Introduction

The Montreal Protocol — the Achievement and the Challenge

The signing of the Montreal Protocol on September 16, 1987, was a remarkable and significant event in modern diplomatic history, one of those rare occasions when individual nations subordinated economic self-interest to the achievement of a common planetary goal. The event was even more remarkable when one considers that it was accomplished in spite of scientific uncertainties about detailed aspects of the depletion process and without immediate evidence of impacts on ecosystems and human health. That an agreement was eventually reached was due not only to an extraordinarily successful collaboration between scientists and policymakers but also to the enormous strides made by the international scientific community in expanding the boundaries of ozone science. The solidity of their achievement can be seen in the very real progress that has been made since 1987 in reducing emissions of ozone-depleting substances

Canada has been concerned about stratospheric ozone depletion since the issue was first raised by scientists in the 1960s and 1970s, and our interest in ozone science goes back even further, to the 1950s, when the first Canadian ozone monitoring programs were established. Over the past couple of decades our involvement in ozone science and contributions to it have been considerable. The Brewer ozone spectrophotometer, now the principal instrument for ground-based ozone measurements, was developed here. Our network of monitoring stations is one of the largest in the world, and, as the home for the World Ozone and Ultraviolet Radiation Data Centre, we are responsible for archiving ozone measurements from around the world. Canada is also proud to have been one of the original parties to the Montreal Protocol and to be among the many countries that have met or exceeded their obligations under the protocol and its amendments.

The present document provides a brief overview of the state of ozone science in 1997, on the 10th anniversary of the Montreal Protocol. Compiled by Canadian scientists, it draws on both Canadian and international research to outline our current understanding of ozone depletion and its effects. It also highlights Canadian research results and data, where appropriate, and emphasizes items of special Canadian concern, such as ozone depletion in the Arctic and the impacts of UV changes on forests and freshwater ecosystems.

The Road to Montreal

The possibility of anthropogenic interference with the ozone layer was raised as early as 1964, when John Hampson of the Canadian Armaments and Research Development Establishment noted the potential for ozone damage as a result of water vapour emissions from rockets and high-flying aircraft. Over the ensuing decade, proposals for the development of supersonic commercial aircraft that would fly in the lower stratosphere brought further attention to the issue, as did the debate over the environmental effects of nuclear weapons. In 1974, however, two articles were published that brought an entirely new dimension to the problem of ozone depletion. The first of these, published in the *Canadian Journal of Chemistry* by Richard Stolarski and Ralph Cicerone of the University of Michigan, described a process by which chlorine from rocket exhausts could catalyze the destruction of large amounts of ozone in the stratosphere over a period lasting many decades. Independently and almost simultaneously, two University of California researchers, Mario Molina and Sherwood Roland, voiced similar concerns about chlorine-catalyzed ozone loss but suggested the existence of a much larger source of anthropogenic chlorine in the stratosphere. In an article in *Nature* they argued that many widely used industrial chlorofluorocarbons (CFCs) had the potential to migrate into the stratosphere, where they would eventually break down as a result of exposure to intense ultraviolet radiation and release significant quantities of chlorine.

The combined implications of these articles were disturbing. Society appeared to face a choice between preserving the integrity of the ozone layer, which prevents biologically destructive levels of ultraviolet radiation from reaching the earth's surface, or preserving the economic benefits provided by CFCs, a valuable and otherwise benign group of chemicals that had become essential to a broad range of applications, including refrigeration and the manufacture of foams and electronic components. The potential risks to ecosystems and human health were large and unprecedented, while the costs of abandoning CFCs appeared considerable. In addition, although ozone destruction by chlorine catalysis was highly plausible, there was as yet no empirical evidence of ozone loss in the stratosphere. A further complication was added in 1975 when S.C. Wofsy, M.B. McElroy, and Y.I. Yung of Harvard University showed that bromine, used in fire-retarding halons, was also a potent destroyer of ozone. Not surprisingly, the issue ignited a major controversy, both within the scientific community and beyond.

