Reprinted from
World Meteorological Organization
Global Ozone Research and Monitoring Project—Report No. 47

EXECUTIVE SUMMARY

SCIENTIFIC ASSESSMENT OF OZONE DEPLETION: 2002

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

CONTENTS

EXECUTIVE SUMMARY

SCIENTIFIC ASSESSMENT OF OZONE DEPLETION: 2002

PREFACE

The present document contains key summaries from the *Scientific Assessment of Ozone Depletion: 2002*. 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.

The Charge to the Assessment Panels

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."

To meet this request, the Scientific Assessment Panel, the Environmental Effects Panel, and the Technology and Economic Assessment Panel have each prepared, about every 3-4 years, major assessment reports that updated the state of understanding in their purviews. These reports have been scheduled to be available to the Parties in advance of their meetings at which they will consider the need to amend or adjust the Protocol.

The Sequence of Scientific Assessments

The scientific assessment summarized in the present document is the latest in a series of nine 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 2002 report is the fifth in the set of major assessments that have been prepared by the Scientific Assessment Panel directly as input to the Montreal Protocol process. The chronology of all 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* (*Montreal Protocol Assessment Supplement*). UNEP (1992).
1992	Copenhagen Adjustments and Amendment	
1994		*Scientific Assessment of Ozone Depletion: 1994.* WMO No. 37.
1995	Vienna Adjustment	

Year	Policy Process	Scientific Assessment
1997	Montreal Adjustments and Amendment	
1998		*Scientific Assessment of Ozone Depletion: 1998.* WMO No. 44.
1999	Beijing Amendment	
2002		*Scientific Assessment of Ozone Depletion: 2002.* WMO No. 47.
2003	15th Meeting of the Parties	

The Current Information Needs of the Parties

The genesis of *Scientific Assessment of Ozone Depletion: 2002* occurred at the 11th Meeting of the Parties to the Montreal Protocol in Beijing, China, at which the scope of the scientific needs of the Parties was defined in their Decision XI/17.5(a): "To request the Scientific Assessment Panel to include the following in the 2002 scientific assessment:

(a) An evaluation of the observed trends in controlled substances and their consistency with reported production of ODS;
(b) A quantification of the ozone-depleting impacts of new (e.g., short-lived) halogen-containing substances;
(c) A characterization of methyl bromide sources and sinks and the likely quantitative implications of the results for the ozone layer;
(d) A characterization of the known interrelations between ozone depletion and climate change including feedbacks between the two;
(e) A description and interpretation of the observed changes in global and polar ozone and in ultraviolet radiation, as well as set future projections and scenarios for those variables, taking into account also the expected impacts of climate change…".

The Assessment Process

The formal planning of the current assessment was started early in 2001. At the request of the Scientific Assessment Panel, the Parties suggested experts from their countries who could participate in the process, and those suggestions contributed about half of the participants who served as authors, contributors, and reviewers. Furthermore, an ad hoc international scientific steering group also suggested participants from the world scientific community. In addition, this steering group contributed to crafting the outline of the assessment report. As in previous assessments, the participants represented experts from the developed and developing world. The developing-world experts bring a special perspective to the process, and their involvement in the process contributes to capacity building.

The information of the 2002 assessment is contained in five chapters, with most containing past trends and future projections associated with ozone-layer topics:

Chapter 1. Controlled Substances and Other Source Gases
Chapter 2. Very Short-Lived Halogen and Sulfur Substances
Chapter 3. Polar Stratospheric Ozone: Past and Future
Chapter 4. Global Ozone: Past and Future
Chapter 5. Surface Ultraviolet Radiation: Past and Future

The interactions between the ozone layer and the climate system are varied and appear appropriately as a special section in most of the chapters.

A special resource for the Panel's work was the earlier report, *Aviation and the Global Atmosphere*. This 1999 assessment of the impacts of aviation on ozone depletion and climate change was a collaboration of the Intergovernmental Panel on Climate Change (IPCC) and the Scientific Assessment Panel of the Montreal Protocol. The assessment had been requested by the International Civil Aviation Organization (ICAO). Because this comprehensive study had been recently done, the present 2002 assessment could cite the major relevant findings of the 1999 study and provide any updates of knowledge that had occurred.

