World Meteorological Organization
Global Ozone Research and Monitoring Project — Report No. 44

# SCIENTIFIC ASSESSMENT OF OZONE DEPLETION: 1998

# EXECUTIVE SUMMARY

National Oceanic and Atmospheric Administration
National Aeronautics and Space Administration
United Nations Environment Programme
World Meteorological Organization
European Commission

# PREFACE

The present document contains key summaries from the *Scientific Assessment of Ozone Depletion: 1998*. The full assessment report will be part of the information upon which the Parties to the United Nations Montreal Protocol will base their future decisions regarding protection of the stratospheric ozone layer.

Specifically, the Montreal Protocol on Substances that Deplete the Ozone Layer states (Article 6): ". . . the Parties shall assess the control measures . . . on the basis of available scientific, environmental, technical, and economic information." To provide the mechanisms whereby these assessments are conducted, the Protocol further states: ". . . the Parties shall convene appropriate panels of experts" and "the panels will report their conclusions . . . to the Parties."

Three assessment reports have been prepared during 1998 to be available to the Parties in advance of their meeting in 1999, at which they will consider the need to amend or adjust the Protocol. The two companion reports to the present scientific assessment focus on the environmental and health effects of ozone layer depletion and on the technological feasibilities and economic implications of various mitigation approaches.

The scientific assessment summarized in the present document is the latest in a series of eight scientific assessments prepared by the world's leading experts in the atmospheric sciences and under the international auspices of the World Meteorological Organization (WMO) and/or the United Nations Environment Programme (UNEP). The present assessment is the fifth in the set that has been prepared directly as input to the Montreal Protocol process. The chronology of the scientific assessments on the understanding of ozone depletion and their relation to the international policy process is summarized as follows:

| Year | Policy Process | Scientific Assessment |
|---|---|---|
| 1981 | | *The Stratosphere 1981. Theory and Measurements.* WMO No. 11. |
| 1985 | Vienna Convention | *Atmospheric Ozone 1985.* Three volumes. WMO No. 16. |
| 1987 | Montreal Protocol | |
| 1988 | | *International Ozone Trends Panel Report 1988.* Two volumes. WMO No. 18. |
| 1989 | | *Scientific Assessment of Stratospheric Ozone: 1989.* Two volumes. WMO No. 20. |
| 1990 | London Adjustments and Amendment | |
| 1991 | | *Scientific Assessment of Ozone Depletion: 1991.* WMO No. 25. |
| 1992 | | *Methyl Bromide: Its Atmospheric Science, Technology, and Economics* (Assessment Supplement). UNEP (1992). |
| 1992 | Copenhagen Adjustments and Amendment | |

| Year | Policy Process | Scientific Assessment |
|---|---|---|
| 1994 | | *Scientific Assessment of Ozone Depletion: 1994.* WMO No. 37. |
| 1995 | Vienna Adjustment | |
| 1997 | Montreal Adjustments and Amendment | |
| 1998 | | *Scientific Assessment of Ozone Depletion: 1998.* WMO No. 44. |
| 1999 | 11th Meeting of the Parties (China) | |

The genesis of *Scientific Assessment of Ozone Depletion: 1998* occurred at the 7th Meeting of the Conference of the Parties to the Montreal Protocol in Vienna, Austria, in December 1995, at which the scope of the scientific needs of the Parties was defined. The formal planning of the present report was started in January 1997 by an *ad hoc* international steering group who crafted the outline and suggested scientists from the world community to serve as authors. The first drafts of the chapters were examined at a meeting that occurred on 12 - 14 November 1997 in Washington, D.C., at which the Lead Authors and a small number of international experts focused on the content of the draft chapter and the coordination among the chapters.

The second drafts of the chapters were reviewed by 124 scientists worldwide in a mail peer review. These comments were considered by the authors. At a Panel Review Meeting in Les Diablerets, Switzerland, held on 1 - 5 June 1998, the responses to these mail review comments were proposed by the authors and discussed by the 73 participants. Final changes to the chapters were decided upon there, and the Executive Summary contained herein was prepared by the participants.

The group also focused on updating a set of questions that are frequently asked about the ozone layer. Based upon the scientific understanding represented by the assessments, answers to these frequently asked questions were updated. These questions and answers are included in this report.

As the accompanying list indicates, the *Scientific Assessment of Ozone Depletion: 1998* is the product of 304 scientists from the developed and developing world[1] who contributed to its preparation and review (218 scientists prepared the report and 148 scientists participated in the peer review process).

What follows is a summary of their current understanding of the stratospheric ozone layer and its relation to humankind.

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[1] Participating were Argentina, Australia, Austria, Belgium, Brazil, Canada, Chile, Czech Republic, Denmark, Egypt, Finland, France, Germany, Greece, India, Iran, Ireland, Italy, Japan, Kenya, Malaysia, New Zealand, Norway, Poland, Russia, South Africa, Republic of Korea, Sweden, Switzerland, Taiwan, The Netherlands, The People's Republic of China, United Kingdom, United States of America, and Venezuela.

# EXECUTIVE SUMMARY

The 1987 Montreal Protocol on Substances that Deplete the Ozone Layer commemorated its 10th anniversary in September 1997. Among the provisions of the Protocol was the requirement that the Parties to the Protocol base their future decisions on the available scientific, environmental, technical, and economic information as assessed by the worldwide expert communities. The advances of the understanding in ozone science over this decade were assessed in 1988, 1989, 1991, and 1994. This information was input to the subsequent Amendments and Adjustments of the 1987 Protocol. The Assessment summarized here is the fifth in that series.