University, government, and industry scientists in various centres around the world responded by intensifying their research activities. The immediate problem was to validate – or invalidate – the new theories of ozone destruction and assess their implications over a wide range of potential impacts. Given the considerable natural variability of ozone concentrations, both geographically and temporally, detecting the imprint of an anthropogenic disturbance and verifying the processes involved were not easy tasks. As researchers uncovered new information about the chemistry and dynamics of the middle atmosphere, the problem became more complex and uncertainties increased. Modelling of processes affecting ozone amounts proved extremely difficult, partly because of limitations of computer power and partly because of uncertainties about reaction rates and other critical aspects of the depletion mechanisms. Consequently, initial projections of depletion by CFCs showed little consistency. Nevertheless, by the mid-1980s, knowledge of ozone-related processes had expanded considerably. When the United Nations Environment Programme (UNEP) and the World Meteorological Organization (WMO) released their first major international ozone assessment in 1986, the report was able not only to provide a comprehensive analysis of the threat from CFCs 11 and 12 but also to identify additional substances that had the potential to deplete stratospheric ozone. In addition, it drew attention to the fact that many of these substances were extremely powerful greenhouse gases whose presence in the atmosphere also had serious implications for global warming and climate change.

At the national level, reaction to the threat of ozone depletion varied considerably. It was strongest in those countries where media interest and vocal environmental movements ensured a place for the issue on the political agenda. Fact-finding commissions were established and research activities intensified in a number of these countries to provide governments with more information about the nature and implications of the problem. By 1978 a few countries had concluded that it would be prudent to curtail the least essential uses of CFCs until there was greater certainty about the risks involved in their use. Thus, the United States banned the use of CFCs in nonessential aerosol sprays in March of that year, and Canada, Norway, and Sweden shortly followed suit. The European Community, after initially rejecting Dutch and later German proposals for CFC restrictions, agreed in 1980 to a more modest 30% cutback in aerosol use.

The ozone issue, however, was fundamentally an international problem, and it could only be resolved by international action. The initiative for promoting this action was taken at a relatively early date by the United Nations Environment Programme, under the leadership of its executive director at the time, Mostafa Tolba. In 1976 UNEP had called for an international conference to discuss an international response to the ozone issue. The conference, held in Washington in March 1977, drafted a "World Plan of Action on the Ozone Layer," which gave UNEP the responsibility for promoting and coordinating international research and data gathering activities. At the same time, a Coordinating Committee on the Ozone Layer, under UNEP direction, was formed to oversee periodic international assessments of the depletion problem.

The possibility of establishing international controls over the production and use of CFCs was first raised a month later at another international meeting in Washington but attracted insufficient support at the time and on subsequent occasions over the next few years. In April 1981, however, UNEP's Governing Council authorized the organization to begin working towards an agreement to protect the ozone layer. The first step in this process was taken in January 1982, when 24 countries met in Stockholm and agreed to launch an "Ad Hoc Working Group of Legal and Technical Experts for the Preparation of a Global Framework Convention for the

Protection of the Ozone Layer." In 1983, the so-called Toronto Group (named after the site of its first meeting and consisting of Canada, Finland, Norway, Sweden, Switzerland, and later the United States) recommended a global ban on nonessential uses of CFC aerosol sprays and proposed that a separate regulatory protocol be developed and adopted simultaneously with the framework convention.

Efforts to complete a framework agreement came to fruition in March 1985 with the signing of the Vienna Convention for the Protection of the Ozone Layer. The participating countries agreed to take measures to protect the ozone layer (although these were not spelled out) and made arrangements for international cooperation in the areas of research, monitoring, and exchange of data on the state of the ozone layer and emissions and concentrations of CFCs and other chemicals. The convention was not accompanied by a regulatory protocol, but under a separate resolution UNEP was authorized to begin negotiations on a legally binding protocol that would be ready in 1987.

Although Vienna was an important milestone, the international consensus needed to support an effective control protocol was still lacking. It was therefore decided to convene two workshops in 1986 to review some of the key economic and scientific issues. Working informally as private citizens rather than as members of national delegations, experts from the UN, governments, industry, universities, and environmental groups met first in Rome and later in Leesburg, Virginia. Though many points of contention remained unresolved, the meetings nevertheless succeeded in building a broader basis of understanding for the negotiations to follow. One of the more important ideas to emerge from these discussions was the concept of an interim protocol – one that did not have to provide a definitive solution to all outstanding problems but allowed for periodic reassessment and revision in the light of changing facts and expanding scientific knowledge.

