Brewer spectrophotometers. In southern Canada, they are located Goose Bay (Labrador), Toronto, Churchill (Manitoba), Regina, Saskatoon and Edmonton, and on Saturna Island in British Columbia. In the Arctic, Brewer instruments are located in Nunavut, at Resolute Bay, Eureka and Alert.

At all these sites, ground-based Brewer spectrophotometer instruments measure ozone. The instruments are programmed to make total ozone measurements with light from the sun and/or moon, and spectral scans of the horizontal ultraviolet irradiance. Since the 1980s, the data from the sites have been used to calibrate satellite measurements.

In addition to the ground-based Brewer ozone observations, some 300 ozonesondes—small instrument packages carried aloft by balloons (see Figure 17)—are launched by Environment Canada throughout the year at Edmonton, Churchill, Goose Bay and all three Arctic sites, to provide direct measurements of ozone concentrations at altitudes of up to 35 km. Ozonesondes have been launched from

Edmonton, Churchill and Goose Bay since about 1970 and from Resolute Bay, Alert and Eureka since 1966, 1987 and 1992, respectively.



Figure 17. Canadian ozonesondes, such as the one shown on the left, are launched from Edmonton, Churchill, Goose Bay, Resolute Bay, Eureka, and Alert to provide ozone measurements at altitudes of up to 35 km.

Source: Janice Lang, DRDC

Since 1991, Canada has participated in the Match ozonesonde program, which coordinates the launches of ozonesondes in the Northern Hemisphere to probe the same air mass at different points as it travels around the Arctic vortex. During a Match campaign, 300 to 600 ozonesondes are launched at 30 sites around the northern hemisphere, including the six Canadian ozonesonde sites. Data from satellites is also collected. By analyzing the differences between measurements taken at various times and places within this air mass, it is possible to determine the amount of ozone loss due to chemical processes alone and to avoid any distortions caused by ozone brought

in by other means, such as atmospheric circulation. Among other things, data from the Match program clearly revealed the crucial role of sunlight in ozone destruction. It also showed the role that polar stratospheric clouds and ice particles play in severe ozone depletion. The ice particles absorb and thereby remove nitrogen compounds from stable reservoir compounds (such as ClONO_2 , BrONO_2 , HCl) to release chlorine or bromine atoms in sunlight, which worsens ozone loss when the Arctic winter is particularly cold.

Canadian researchers from universities and governments worked together to detect ozone chemical changes in the stratosphere using very large (about 10 stories tall) research balloons. These balloons, as shown in Figure 18 were launched from Vanscoy, Saskatchewan, to study the stratosphere. They carried a gondola of instruments to an altitude of 35 km at which point it was released remotely to parachute safely back to the surface.



Figure 18. At ten storeys tall, the Mantra research balloon carries instruments in a small gondola to an altitude of 35 km.

Analysis of observations

Figure 19 shows a downward trend in the total ozone content of the lower stratosphere over the Arctic beginning in the early 1980s. Severe ozone depletion episodes occurred in 1996, 1997, 2000, 2003 and 2005. During these years, the Arctic stratosphere was cold enough for the formation of polar stratospheric clouds, and the cold lasted long enough to allow for severe ozone depletion in the spring.

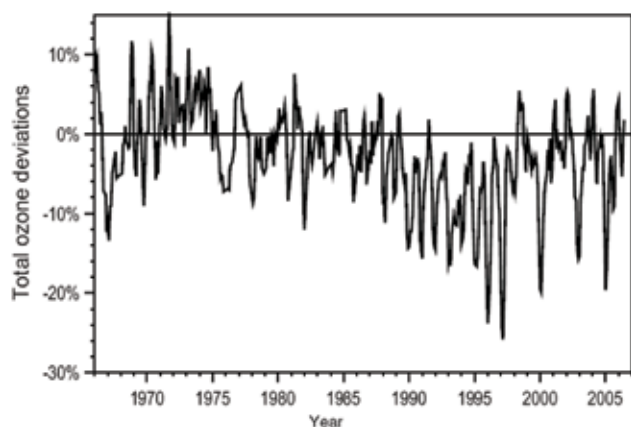


Figure 19. The deviation of the total ozone from the 1966–1987 mean in percent, based on data from ozon-sonde flights launched from Resolute Bay, Eureka, and Alert, Nunavut.
Source: Fioletov 2008