## Recent Major Scientific Findings and Observations

Since the *Scientific Assessment of Ozone Depletion: 1994*, significant advances have continued to be made in the understanding of the impact of human activities on the ozone layer, the influence of changes in chemical composition on the radiative balance of the Earth's climate, and, indeed, the coupling of the ozone layer and the climate system. Numerous laboratory investigations, atmospheric observations, and theoretical and modeling studies have produced several key ozone- and climate-related findings:

- **The total combined abundance of ozone-depleting compounds in the lower atmosphere peaked in about 1994 and is now slowly declining. Total chlorine is declining, but total bromine is still increasing.** As forecast in the 1994 Assessment, the long period of increasing total chlorine abundances – primarily from the chlorofluorocarbons (CFCs), carbon tetrachloride ($CCl_4$), and methyl chloroform ($CH_3CCl_3$) – has ended. The peak total tropospheric chlorine abundance was 3.7 ± 0.1 parts per billion (ppb) between mid-1992 and mid-1994. The declining abundance of total chlorine is due principally to reduced emissions of methyl chloroform. Chlorine from the major CFCs is still increasing slightly. The abundances of most of the halons continue to increase (for example, Halon-1211, almost 6% per year in 1996), but the rate has slowed in recent years. These halon increases are likely to be due to emissions in the 1990s from the halon "bank," largely in developed countries, and new production of halons in developing countries. The observed abundances of CFCs and chlorocarbons in the lower atmosphere are consistent with reported emissions.

- **The observed abundances of the substitutes for the CFCs are increasing.** The abundances of the hydrochlorofluorocarbons (HCFCs) and hydrofluorocarbons (HFCs) are increasing as a result of a continuation of earlier uses and of their use as substitutes for the CFCs. In 1996, the HCFCs contributed about 5% to the tropospheric chlorine from the long-lived gases. This addition from the substitutes offsets some of the decline in tropospheric chlorine associated with methyl chloroform, but is nevertheless about 10 times less than that from the total tropospheric chlorine growth rate throughout the 1980s. The atmospheric abundances of HCFC-141b and HCFC-142b calculated from reported emissions data are factors of 1.3 and 2, respectively, smaller than observations. Observed and calculated abundances agree for HCFC-22 and HFC-134a.

- **The combined abundance of stratospheric chlorine and bromine is expected to peak before the year 2000.** The delay in this peak in the stratosphere compared with the lower atmosphere reflects the average time required for surface emissions to reach the lower stratosphere. The observations of key chlorine compounds in the stratosphere up through the present show the expected slower rate of increase and show that the peak had not occurred at the time of the most recent observations that were analyzed for this Assessment.

- **The role of methyl bromide as an ozone-depleting compound is now considered to be less than was estimated in the 1994 Assessment, although significant uncertainties remain.** The current best estimate of the Ozone Depletion Potential (ODP) for methyl bromide ($CH_3Br$) is 0.4, compared with an ODP of 0.6 estimated in the previous Assessment. The change is due primarily to both an increase in the estimate of ocean removal processes and the identification of an uptake by soils, with a smaller contribution from the change in our estimate of the atmospheric removal rate. Recent research has shown that the science of atmospheric methyl bromide is complex and still not well understood. The current understanding of the sources and sinks of atmospheric methyl bromide is incomplete.

- **The rate of decline in stratospheric ozone at midlatitudes has slowed; hence, the projections of ozone loss made in the 1994 Assessment are larger than what has actually occurred.** Total column ozone decreased significantly at midlatitudes (25-60°) between 1979 and 1991, with estimated linear downward trends of 4.0, 1.8, and 3.8% per decade, respectively, for northern midlatitudes in winter/spring, northern midlatitudes in summer/fall, and southern midlatitudes year round. However, since 1991 the linear trend observed during the 1980s has not continued, but rather total column ozone has been almost constant at midlatitudes in both hemispheres since the recovery from the 1991 Mt. Pinatubo eruption. The observed total column ozone losses from 1979 to the period 1994-1997 are about 5.4, 2.8, and 5.0%, respectively, for northern midlatitudes in winter/spring, northern midlatitudes in summer/fall, and southern midlatitudes year round, rather than the values projected in the 1994 Assessment assuming a linear trend: 7.6, 3.4, and 7.2%, respectively. The understanding of how changes in stratospheric chlorine/bromine and aerosol loading affect ozone suggests some of the reasons for the unsuitability of using a linear extrapolation of the pre-1991 ozone trend to the present.

- **The link between the long-term build-up of chlorine and the decline of ozone in the upper stratosphere has been firmly established.** Model predictions based on the observed build-up of stratospheric chlorine in the upper stratosphere indicate a depletion of ozone that is in good quantitative agreement with the altitude and latitude dependence of the measured ozone decline during the past several decades, which peaks at about 7% per decade near 40 km at midlatitudes in both hemispheres.

- **The springtime Antarctic ozone hole continues unabated.** The extent of ozone depletion has remained essentially unchanged since the early 1990s. This behavior is expected given the near-complete destruction of ozone within the Antarctic lower stratosphere during springtime. The factors contributing to the continuing depletion are well understood.

- **The late-winter/spring ozone values in the Arctic were unusually low in 6 out of the last 9 years, the 6 being years that are characterized by unusually cold and protracted stratospheric winters.** The possibility of such depletions was predicted in the 1989 Assessment. Minimum Arctic vortex temperatures are near the threshold for large chlorine activation. Therefore, the year-to-year variability in temperature, which is driven by meteorology, leads to particularly large variability in ozone for current chlorine loading. As a result, it is not possible to forecast the behavior of Arctic ozone for a particular year. Elevated stratospheric halogen abundances over the next decade or so imply that the Arctic will continue to be vulnerable to large ozone losses.

- **The understanding of the relation between increasing surface UV-B radiation and decreasing column ozone has been further strengthened by ground-based observations, and newly developed satellite methods show promise for establishing global trends in UV radiation.** The inverse dependence of surface UV radiation and the overhead amount of ozone, which was demonstrated in earlier Assessments, has been further demonstrated and quantified by ground-based measurements under a wide range of atmospheric conditions. In addition, the influences of other variables, such as clouds, particles, and surface reflectivity, are better understood. These data have assisted the development of a satellite-based method to estimate global UV changes, taking into account the role of cloud cover. The satellite estimates for 1979-1992 indicate that the largest UV increases occur during spring at high latitudes in both hemispheres.