The actual negotiation of the protocol began in Geneva in December 1986. Subsequent meetings in Vienna and again in Geneva helped to narrow the outstanding differences, but when the delegates convened in Montreal on September 8, 1987, important disagreements remained over such basic issues as the chemicals to be controlled, the use of production or consumption as the basis for restrictions, the extent of the controls and the timing of their implementation, the choice of a base year, and arrangements for developing countries. It was only after further intensive negotiation that agreement was finally reached on the 16th.

The conclusion of such an important and unprecedented agreement owes much to the skill and persistence of those who negotiated it, but a number of other important factors contributed to this achievement. The role of the international scientific community was particularly vital. Although scientists were unable to eliminate many of the uncertainties that surrounded and still surround the stratospheric ozone issue, they were successful in reducing the range of uncertainty and in building a compelling case for action. Chance played a role as well, most notably with the discovery of the Antarctic ozone hole in 1985. The ozone hole did not confirm existing theories about the destruction of the ozone layer – it only raised new questions – but it did create a greater awareness among opinion leaders and the public that something serious was happening to the atmosphere and that precautionary action was necessary. An agreement also became much more likely after 1986, when the American chemical industry, one of the larger producers of CFCs in the world, abandoned its opposition to controls. Finally, it was the very flexibility of the agreement that made it acceptable to many of the parties. It did not attempt the impossible task of solving so complex a problem in one step. Instead, it set up a mechanism for continuing review, so that policy could be refined in the light of new realities and the best available information. Indeed, one of its most important achievements was that it created a mechanism for continuing action. As Mostafa Tolba pointed out, the Montreal Protocol was a starting point, "the beginning of the real work to come."

Mileposts: 1987–1997

The past decade has seen a number of very significant advances in ozone science, both in terms of improvements in research and monitoring capabilities and actual advances in our understanding of ozone depletion and its effects on radiation at the earth's surface. One of the most important developments occurred in the late 1980s, when intensive research efforts unravelled the mystery of the Antarctic ozone hole and uncovered the role of polar stratospheric clouds (PSCs) and hetereogeneous chemistry in its genesis. By 1990, important evidence about ozone trends in other parts of the world was also becoming available, and depletions of about 5% per decade were detected over the northern midlatitudes. After the eruption of Mount Pinatubo in 1991, it became apparent as well that sulphate aerosols injected into the stratosphere by volcanic activity could cause significant depletion. More recently, there has been evidence that significant depletions have been occurring in the Arctic as a result of heterogeneous reactions on PSCs. In 1993, the expected link between ozone depletion and increases in UV radiation at the surface was finally confirmed through the analysis of spectral data. The study, by Environment Canada scientists, has recently been extended to cover an 11-year period ending in 1996. It shows a positive trend of approximately 1% per year in the summer radiation at 300 nm.

Other noteworthy scientific advances of the past decade include:

- a greater understanding of the transport of ozone and other trace gases as a result of the identification of the role of small-scale filamentary structures in mixing processes in the upper troposphere and lower stratosphere
- the application of new techniques for measuring ozone and other atmospheric constituents from the ground, balloons, and satellites
- advances in chemical modelling, including the ability to incorporate chemical processes in general circulation models and forecast models
- a substantial increase in the number of stations making spectral UV measurements and in the length of the data record
- an evaluation and, in some cases, verification by measurements of the effects of CFCs and other ozone-depleting substances on radiative forcing and climate change
- evidence of a possible link between climate change and ozone depletion in the Arctic
- better understanding of the effects of clouds, sulphur dioxide, and albedo on UV irradiance

Improvements in our understanding of depletion processes as well as further evidence of ozone loss has precipitated a significant tightening and extension of the protocol's regulatory regime. The original agreement had required a 50% reduction in CFC use by mid-1998 and a freeze of halon consumption at 1986 levels by 1992, but amendments passed at meetings in London (1990) and Copenhagen (1992) targeted these substances for virtual elimination and then advanced the phase-out dates to the end of 1994 for halons and the end of 1995 for CFCs. In addition, carbon tetrachloride and methyl chloroform, HCFCs and HBFCs (used as substitutes for CFCs and halons), and methyl bromide were brought under regulatory control. Carbon tetrachloride, methyl chloroform, and HBFCs were scheduled for elimination by the end of 1995, while consumption of HCFCs was scheduled to be eliminated by 2030. Further meetings in Vienna (1995) and Costa Rica (1996) led to reductions in the use of methyl bromide and agreement to end its use entirely by 2010.