The four yearly ozone records from Resolute Bay (figures 22a–22d) provide a particularly striking illustration of seasonal and annual trends in the Arctic ozone layer during cold years. The figures show the seasonal pattern (middle dashed line), with ozone amounts normally peaking in February to April and reaching a minimum in August and September. In each of the four years shown, however, severe ozone depletion was observed over the Arctic; the Resolute graphs show a significant departure from the normal levels during the spring. In the spring of 1997, in particular, values were observed below 240 DU, much lower than the average minimum of 380 DU during a normal spring. In years characterized by a warm stratosphere over the Arctic, observations show that Arctic ozone depletion was similar to that which occurred over the rest of Canada, typically 5 to 10 percent below normal values in the spring.

Arctic Ozone Research

Arctic ozone research received a boost in 1992 with the opening of the Arctic Stratospheric Ozone Observatory on Ellesmere Island (Figure 20). In 2006, the Observatory was renamed the Polar Environment Atmospheric Research Laboratory (PEARL) after being taken over by the Canadian Network for the Detection of Atmospheric Change, a Canadian university consortium led by Dr. J. Drummond from Dalhousie University. Scientific research at PEARL includes taking comprehensive measurements of air quality, stratospheric ozone concentrations and climate change in the Arctic atmosphere. Since 2004, PEARL has also been the site of a measurement campaign to validate data from a Canadian satellite.



Figure 20. The Eureka Polar Environment Atmospheric Research Laboratory on Ellesmere Island in the Canadian high Arctic. The beam from the top of the roof is the LIDAR laser.

The Canadian Space Agency funded the development of the Atmospheric Chemistry Experiment satellite (Figure 21), also called SCISAT, to make atmospheric measurements relevant to ozone



Figure 21. The Atmospheric Chemistry Experiment satellite, also called SCISAT.

depletion, primarily focused on the Arctic stratosphere in the winter and spring. The satellite was launched on August 12, 2003, and is currently making valuable occultation measurements with a Fourier Transform Infrared spectrometer (FTIR) and an Environment Canada-developed diode-array spectrometer. The data have provided concentration profiles of more than 10 trace gases as well as information about the characteristics and occurrence of polar stratospheric clouds. The team behind the satellite comprised members from Canada, Belgium, France and the U.S.A.

From early December to March, a Light Detection and Ranging (LIDAR) instrument is used at PEARL 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