- **Stratospheric ozone losses have caused a cooling of the global lower stratosphere and global-average negative radiative forcing of the climate system.** The decadal temperature trends in the stratosphere have now been better quantified. Model simulations indicate that much of the observed downward trend in lower stratospheric temperatures (about 0.6˚C per decade over 1979-1994) is attributed to the ozone loss in the lower stratosphere. A lower stratosphere that is cooler results in less infrared radiation reaching the surface/troposphere system. Radiative calculations, using extrapolations based on the ozone trends reported in the 1994 Assessment for reference, indicate that stratospheric ozone losses since 1980 may have offset about 30% of the positive forcing due to increases in the well-mixed greenhouse gases (i.e., carbon dioxide, methane, nitrous oxide, and the halocarbons) over the same time period. The climatic impact of the slowing of midlatitude ozone trends and the enhanced ozone loss in the Arctic has not yet been assessed.

- **Based on past emissions of ozone-depleting substances and a projection of the maximum allowances under the Montreal Protocol into the future, the maximum ozone depletion is estimated to lie within the current decade or the next two decades, but its identification and the evidence for the recovery of the ozone layer lie still further ahead.** The falloff of total chlorine and bromine abundances in the stratosphere in the next century will be much slower than the rate of increase observed in past decades, because of the slow rate at which natural processes remove these compounds from the stratosphere. The most vulnerable period for ozone depletion will be extended into the coming decades. However, extreme perturbations, such as natural events like volcanic eruptions, could enhance the loss from ozone-depleting chemicals. Detection of the beginning of the recovery of the ozone layer could be achievable early in the next century if decreasing chlorine and bromine abundances were the only factor. However, potential future increases or decreases in other gases important in ozone chemistry (such as nitrous oxide, methane, and water vapor) and climate change will influence the recovery of the ozone layer. When combined with the natural variability of the ozone layer, these factors imply that unambiguous detection of the beginning of the recovery of the ozone layer is expected to be well after the maximum stratospheric loading of ozone-depleting gases.

## Supporting Scientific Evidence and Related Issues

### RECENT HALOGEN AND METHANE CHANGES

- Tropospheric abundances of total organic chlorine (Cl) contained in long- and short-lived halocarbons reached maximum values of 3.7 ± 0.1 parts per billion (ppb) between mid-1992 and mid-1994 and are beginning to decrease slowly in the global troposphere. The decline in the tropospheric abundance of methyl chloroform ($CH_3CCl_3$) (at a rate of about 40 to 42 parts per trillion (ppt) Cl $yr^{-1}$ in 1996) is the principal cause of the decrease and reversal in the Cl growth rate. At the same time, chlorine from the sum of the major CFCs grew at 7 ppt Cl $yr^{-1}$ (CFC-12, 9 ppt Cl $yr^{-1}$; CFC-11, -2 ppt Cl $yr^{-1}$; CFC-113, 0 ppt Cl $yr^{-1}$) and by 10 ppt Cl $yr^{-1}$ from the three major hydrochlorofluorocarbons (HCFCs) (HCFC-22, 5 ppt Cl $yr^{-1}$; HCFC-141b, 4 ppt Cl $yr^{-1}$; HCFC-142b, 1 ppt Cl $yr^{-1}$). The rate of decay of $CH_3CCl_3$ is expected to slow down to less than 10 ppt Cl $yr^{-1}$ by 2005. By that point its concentration should be so small that it will no longer be an important contributor to atmospheric organic chlorine.

- Space-based remote measurements of hydrogen chloride (HCl), hydrogen fluoride (HF), and total chlorine in the stratosphere, as well as column abundances of HCl, chlorine nitrate ($ClONO_2$), HF, and carbonyl difluoride ($COF_2$) from the ground, are consistent with the content and rate of change of the total organic chlorine and fluorine abundance of the troposphere. These observations provide evidence that the rate of increase of stratospheric chlorine loading has slowed in recent years.

- Growth in the tropospheric concentrations of HCFCs and hydrofluorocarbons (HFCs) has been observed as expected from continuation of previous uses and from their use as replacements for chlorofluorocarbons (CFCs). Emissions calculated by industry from sales and use data are in accordance with the current global abundances of HCFC-22 and HFC-134a. For HCFC-141b and -142b, the industry data underestimate the current global abundances by factors of approximately 1.3 and 2 respectively. No production and sales data are currently available for other HCFCs and HFCs being used as CFC alternatives.

- New studies suggest a major reduction in the magnitude of the estimated oceanic source of methyl chloride ($CH_3Cl$). As a result, the sum of known sources is inadequate to explain the observed atmospheric burden of $CH_3Cl$, thus requiring a larger contribution from other sources, either natural or anthropogenic.

- Tropospheric bromine loading continues to rise largely because of the ongoing growth of Halon-1211 (almost 6% $yr^{-1}$), Halon-2402 (2% $yr^{-1}$), and Halon-1301 (1% $yr^{-1}$). Possible causes are the large "banking" in developed countries of that compound during the 1980s and its subsequent use and release during the 1990s, and new production in developing countries. Continued increases of halons over the next few years could cause the abundance of equivalent chlorine to decline more slowly than predicted in the 1994 Assessment.

- Recent measurements and intercomparisons of calibration standards have confirmed that the average global mixing ratio of methyl bromide ($CH_3Br$) is between 9 and 10 ppt and that the interhemispheric ratio is 1.3 ± 0.1 (north/south). New estimates of methyl bromide losses yield magnitudes of 77 Gg $yr^{-1}$ (ranging from 37 to 133 Gg $yr^{-1}$) for ocean uptake; 42 Gg $yr^{-1}$ (ranging from 10 to 214 Gg $yr^{-1}$) for soil uptake; and 86 Gg $yr^{-1}$ (ranging from 65 to 107 Gg $yr^{-1}$) for removal by hydroxyl radical (OH), for a total removal rate of 205 Gg $yr^{-1}$ with a range of about 110 to 450 Gg $yr^{-1}$. The current best estimate of the lifetime of atmospheric $CH_3Br$, as calculated from losses within the atmosphere, to the ocean, and to soils, is 0.7 years, with a range of 0.4 to 0.9 years. The Ozone Depletion Potential (ODP) of methyl bromide is 0.4, with a range of 0.2 to 0.5.