Present Trends

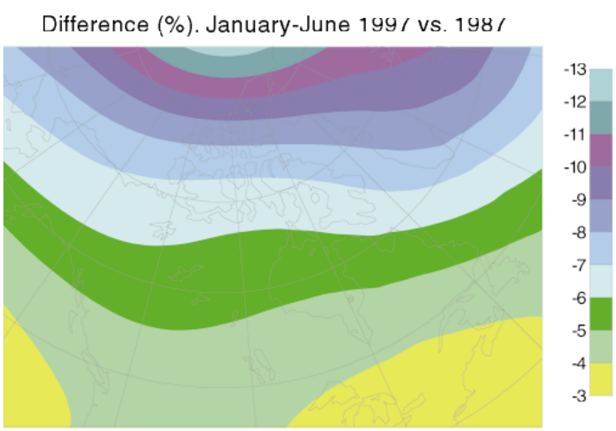
The greatest and most dramatic ozone loss has occurred during early spring over the Antarctic, where total ozone values have dropped by more than 65% since 1975. Ozone losses over the Arctic for this period have been less severe, because of differences in circulation patterns, but are still in the area of 12%. In the midlatitudes, ozone has been declining at a rate of about 5% per decade.

The accompanying maps show the differences between ozone amounts over Canada at the time of the signing of the Montreal Protocol in 1987 and a decade later in 1997. The decline in ozone values between the two six-month periods is greatest (as much as 12%) in the high Arctic and lowest (about 3%) over the southeast. However, in 1996 Arctic ozone values were briefly about 30% below normal, while during the spring of 1997 they were as much as 45% below normal over the high Arctic and about 7% below normal over the midlatitude regions of the country. The exceptionally large depletion in the Arctic during the past spring is likely the result of unusual upper wind and temperature patterns that may, in turn, be related to the radiative effects of increased concentrations of greenhouse gases.

Meanwhile, as a result of the Montreal Protocol, the rate at which atmospheric concentrations of CFCs have increased has slowed noticeably since about 1990 and, in the case of CFC-11, concentrations have actually begun to decrease. As concentrations of CFCs and other ozone-depleting substances in the stratosphere decline, concentrations of chlorine and bromine should follow suit. If the provisions of the Montreal Protocol are fully obeyed by all the parties, the current stratospheric chlorine concentration of 3.5 parts per billion (ppb) is expected to peak within the next few years and then decrease gradually, returning to its natural level of 1.0 ppb some time after 2100.

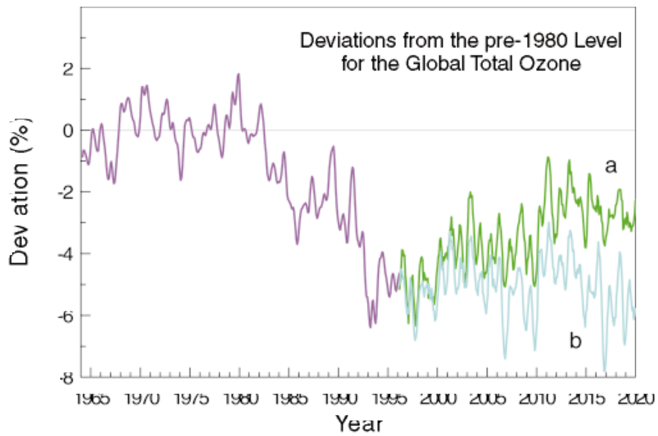
Given the expected decreases in concentrations of ozone-depleting substances and stratospheric chlorine and bromine, when can we expect the ozone layer to recover, and when will we be able to detect that a recovery is under way? The accompanying graph shows how ozone has decreased from 1965 to 1996. It then compares, in a simplified fashion, what might happen if our current assumptions about ozone depletion are correct, and the Montreal Protocol and its amendments are fully implemented, with an alternative scenario in which concentrations of ozone-depleting substances remain unchanged at 1997 levels. Although the scientific basis for the graph is minimal, it does illustrate that evidence of a clear trend towards increasing ozone amounts may not emerge until after 2005 or 2010. In reality, however,

How Has the Ozone Layer Over Canada Changed Since 1987?