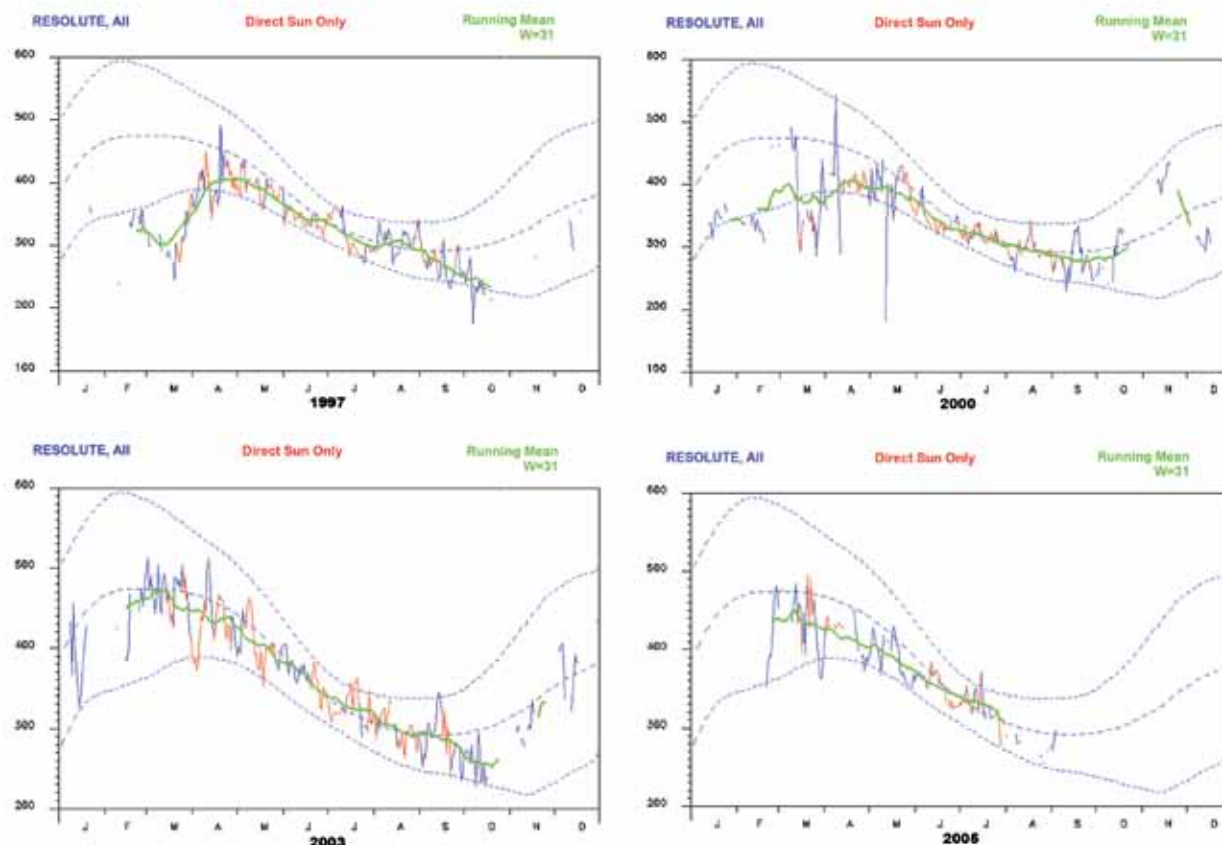


Figure 22. Total ozone over Resolute Bay during (a) 1997, (b) 2000, (c) 2003 and (d) 2005, in which the Arctic spring stratosphere was very cold and severe ozone depletion was observed. The centre dashed line shows average ozone values, while the upper and lower dashed lines show average maximum and minimum values, respectively. After severe depletion in the spring, the ozone layer recovered each year, to values close to or slightly below the long-term average.

concentrations of fine sulphate particles associated with volcanic eruptions, polar stratospheric clouds and Arctic haze (a kind of smog 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 the satellite and LIDAR not only act as a check of the accuracy of total ozone amounts but also point to atmospheric temperatures and light-scattering patterns that indicate the presence of polar stratospheric clouds, as shown in Figure 23.



Figure 23. Polar stratospheric clouds photographed over Sweden in 2000.

Source: NASA

Scientists at PEARL also use a FTIR spectrometer to measure the chemical content of the stratosphere. Among the chemicals the FTIR tracks, one of the most important is chlorine monoxide, since a rise in chlorine monoxide concentrations in the stratosphere is a key indicator that the catalytic destruction of ozone is taking place. The results of these measurements are also used to determine the relationship between chlorine monoxide concentrations and ozone depletion.

Computer models are essential tools for improving our understanding of atmospheric processes

and how natural and human-induced changes affect them. As already mentioned, university and government scientists developed the Canadian Middle Atmosphere Model over the last 10 years to generate more detailed representations of chemical and physical processes in the stratosphere than had previously been possible. The model was part of the most recent comparison of models by the World Meteorological Organization, which was aimed at assessing the current capabilities of middle atmospheric global climate models to describe the current and future states of the stratosphere, chlorine abundance and the impact of greenhouse gases.

Protecting the ozone layer

As a party to the 1985 Vienna Convention for the Protection of the Ozone Layer and the 1987 Montreal Protocol, which are the major international agreements for protecting the ozone layer, Canada coordinates its research and monitoring activities closely with those of other nations. Countries that are party to the Montreal Protocol are aware of the need for long-term, consistent and high-quality observations and for a high-quality data centre for the benefit of research and monitoring. Since 1961, Environment Canada has run the World Ozone and Ultraviolet Radiation Data Centre in Toronto on behalf of the World Meteorological Organization and the global scientific community. Currently, the centre's data archives contain a wide variety of ozone and ultraviolet radiation data products. The centre accepts ozone data in near real time and posts current maps of column ozone obtained from current ground-based and satellite instruments. Daily hemispheric and global maps are available for all data periods over the last 40 years. Analyses from the data centre contribute to the national and international ozone assessment process and to the preparation of the World Meteorological Organization's *Ozone Bulletins*. Time series graphs are also produced from data archive files. The Centre's website (www.woudc.org/index_e.html) contains data from more than 400 stations around the world (see Figure 24).