- No new important sources of methyl bromide have been identified. The ocean now appears to be a net sink, with an estimated net flux from the atmosphere of -21 Gg $yr^{-1}$ (ranging from -3 to -32 Gg $yr^{-1}$). Estimates of ocean emissions of order 60 Gg $yr^{-1}$ can be directly deduced from the above estimates for uptake and net ocean flux. The total emission of $CH_3Br$ from identified sources is 122 Gg $yr^{-1}$, with a range of 43 to 244 Gg $yr^{-1}$. The best-quantified source is fumigation, with a magnitude of 41 Gg $yr^{-1}$ and a range of 28 to 64 Gg $yr^{-1}$. Other anthropogenic sources include biomass burning (20 Gg $yr^{-1}$, ranging from 10 to 40 Gg $yr^{-1}$) and leaded gasoline use (5 Gg $yr^{-1}$, ranging from negligible to 10 Gg $yr^{-1}$). Identified sources of $CH_3Br$ thus constitute only about 60% of identified sinks on a globally averaged basis. This disagreement is difficult to reconcile with estimated uncertainties in the source and sink terms. The short lifetime of methyl bromide, coupled with the inhomogeneity of its sources and sinks, complicates the interpretation of its global budget.

- Based on the most recent analysis of the methyl chloroform ($CH_3CCl_3$) observational record (including a refinement in calibration), the estimated atmospheric lifetimes (with respect to reactive removal by OH) of $CH_3CCl_3$, HCFCs, HFCs, and $CH_4$ have been reduced by about 15% since the 1994 Assessment. The 1995 assessment of the Intergovernmental Panel on Climate Change (IPCC) mostly reflected these revisions, with a slightly smaller correction factor of about 10%. For species whose chemical lifetime is shorter than 1 to 2 years, the use of a global-mean lifetime may not be appropriate.

- The atmospheric abundance of $CH_4$ continues to increase, but with a declining growth rate. The average growth rate between 1980 and 1992 of about 10 ppb $yr^{-1}$ can be compared with the 1996-1997 rate of approximately 3 to 4 ppb $yr^{-1}$. The current best estimate for the total atmospheric lifetime of methane has been lowered to 8.9 ± 0.6 years.

## STRATOSPHERIC PARTICLES

- Observations and models have further confirmed that stratospheric sulfate aerosol (SSA) and polar stratospheric clouds (PSCs) play a key role in ozone loss chemistry through heterogeneous reactions that activate halogen species and deactivate nitrogen species.

- Observations have increased our knowledge of particle formation processes, the dispersal and decay of volcanic SSA, and particle climatology. They show that supercooled ternary solution (STS) droplets that form from SSA without a nucleation barrier are an important class of PSC particles. The formation processes of solid PSC particles that play a significant role in denitrification of the polar vortices remain uncertain. Recent studies suggest that mesoscale temperature fluctuations, especially over mountain ranges, may be important in PSC formation processes, particularly in the Arctic.

- The two most recent major volcanic eruptions, El Chichón (1982) and Mt. Pinatubo (1991), both temporarily increased SSA amounts by more than an order of magnitude.

- There is no clear trend in SSA abundances from 1979 to 1997, demonstrating that any anthropogenic contribution must be smaller than thought in the 1994 Assessment. SSA models including known tropospheric sulfur sources underpredict 1979 values, which were thought to represent the non-volcanic background, but it is not clear that this period was truly free of volcanic influence.

## OZONE IN THE MIDLATITUDES AND TROPICS

- As noted in the 1994 Assessment, Northern Hemisphere midlatitude column ozone decreased markedly in 1992-1993, following the large enhancement of stratospheric aerosol caused by the eruption of Mt. Pinatubo in 1991. Column ozone has now reached amounts higher than a linear extrapolation of the pre-Pinatubo trend would predict. Between 25 and 60˚N, ozone abundances for 1994-1997 averaged about 4% below 1979 values, although with large variability, while extrapolation of the pre-1991 trend would predict current (1997) abundances about 5.5% below 1979 values. The corresponding winter/spring and summer/fall losses average about 5.4 and 2.8%, respectively, while a linear extrapolation would predict 7.6 and 3.4%, respectively. The average ozone abundances between 25 and 60˚S are currently about 4% (satellite) or 5% (ground) below 1979 values, while the linear extrapolation would predict 7.2% (both satellite and ground).

- Our understanding of how changes in halogen and aerosol loading affect ozone suggests some of the reasons for the unsuitability of using a linear extrapolation of the pre-1991 ozone trend to the present. For example, observations of stratospheric HCl and $ClONO_2$ show a build-up of stratospheric chlorine in recent years consistent with halocarbon emissions, but slower than would have been predicted by the chlorine trends observed before 1992. In addition, enhanced stratospheric aerosol was also present throughout much of the decade of the 1980s due to earlier volcanic eruptions (e.g., El Chichón and Ruiz), likely enhancing the downward trend of ozone observed even before Pinatubo.

- There are no statistically significant trends in total ozone in the equatorial regions (20˚S to 20˚N).

- The amplitude of the annual cycle of ozone at middle to high latitudes has decreased by approximately 15% in the last decades because larger declines have occurred during the season of maximum ozone values.

- For northern midlatitudes, combined vertical profile ozone trends through 1996 are negative at all altitudes between 12 and 45 km and are statistically significant at the $2\sigma$ level. The downward trend is largest near 40 and 15 km (approximately 7% per decade) and is smallest at 30 km (2% per decade). The bulk of column ozone decline is between the tropopause and 25 km.