The upper map shows average ozone levels over Canada for January–June 1987, while the middle map shows the same information for January–June 1997. The percentage differences between the two periods are plotted in the lower map, which shows declines ranging from 3% over southern Canada and about 4% over the Prairies up to 12% in the high Arctic. Although these differences are consistent with decadal trends, a comparison of other years, such as 1985 and 1995, would yield different results. The maps have been constructed from both ground-based and satellite measurements.

When Might the Recovery of the Ozone Layer Be Detectable?



The graph shows the global total ozone record from 1964 to 1996 and two hypothetical projections based on different scenarios. Branch (a), which expresses the best case, assumes that the Montreal Protocol and its amendments will be fully implemented and that concentrations of chlorine and bromine will decline according to the projections contained in the 1994 UNEP Assessment. It also assumes that ozone depletion has been due only to known ozone-depleting substances. Branch (b) is based on the assumption that concentrations of all ozone-depleting substances remain at their 1997 levels.

Although these projections are relatively crude, they do illustrate that several years will be needed to detect the start of any recovery and several more to estimate its extent. The actual recovery scenario is likely to be somewhere between these two cases because the protocol may not be fully adhered to by all parties and other factors or as yet unidentified substances may be contributing to depletion.

The graph is derived from a very simple statistical model of seasonally dependent, chlorine-induced depletion, modified by the addition of random noise and the quasi-biennial and solar cycles in ozone.

such evidence may be delayed even further because compliance with the protocol may not be complete and there are still uncertainties in our understanding of the science. These uncertainties also make it difficult to predict confidently when ozone concentrations will finally return to natural levels. As the recent and unexpectedly large Arctic depletions indicate, the ozone issue can still produce surprises.

The Future Agenda

Reliable forecasts of a future ozone recovery ultimately depend on the comprehensive and accurate modelling of atmospheric chemistry and dynamics. At the present time, however, our models generally underestimate the amount of ozone depletion that has actually occurred and cannot accurately simulate all aspects of ozone distribution with altitude, location, and time of year. These limitations suggest that there may be gaps in our knowledge of ozone chemistry and atmospheric dynamics. They may also point to the presence of other as yet unidentified ozone-depleting substances in the stratosphere. In addition, the unexpected extent of recent ozone depletions in the Arctic indicate a need for further study of the Arctic atmosphere and, in particular, of the effects on it of increased concentrations of greenhouse gases. It is now fairly certain that increased concentrations of these gases have caused stratospheric cooling, and a cooler Arctic stratosphere would generally offer a more favourable environment for ozone destruction. Finally, although many of the effects of enhanced UV radiation on biological systems are reasonably well known, our knowledge is far from complete, and it is possible that additional damage mechanisms remain to be identified. Also, the implications of ecological interactions and other environmental stresses in connection with UV effects have yet to be explored in detail.

In spite of the truly remarkable progress that has been made in ozone science over the past decade, the problem of ozone depletion has not yet been solved. Our challenge for the next decade, therefore, is to fill in these gaps in our knowledge of chlorine- and bromine-induced depletion while expanding our understanding of the effect of other factors on ozone amounts. At the same time, we must continue our efforts to monitor and detect the recovery of the ozone layer and expand our work on the biological effects of enhanced UV radiation.

The successful implementation of this agenda over the next 10 years will give us a much better basis for ensuring the ultimate recovery of the ozone layer and for developing effective responses for the protection of human health and ecosystem vitality in the meantime. It will also enhance our understanding of the complex interactions of radiative, dynamical, and photochemical processes that drive the atmosphere and thus give us better tools with which to predict how the atmosphere will respond to other perturbations that may occur in the future.