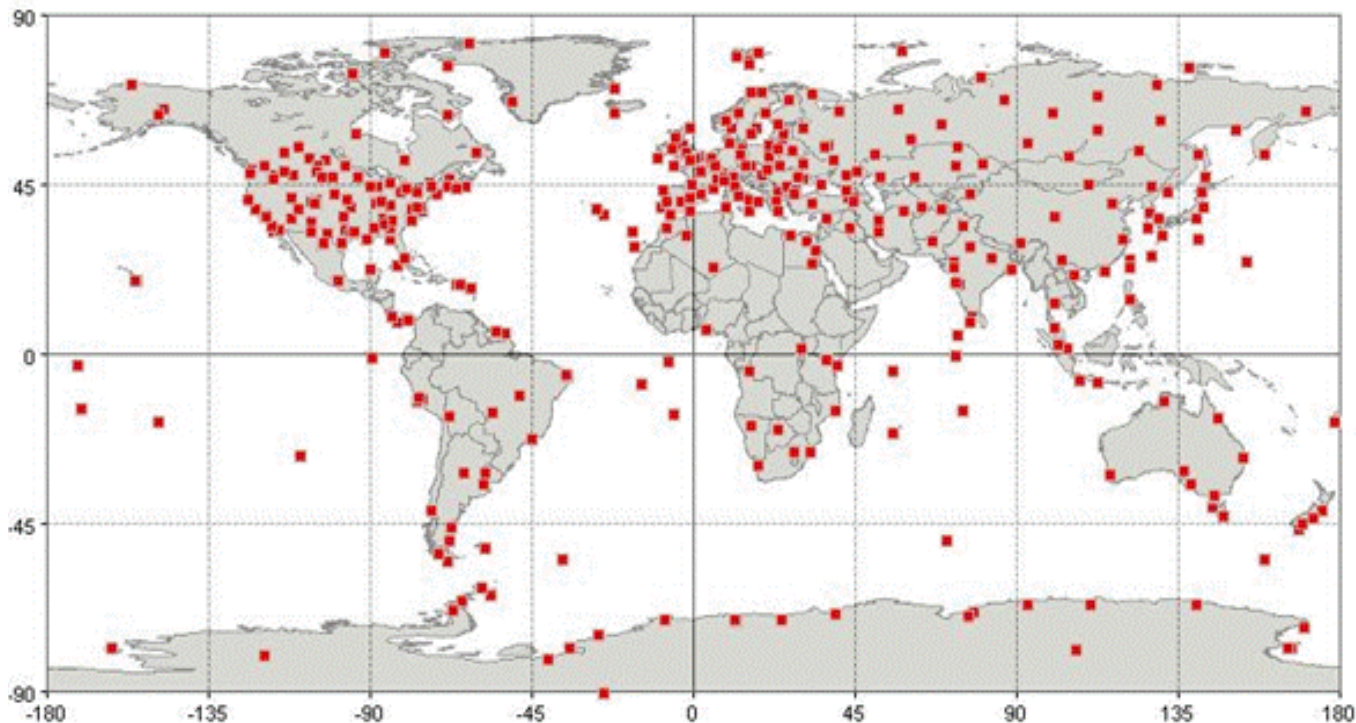


Figure 24. This map shows the locations of Brewer and Dobson instruments reporting total ozone data to the World Ozone and Ultraviolet Data Centre (WOUDC) in Toronto. The Centre’s website (www.woudc.org/index_e.html) contains data from more than 400 stations around the world.

Since the late 1970s, Canadian research has been at the forefront of efforts to protect the ozone layer. Credited with playing an important role in the development of the Montreal Protocol in 1987, Canada has continued to be a world leader hosting meetings on the occasions of the 10th and 20th anniversaries of the Montreal Protocol, which took place in 1997 and 2007, respectively. For the 10th anniversary, Canadian scientists produced the first Canadian assessment on the ozone layer, *Ozone Science: A Canadian Perspective on the Changing Ozone Layer*, which was distributed to delegates at the meeting in September 1997.

For the 20th anniversary in September 2007, a Canadian brochure was produced containing articles on the history of ozone depletion, a review of ozone science in Canada, and the findings of the 2007 Canadian ozone science assessment. The assessment, which comprises a series of papers by leading Canadian scientists from government and academia in ozone and ultraviolet radiation science,

was published in the journal *Atmosphere-Ocean* as a special issue in March 2008. All these products are available on the Internet (www.msc-smc.ec.gc.ca/saib/ozone/ozone_e.html).