- The re-evaluation of the Stratospheric Aerosol and Gas Experiment (SAGE) I/II satellite data indicates that there are no significant interhemispheric differences in upper stratospheric trends through 1996. Agreement is good, within estimated uncertainties, between SAGE I/II and ozonesonde trends in the lower to middle stratosphere in northern midlatitudes.

- The total ozone and the vertical profile trends derived for the northern midlatitudes are consistent with each other over the periods studied.

- Most of the midlatitude column ozone decline during the last two decades arose because of depletion in the lower stratosphere. That region is influenced by local chemical ozone loss that is enhanced by volcanic aerosol, and by transport from other regions. The vertical, latitudinal, and seasonal characteristics of the depletion of midlatitude ozone are broadly consistent with the understanding that halogens are the primary cause. The expected low ozone amounts in the midlatitude lower stratosphere following the Mt. Pinatubo eruption further strengthened the connection between ozone destruction and anthropogenic chlorine.

- Models that represent processes affecting ozone are able to calculate variations in ozone abundances that are broadly consistent with the observed midlatitude column ozone trend as well as the response to volcanic enhancement of stratospheric sulfate aerosol. In particular, models reproduce the lower ozone abundances observed immediately following Mt. Pinatubo and the subsequent increases as the aerosol disappeared.

- Current two-dimensional (2-D) assessment models that allow for the observed build-up of stratospheric chlorine calculate reductions in ozone that are in good quantitative agreement with the altitude and latitude dependence of the measured decline in upper stratospheric ozone during the past several decades. This clearly confirms the hypothesis put forth in 1974 that release of CFCs to the atmosphere would lead to a significant reduction of upper stratospheric ozone, with the peak percentage decline occurring around 40 km.

- Comparison of recent observations and model results shows that the overall partitioning of reactive nitrogen and chlorine species is well understood for the upper stratosphere. The previously noted discrepancy for the chlorine monoxide/hydrogen chloride (ClO/HCl) ratio has been resolved based on new kinetic information. Balloonborne observations of OH and hydroperoxyl radicals ($HO_2$) agree well with theory, but satellite and ground-based observations of these species exhibit systematic differences compared with model calculations.

- An improved understanding of the relevant kinetic processes has resulted in a close balance between the calculated production and loss of ozone at 40 km (i.e., the long-standing difference between calculated and observed ozone abundance has been mostly resolved).

- Constituent measurements show that the tropics are relatively isolated from midlatitudes in the lower stratosphere. The extent of isolation affects the budgets (and lifetimes) of chemical species that affect ozone abundance.

### OZONE IN HIGH-LATITUDE POLAR REGIONS

- The large ozone losses in the Southern Hemisphere polar region during spring continued unabated with approximately the same magnitude and areal extent as in the early 1990s. In Antarctica, the monthly total ozone in September and October has continued to be 40 to 55% below the pre-ozone-hole values of approximately 320 m-atm cm (“Dobson units”), with up to a 70% decrease for periods of a week or so. This depletion occurs primarily over the 12- to 20-km altitude range, with most of the ozone in this layer disappearing during early October. These ozone changes are consistent overall with our understanding of chemistry and dynamics.

- In the Arctic vortex, low column ozone values were observed in the late-winter/spring for 6 out of the last 9 years. Monthly mean values were about 100 m-atm cm below 1960-1970 averages, with shorter-period differences exceeding 200 m-atm cm (equivalent to about 20 to 45% of values found in the 1960s and early 1970s). Within the column, the largest ozone differences were observed in the lower stratosphere.

- Years with large seasonal ozone depletion in the late-winter/spring Arctic are characterized by specific meteorological conditions. These conditions are lower-than-normal late-winter Arctic temperatures, which lead to enhanced activated chlorine, and a more isolated vortex and weaker planetary-wave driving, which lead to less transport of ozone-rich air into the Arctic. Low temperatures, an isolated vortex, and reduced wave driving are coupled processes that occur in concert in the stratosphere. Chemical ozone losses have been identified within the Arctic vortex and are associated with activated chlorine augmented by bromine. The total seasonal chemical ozone losses within the vortex have been estimated to be approximately 100 m-atm cm.

- With the present high abundances of chlorine loading, late-winter/spring Arctic chemical ozone loss is particularly sensitive to meteorological conditions (temperature and vortex isolation) because minimum vortex temperatures are at a critical value in terms of activating chlorine. Winter vortex temperatures in the 1990s have been particularly low. In the absence of low temperatures and an isolated vortex, reduced chemical ozone loss would be expected. However, such a reduced ozone loss would not indicate chemical recovery. The Arctic will remain vulnerable to extreme seasonal loss as long as chlorine loading remains high.

- Chlorine activation in liquid particles in the lower stratosphere (both SSA and liquid PSCs) increases strongly with decreases in temperature and is at least as effective as that on solid particles. Thus, chlorine activation is to a first approximation controlled by temperature and water vapor pressure and only secondarily by particle composition.

- Rapid polar ozone loss requires enhanced chlorine monoxide in the presence of sunlight. Maintenance of elevated ClO in late-winter/spring is dependent upon temperature and requires either repeated heterogeneous processing or denitrification. Since the 1994 Assessment, new understanding has shown that cold liquid aerosol can maintain elevated ClO in non-denitrified air.

### STRATOSPHERIC TEMPERATURES

- Radiosonde and satellite observations indicate a decadal cooling trend of the global, annual-mean lower stratosphere (approximately 16 to 21 km) since about 1980. Over the period 1979 to 1994, its amplitude is approximately 0.6˚C per decade. At midlatitudes the trend is larger (approximately 0.75˚C per decade) and broadly coherent among the various datasets with regard to the magnitude and statistical significance.

- Substantial cooling (approximately 3˚C per decade) is observed in the polar lower stratosphere during late-winter/spring in both hemispheres. A decadal-scale cooling is evident in the Antarctic since the early 1980s and in the Arctic since the early 1990s. However, the dynamical variability is large in these regions, particularly in the Arctic, and this introduces difficulties in establishing the statistical significance of trends.

- The vertical profile of the annual-mean stratospheric temperature change observed in the Northern Hemisphere midlatitudes is robust for the 1979-1994 period within the different datasets. The trend consists of an approximately 0.75˚C per decade cooling of the 15- to 35-km region, a slight reduction in the cooling at about 35 km, and increased cooling with height above 35 km (approximately 2˚C per decade at 50 km).

- Model simulations based on known changes in the stratospheric concentrations of various radiatively active species indicate that the depletion of lower stratospheric ozone is the dominant radiative factor in the explanation of the observed global-mean lower stratospheric cooling trends for the period 1979-1990 (approximately 0.5°C per decade). The contribution to these trends from increases in well-mixed greenhouse gases is estimated to be less than one-fourth that due to ozone loss.

- Model simulations indicate that ozone depletion is an important causal factor in the latitude-month pattern of the decadal (1979-1990) lower stratospheric cooling. The simulated lower stratosphere in Northern and Southern Hemisphere midlatitudes and in the Antarctic springtime generally exhibit a statistically significant cooling trend over this period consistent with observations.

- In the middle and upper stratosphere, both the well-mixed greenhouse gases and ozone change contribute in an important manner to the cooling. However, the computed cooling due to these gases underestimates the observed decadal trend.

### TROPOSPHERIC OZONE

- Trends in tropospheric ozone since 1970 in the Northern Hemisphere show large regional differences, with increases in Europe and Japan, decreases in Canada, and only small changes in the United States. The trend in Europe since the mid-1980s has reduced to virtually zero (at two recording stations). In the Southern Hemisphere, small increases have now been observed in surface ozone.

- Recent field studies have shown that anthropogenic emissions of ozone precursors (nitrogen oxides, carbon monoxide, and hydrocarbons) lead to large-scale production of ozone, which, through long-range transport, influences the ozone concentration in large regions of the troposphere in both hemispheres. However, significant uncertainties remain in the budget of tropospheric ozone, its precursors, and the chemical and physical processes involved. Large spatial and temporal variability is observed in tropospheric ozone, resulting from important regional differences in the factors controlling its concentration.

- Important improvements in global chemical transport models (CTMs) have allowed better simulations of tropospheric ozone distributions and of ozone perturbations resulting from anthropogenic emissions.

- Considerable progress has been made in testing tropospheric photochemistry through field measurements. Our theoretical understanding of tropospheric OH is nevertheless incomplete, specifically in regard to sources of upper tropospheric OH and polluted conditions.

- Increases in air traffic and the resulting emissions could have impacts on atmospheric chemistry and cloud formation, with implications for the ozone layer and the climate system. The understanding of the effects of aircraft emissions are currently being assessed as part of the Intergovernmental Panel on Climate Change (IPCC) special report *Aviation and the Global Atmosphere: 1999*. Consequently, this topic is not included in the scope of the present Assessment.

### CHANGES IN UV RADIATION

- The inverse correlation between ozone column amounts and ultraviolet-B (UV-B) irradiance has been reconfirmed and firmly established by numerous ground-based measurements. The ground-based measurements have increased our understanding of additional effects such as albedo, altitude, clouds and aerosols, and geographic differences on UV irradiance at the Earth's surface.

- A controversy concerning anomalous UV-trend estimates from the Robertson-Berger (RB) meter network located in the continental United States. (1974-1985) has been explained in terms of poor calibration stability. The reanalysis of this U.S. RB-meter dataset shows that the errors are too large for determining UV-irradiance trends over that period.

- Increases in UV-B irradiance (e.g., 1989-1997; 1.5% $yr^{-1}$ at 300 nm, 0.8% $yr^{-1}$ at 305 nm) have been detected with a few ground-based spectroradiometers at midlatitudes (near 40°) and are consistent with expected changes from the decreasing amounts of ozone. Although these UV changes are consistent with those estimated from satellite data, the ground-based data records from suitably stable and calibrated instruments are not yet long enough to determine decadal trends. Local irradiance changes, not seen in the coarse-spatial-resolution satellite data, caused by pollution and aerosols have been detected in both UV-B (280 to 315 nm) and UV-A (315 to 400 nm).

- New satellite estimates of global (±65°) UV irradiance that now include cloud, surface reflectivity, and aerosol effects have been estimated from measured backscattered radiances from the Total Ozone Mapping Spectrometer (TOMS) using radiative transfer models. Climatological maps of UV irradiance can be produced from the daily data. In addition, the satellite data have been used to estimate zonally averaged global and seasonal trends in UV irradiance from 1979 to 1992. For this period, annual erythemal UV-irradiance decadal increases were estimated to be 3.7 ± 3% at 60°N and 3 ± 2.8% at 40°N. Larger decadal increases were observed in the Southern Hemisphere: 3.6 ± 2% at 40°S and 9 ± 6% at 60°S. No statistically significant trends were observed between ±30° latitude. Zonally averaged UV-A irradiances have not changed.

- Current zonal-average UV-irradiance trend estimations from satellite data that include cloud effects are nearly identical to clear-sky estimates. The currently estimated trends are slightly lower than the clear-sky trend estimates in the 1994 Assessment because of the new TOMS retrieval algorithm.

- Instrument intercomparison and newly developed calibration and database centers have improved the quality and availability of ground-based data.

### CHANGES IN CLIMATE PARAMETERS

- Increased penetration of UV radiation to the troposphere as a result of stratospheric ozone depletion influences key photochemical processes in the troposphere. Model results suggest that a 1% decrease in global total ozone leads to a global increase of 0.7 to 1% in globally averaged tropospheric OH, which would affect the lifetimes of several climate-related gases.