The Polar Environment Atmospheric Research Laboratory in the mountains above Eureka, Nunavut.

To help make ozone recovery a reality, Canada has continued to develop effective policies based on an improved understanding of ozone depletion science. From the review of this science, it is clear that uncertainties remain, particularly in the Arctic, where severe ozone depletions still occur. Arctic ozone depletion affects ozone levels over southern Canada in the spring and summer. Canada maintains a monitoring program to track these changes and determine their impact on Canadians. Our monitoring system also contributes to global efforts to track the long-term evolution of the ozone layer. Canada continues to build its understanding of Arctic ozone science by maintaining its ground-based ozone network and the Ozonesonde Network, and by improving computer models to simulate ozone depletion chemistry, dynamics and radiative processes. Many gaps in current knowledge are likely to be filled by Canada's highly successful science satellite program.



*Polar Environment Atmospheric
Research Laboratory, Eureka,
Nunavut, bathed in moonlight*

The Future of the Arctic Ozone Layer

The overall concentration of ozone-depleting substances in the troposphere has decreased by eight to nine percent from its peak in the mid-1990s to 2006, as shown in Figure 25. Most of the decline has been due to short-lived gases, such as methyl chloroform, which reside in the atmosphere for less than a year and are then removed. In light of this, future decline in the concentrations of chlorine and bromine compounds will be slower, since it will require the break down and removal of the long-lived gases. As shown in Figure 26, the major gases in this group are chlorofluorocarbons 11 and 12, which remain in the atmosphere for 50 and 100 years, respectively. Chlorofluorocarbon 12 with its lifetime of 100 years has stabilized in the atmosphere since global production has only been greatly eliminated since the mid 1990s. The overall reduction in the concentration of ozone-depleting substances in the atmosphere has shown that the Montreal Protocol and its amendments have been effective.

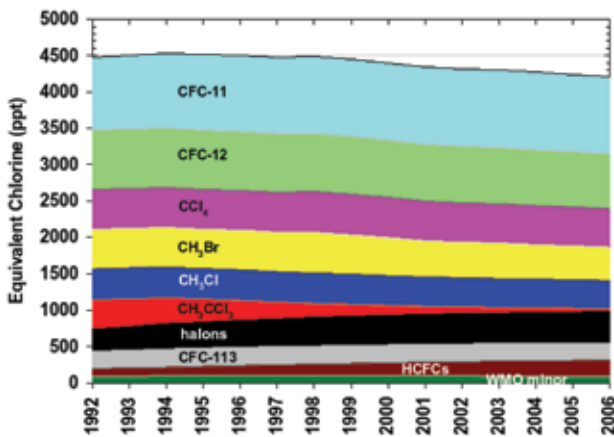


Figure 25. The contribution of all the long-lived chlorine and bromine-containing gases to the calculated equivalent chlorine abundance in the atmosphere. The total equivalent chlorine reached a maximum between 1992 and 1998, after which it declined. The decline has been attributed to the impact of the Montreal Protocol controls.

Source: Earth System Research Laboratory (www.esrl.noaa.gov)

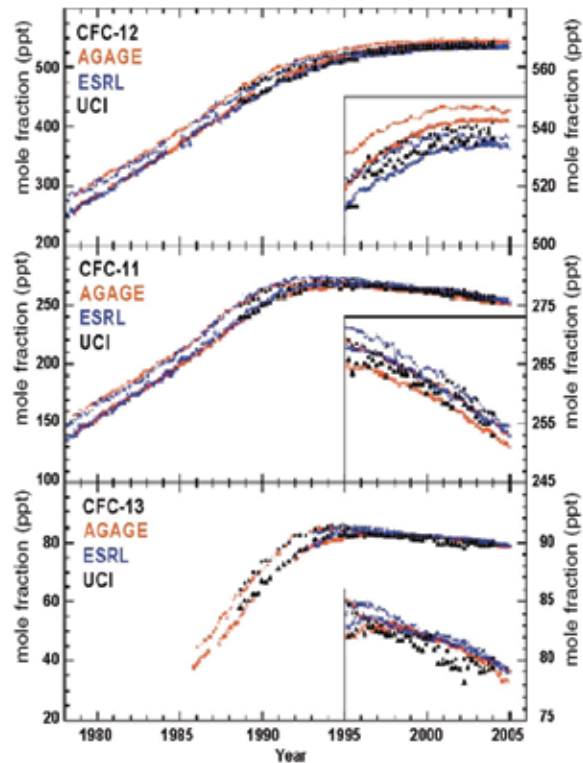


Figure 26. The concentration of chlorofluorocarbons in the troposphere as observed at sites around the globe. Chlorofluorocarbons are highly stable in the troposphere and only break up when exposed to the intense ultraviolet radiation of the upper stratosphere. The chlorine they contain eventually returns to the troposphere to be removed, but the process takes about 50 years for chlorofluorocarbon 11 and about 100 years for chlorofluorocarbon 12.