- The global average radiative forcing due to changes in stratospheric ozone since the late 1970s, using extrapolations based on the ozone trends reported in the 1994 Assessment for reference, is estimated to be $-0.2 \pm 0.15\ Wm^{-2}$, which offsets about 30% of the forcing due to increases in other greenhouse gases over the same period. The climatic impact of the slowing of midlatitude trends and the enhanced ozone loss in the Arctic has not yet been assessed. Recovery of stratospheric ozone would reduce the offset to the radiative forcing of the other greenhouse gases. The ozone recovery will therefore lead to a more rapid increase in radiative forcing than would have occurred due to increases in other greenhouse gases alone.

- The global average radiative forcing due to increases in tropospheric ozone since preindustrial times is estimated to be $+0.35 \pm 0.15\ Wm^{-2}$, which is about 10 to 20% of the forcing due to long-lived greenhouse gases over the same period.

- Coupled ocean-atmosphere general circulation models (GCMs) have been used to calculate the impact of stratospheric ozone loss on the thermal structure of the atmosphere. The calculated altitude of the transition from tropospheric warming to stratospheric cooling due to increases in well-mixed greenhouse gases is in better agreement with observations when ozone depletion is taken into account.

- Radiative forcings and Global Warming Potentials (GWPs) are now available for an expanded set of gases. New categories include fluorinated organic molecules. The CFC-11 radiative forcing has been revised by +12% from the value used since IPCC (1990), primarily because of the use of an improved vertical profile of CFC-11 mixing ratio. This and other updates lead to GWPs relative to $CO_2$ that are typically 20% higher than those in IPCC (1995).

## FUTURE HALOGEN CHANGES

- Large reductions in the production and atmospheric release of ozone-depleting substances (ODSs) have been achieved by international regulations (Montreal Protocol and its Amendments and Adjustments). Without such controls, and assuming a (conservative) 3% annual growth rate in production, ODSs would have led to an equivalent effective chlorine loading of around 17 ppb in 2050. The control measures of the original Montreal Protocol (1987) reduce this to approximately 9 ppb; the Amendments of London (1990) to about 4.6 ppb; and the Amendments of Copenhagen (1992) to approximately 2.2 ppb (but with stratospheric halogen loading increasing again in the second half of the 21st century). The Adjustments of Vienna (1995) and the Amendments of Montreal (1997) further reduce this to about 2.0 ppb (approximately the 1980 abundance) around the year 2050.

- Stratospheric halogen loading lags tropospheric loading by up to 6 years. Given that tropospheric halogen loading peaked around 1994 and assuming a scenario with a 3-yr lag time, the equivalent effective stratospheric chlorine loading is estimated to have peaked in 1997, at an abundance 1.7 times higher than in 1980. If annual ozone trends observed in the 1980s are attributed solely to these halogen increases, the peak ozone reductions in 1997, relative to 1980, are estimated to be about 5% at 45˚N and 6% at 45˚S. The corresponding increases in erythemally weighted UV radiation in 1997 are estimated to be 5% at 45˚N and 8% at 45˚S relative to the 1980 values.

## RECOVERY OF THE OZONE LAYER

- In the absence of other changes, stratospheric ozone abundances should rise in the future as the halogen loading falls in response to regulation. However, the future behavior of ozone will also be affected by the changing atmospheric abundances of methane ($CH_4$), nitrous oxide ($N_2O$), water vapor ($H_2O$), sulfate aerosol, and changing climate. Thus, for a given halogen loading in the future, the atmospheric ozone abundance may not be the same as found in the past for that same halogen loading.

- Several two-dimensional models were used to look at the response of ozone to past and future changes in atmospheric composition. Future global ozone abundances are predicted to recover only slowly toward their 1980 values. The return toward 1980 ozone values in the models depends sensitively on the emission scenarios used. The $CH_4$ scenario used here has a lower growth rate than in previous assessments, which slows the modeled ozone recovery significantly. Understanding the methane trend is an important priority for understanding the future ozone recovery.

- Temperatures in the Arctic winter lower stratosphere are generally close to the threshold for substantial chlorine activation, making Arctic ozone particularly sensitive to small changes in temperature (e.g., cooling of the lower stratosphere by changes in greenhouse gases). Preliminary calculations with coupled chemistry/climate models suggest that recovery in the Arctic could be delayed by this cooling and, because of the large natural variability, recovery will be difficult to detect unambiguously until well into the next century.

- The detection of the onset of ozone recovery from halogen-induced depletion should be possible earlier in the Antarctic than in the Arctic or globally because there is less variability in the ozone loss in the Antarctic. Estimates of the timing of the detection of the onset of ozone recovery are uncertain. However, it is clear that unambiguous detection of the beginning of recovery will be delayed beyond the maximum loading of stratospheric halogens.

## Implications for Policy Formulation

The results from more than two decades of research have provided a progressively better understanding of the interaction of human activities and the chemistry and physics of the global atmosphere. New policy-relevant insights to the roles of trace atmospheric constituents have been conveyed to decision-makers through the international state-of-the-understanding assessment process. This information has served as a key input to policy decisions by governments, industry, and other organizations worldwide to limit the anthropogenic emissions of gases that cause environmental degradation: (1) the 1987 Montreal Protocol on ozone-depleting substances, and its subsequent Amendments and Adjustments, and (2) the 1997 Kyoto Protocol on substances that alter the radiative forcing of the climate system.

The research findings that are summarized above are of direct interest and significance as scientific input to governmental, industrial, and other policy decisions associated with the Montreal Protocol (ozone layer) and the Kyoto Protocol (climate change):

- **The Montreal Protocol is working.** Global observations have shown that the combined abundance of anthropogenic chlorine-containing and bromine-containing ozone-depleting substances in the lower atmosphere peaked in 1994 and has now started to decline. One measure of success of the Montreal Protocol and its subsequent Amendments and Adjustments is the forecast of "the world that was avoided" by the Protocol:

    - The abundance of ozone-depleting gases in 2050, the approximate time at which the ozone layer is now projected to recover to pre-1980 levels, would be at least 17 ppb of equivalent effective chlorine (this is based on the conservative assumption of a 3% per annum growth in ozone-depleting gases), which is about 5 times larger than today's value.

    - Ozone depletion would be at least 50% at midlatitudes in the Northern Hemisphere and 70% at midlatitudes in the Southern Hemisphere, about 10 times larger than today.

    - Surface UV-B radiation would at least double at midlatitudes in the Northern Hemisphere and quadruple at midlatitudes in the Southern Hemisphere compared with an unperturbed atmosphere. This compares to the current increases of 5% and 8% in the Northern and Southern Hemispheres, respectively, since 1980.

    Furthermore, all of the above impacts would have continued to grow in the years beyond 2050. It is important to note that, while the provisions of the original Montreal Protocol in 1987 would have lowered the above growth rates, recovery (i.e., an improving situation) would have been impossible without the Amendments and Adjustments (London, 1990; Copenhagen, 1992; and Vienna, 1995).

- **The ozone layer is currently in its most vulnerable state.** Total stratospheric loading of ozone-depleting substances is expected to maximize before the year 2000. All other things being equal, the current ozone losses (relative to the values observed in the 1970s) would be close to the maximum. These are:

  - about 6% at Northern Hemisphere midlatitudes in winter/spring;
  - about 3% at Northern Hemisphere midlatitudes in summer/fall;
  - about 5% at Southern Hemisphere midlatitudes on a year-round basis;
  - about 50% in the Antarctic spring; and
  - about 15% in the Arctic spring.

  Such changes in ozone are predicted to be accompanied by increases in surface erythemal radiation of 7, 4, 6, 130, and 22%, respectively, if other influences such as clouds remain constant. It should be noted that these values for ozone depletion at midlatitudes are nearly a factor of 2 lower than projected in 1994, primarily because the linear trend in ozone observed in the 1980s did not continue in the 1990s. However, springtime depletion of ozone in Antarctica continues unabated at the same levels as observed in the early 1990s, and large depletions of ozone have been observed in the Arctic in most years since 1990, which are characterized by unusually cold and protracted winters.

  Some natural and anthropogenic processes that do not in themselves cause ozone depletion can modulate the ozone loss from chlorine and bromine compounds, in some cases very strongly. For example, in coming decades midlatitude ozone depletion could be enhanced by major volcanic eruptions, and Arctic ozone depletion could be increased by cold polar temperatures, which in turn could be linked to greenhouse gases or to natural temperature fluctuations. On the other hand, increases in methane would tend to decrease chlorine-catalyzed ozone loss.

  The current vulnerability to ozone depletion over the next few decades is primarily due to past use and emissions of the long-lived ozone-depleting substances. The options to reduce this vulnerability over the next two decades are thus rather limited. The main drivers of ozone change could be natural and anthropogenic processes not related to chlorine and bromine compounds, but to which the ozone layer is sensitive because of the elevated abundances of ozone-depleting substances.

- **The ozone layer will slowly recover over the next 50 years.** The stratospheric abundance of halogenated ozone-depleting substances is expected to return to its pre-1980 (i.e., “unperturbed”) level of 2 ppb chlorine equivalent by about 2050, assuming full compliance with the Montreal Protocol and its Amendments and Adjustments. The atmospheric abundances of global and Antarctic ozone will start to slowly recover within coming decades toward their pre-1980 levels once the stratospheric abundances of ozone-depleting (halogen) gases start to decrease. However, the future abundance of ozone will be controlled not only by the abundance of halogens, but also by the atmospheric abundances of methane, nitrous oxide, water vapor, and sulfate aerosols and by the Earth’s climate. Therefore, for a given halogen loading in the future, atmospheric ozone abundance is unlikely to be the same as found in the past for the same halogen loading.

- **Few policy options are available to enhance the recovery of the ozone layer.** Relative to the current, but not yet ratified, control measures (Montreal, 1997), the equivalent effective chlorine loading above the 1980 level, integrated from now until the 1980 level is re-attained, could be decreased by:

  - 9% by eliminating global Halon-1211 emissions in the year 2000, thus requiring the complete elimination of all new production and destruction of all Halon-1211 in existing equipment;

  - 7% by eliminating global Halon-1301 emissions in the year 2000, thus requiring the complete elimination of all new production and destruction of all Halon-1301 in existing equipment;

- 5% by eliminating the global production of all HCFCs in the year 2004;
- 2.5% by eliminating the global production of all CFCs and carbon tetrachloride in the year 2004;
- 1.6% by reducing the cap on HCFC production in developed countries from 2.8% to 2.0% in the year 2000, by advancing the phase-out from the year 2030 to 2015, and by instituting more rapid intermediate reductions; and
- about 1% by eliminating the global production of methyl bromide beginning in 2004.

These policy actions would advance the date at which the abundance of effective chlorine returns to the 1980 value by 1-3 years. A complete and immediate global elimination of all emissions of ozone-depleting substances would result in the stratospheric halogen loading returning to the pre-1980 values by the year 2033. It should also be noted that if the currently allowed essential uses for metered dose inhalers are extended from the year 2000 to 2004, then the equivalent effective chlorine loading above the 1980 level would increase by 0.3%.

- **Failure to comply with the international agreements of the Montreal Protocol will affect the recovery of the ozone layer.** For example, illegal production of 20-40 ktonnes per year of CFC-12 and CFC-113 for the next 10-20 years would increase the equivalent effective chlorine loading above the 1980 abundance, integrated from now until the 1980 abundance is re-attained, by about 1-4% and delay the return to pre-1980 abundances by about a year.

- **The issues of ozone depletion and climate change are interconnected; hence, so are the Montreal and Kyoto Protocols.** Changes in ozone affect the Earth's climate, and changes in climate and meteorological conditions affect the ozone layer, because the ozone depletion and climate change phenomena share a number of common physical and chemical processes. Hence, decisions taken (or not taken) under one Protocol have an impact on the aims of the other Protocol. For example, decisions made under the Kyoto Protocol with respect to methane, nitrous oxide, and carbon dioxide will affect the rate of recovery of ozone, while decisions regarding controlling HFCs may affect decisions regarding the ability to phase out ozone-depleting substances.