Source: World Meteorological Organization 2007

The concentration of ozone-depleting substances is uniform in the troposphere and only decreases in the stratosphere, where the substances are broken down under the intense ultraviolet radiation. Since ozone-depleting chemicals take up to four years to reach the stratosphere and break down, the decline in stratospheric levels of chlorine and bromine will lag any decrease in the lower atmosphere by a few years. For example, the amount of chlorine in the stratosphere, currently 3.5 parts per billion, peaked

around 2000 and decreased thereafter, some five years after the peak in the troposphere.

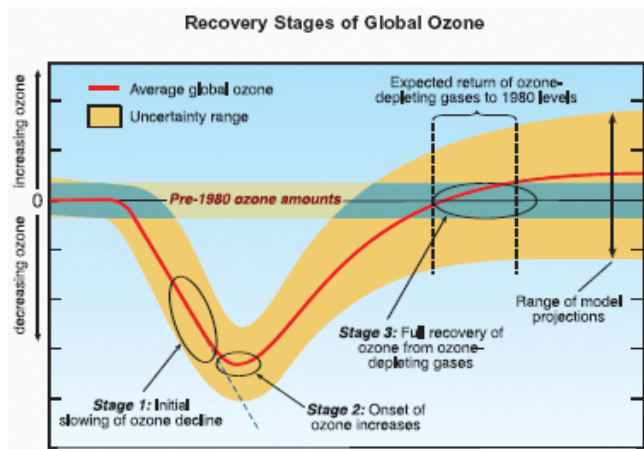


Figure 27. A schematic representation of the stages of the global ozone recovery. Currently, the ozone layer is in stage two, near the maximum level of ozone depletion. Over the next 10 to 20 years, ozone should begin to increase.

Source: World Meteorological Organization 2007

The ability of the Arctic ozone layer to recover to its pre-1980 state will depend on the decrease in the concentration of ozone-depleting substances and on meteorology, with the former being the main factor. Computer models indicate that it is reasonable to expect a substantial degree of recovery in ozone values in middle latitudes by 2050, as the global concentration of ozone-depleting substances declines to its pre-1980 levels. By 2060 to 2070, the concentration of ozone-depleting substances should be close to their pre-1980 levels, allowing ozone levels to return to pre-1980 global levels, as shown in Figure 27. The meteorology of the Arctic atmosphere will also be important in enabling the recovery of the Arctic ozone layer. In years when the Arctic stratosphere is very cold, severe ozone depletion will be possible until the concentration of ozone-depleting substances is greatly reduced.

The Arctic ozone layer will be particularly vulnerable over the next 15 years, while atmospheric concentrations of ozone-depleting substances decline from their peak levels. During this period, the Arctic will be especially vulnerable to very cold winters, as continuing increases in greenhouse

gases lead to further cooling of the stratosphere and more frequent formation of polar stratospheric clouds. The warming of the troposphere and the cooling of the stratosphere will continue to change the dynamics of wind circulations in the atmosphere, influencing the speed of the polar flow in the stratosphere. Although ozone depletion over the Arctic will be primarily determined by the concentration of ozone-depleting substances in the atmosphere and meteorological conditions, higher ozone concentrations, resulting from natural or anthropogenic increases in the Dobson-Brewer circulation, will have an impact on the chemistry and dynamics in the Arctic atmosphere. 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.

Current efforts to rid the atmosphere of ozone-depleting substances are having a positive impact on climate change that, in turn, could have consequences for Arctic ozone depletion in the future. Hydrochlorofluorocarbons and hydrofluorocarbons, the most widely used replacements for chlorofluorocarbons, are also greenhouse gases, and some of them are nearly as effective as chlorofluorocarbons as global warming agents. Consequently, their use will contribute to further greenhouse warming and related cooling of the stratosphere. For that reason, participants in the 2007 Montreal Protocol meetings decided to accelerate the phase-out of the production and consumption of hydrochlorofluorocarbons. Developed countries will complete this phase-out in 2020, while developing countries agreed to reduce the production and consumption of these chemicals by 67.5 percent by 2025 and to completely phase them out by 2030.

Over the much longer term, the health of the ozone layer is dependent on our ability to eliminate ozone-depleting substances in the atmosphere and to prevent the release of stored or new chemicals. The status of the ozone layer will also depend on our success in controlling increases in the levels of greenhouse gases and other pollutants. All these

issues are linked, as described above, through a variety of physical and chemical interactions, and it makes scientific sense to address them through a comprehensive and integrated approach.

In dealing with all of these complex problems, research and monitoring will continue to play an important role in supporting policy development. Continuing monitoring and analysis of stratospheric ozone amounts and ultraviolet radiation, as well as of ozone-depleting substances 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 and dynamics will also be essential if scientists are to reduce the gaps in current understanding of ozone depletion and improve their capability to predict what is likely to happen to the ozone layer in the future.

Useful Links on the Internet



General interest on ozone depletion

Environment Canada, Experimental-Studies Section:
<http://exp-studies.tor.ec.gc.ca>

Canadian Space Agency:
www.space.gc.ca/asc/eng/satellites/scisat/ozone.asp

U.S. Climate Prediction Center:
www.cpc.ncep.noaa.gov/products/stratosphere

Arctic

Arctic Climate Impact Assessment:
www.acia.uaf.edu

U.S. National Snow and Ice Data Center:
<http://nsidc.org/arcticseaicenews/index.html>

Canadian Ice Service:
<http://ice-glaces.ec.gc.ca>

Antarctic

Ozone Hole Watch:
<http://ozonewatch.gsfc.nasa.gov/index.html>

Tropospheric Emission Monitoring Internet Site (TEMIS):
www.temis.nl/protocols/o3hole

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Glossary

Climate change: Any significant, long-term change in average weather patterns over an appropriately long time period.

Dobson Unit (DU): The standard unit for determining the thickness of the ozone layer by quantifying the solar radiation absorption of ozone in an atmospheric column. One Dobson unit equals 0.01 mm of separated and purified ozone in an atmospheric column at normal temperature and pressure.

Greenhouse gases: Gases in the atmosphere that absorb and emit radiation within the thermal infrared range.

Occultation: The analysis of light from the sun or a star as it is interrupted by the Earth's atmosphere to yield information on the composition, structure and dynamics of the atmosphere.

Ozone mixing ratio: An expression of the concentration of ozone calculated by determining the ratio between the weight of ozone, in micrograms, and the weight of air, in grams.

Ozone partial pressure: The pressure that ozone would exert in a gaseous mixture if it were alone in a container.

Ozone: A pungent, colorless, toxic gas with the formula O_3 , an allotropic triatomic variety of oxygen.

Ozone depletion: The disappearance of an amount of stratospheric ozone caused by anthropogenic chemicals and other dynamic phenomena.

Ozone-depleting substances: A chemical substance presumed to cause stratospheric ozone depletion (chlorofluorocarbons, hydrochlorofluorocarbons, halons, methyl bromide).

Polar stratospheric clouds: Ice clouds found in the polar stratosphere at temperatures below $-78^{\circ}C$.

Solar cycle: The 11-year cycle of sunspots on the surface of the sun that causes a variation in the quantity of energy normally emitted by the sun.

Stratosphere: The atmospheric layer above the top of the troposphere (8–18 km) and below the mesosphere (80 km).

Troposphere: The lowest turbulent layer of the atmosphere where most weather occurs.

Ultraviolet radiation: Radiation in the electromagnetic spectrum outside the violet regions, with wavelengths of 220 to 400 nm (UVA, 320 to 400 nm; UVB, 280 to 320 nm; and UVC, below 280 nm).

Notes





*Scientist checking
instrumentation at Eureka*

WWW.ec.gc.ca

Additional information can be obtained at:

Environment Canada

Inquiry Centre

351 St. Joseph Boulevard

Place Vincent Massey, 8th Floor

Gatineau QC K1A 0H3

Telephone: 1-800-668-6767 (in Canada only) or 819-997-2800

Fax: 819-994-1412

TTY: 819-994-0736

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