The initial plans for the chapters of the 2002 Scientific Assessment Panel's report were examined at a meeting that occurred on 27-28 June 2001 in London, United Kingdom. The Lead Authors and Cochairs focused on the content of the draft chapters and establishing the needs for coordination among the chapters.

The first drafts of the chapters were examined at a meeting that occurred on 28-30 November 2001 in Fairfax, Virginia, United States, at which the Lead Authors, Cochairs, and a small group of international experts focused on the scientific content of the draft chapters.

The second drafts of the chapters were reviewed by 133 scientists worldwide in a mail peer review. Those comments were considered by the authors. At a Panel Review Meeting in Les Diablerets, Switzerland, held on 24-28 June 2002, the responses to these mail review comments were proposed by the authors and discussed by the 74 participants. Final changes to the chapters were decided upon at this meeting. The Executive Summary contained herein (and posted on the UNEP and WMO web sites on 23 August 2002) was prepared and completed by the attendees of the Les Diablerets meeting.

The 2002 State-of-Understanding Report

In addition to the scientific chapters and the Executive Summary, the assessment also focuses on 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 prepared, with different readerships in mind, e.g., students and the general public. These questions and answers are included in the full report and are available also as a separate publication.

As the accompanying list indicates, the *Scientific Assessment of Ozone Depletion: 2002* is the product of 275 scientists from the developed and developing world who contributed to its preparation and review[1] (170 scientists prepared the report and 182 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.

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

EXECUTIVE SUMMARY

The provisions of the 1987 Montreal Protocol on Substances that Deplete the Ozone Layer include the requirement that the Parties to the Protocol base their future decisions on the current scientific, environmental, technical, and economic information that is assessed through panels drawn from the worldwide expert communities. To provide that input to the decision-making process, advances in understanding on these topics were assessed in 1989, 1991, 1994, and 1998. This information helped support discussions among the Parties that led to the subsequent Amendments and Adjustments of the 1987 Protocol. The 2002 Scientific Assessment summarized here is the fifth in that series.

RECENT MAJOR FINDINGS AND CURRENT SCIENTIFIC UNDERSTANDING

Since the *Scientific Assessment of Ozone Depletion: 1998*, numerous laboratory investigations, atmospheric observations, and theoretical and modeling studies have produced new key findings and have strengthened overall understanding of the ozone layer and its effect on ultraviolet (UV) radiation. These advances are highlighted in the following summary of the current understanding of the impact of human activities and natural phenomena on the ozone layer and the coupling of the ozone layer and the climate system.

Changes in Ozone-Depleting Compounds

- **In the troposphere (i.e., lower atmosphere), observations show that the total combined effective abundance of ozone-depleting compounds continues to decline slowly from the peak that occurred in 1992-1994. Total chlorine is declining, while bromine from industrial halons is still increasing, albeit at a slower rate than was occurring previously (and as reported in the 1998 Assessment).** Total tropospheric *chlorine* from the long- and short-lived chlorocarbons was about 5% lower in 2000 than that observed at its peak in 1992-1994, and the rate of change in 2000 was about −22 parts per trillion (ppt) per year (−0.6% per year). The once-dominant influence of methyl chloroform (CH_3CCl_3) on this total decline is diminishing because the atmospheric abundance of methyl chloroform is sharply decreasing. Total chlorine from the major chlorofluorocarbons (CFCs) is no longer increasing, in contrast to the slight increase that was occurring at the time of the 1998 Assessment. Specifically, in 2000, the atmospheric abundances of CFC-11 and CFC-113 continued to decrease, while the rate of increase of CFC-12 had slowed. Total tropospheric bromine from halons continued to increase at about 3% per year, which is about two-thirds of the rate for 1996 reported in the 1998 Assessment. The observed abundances of CFCs, hydrochlorofluorocarbons (HCFCs), and methyl chloroform in the lower atmosphere continue to be consistent with reported production and estimated emissions.

- **Analyses of air trapped in snow since the late 19th century have confirmed that non-industrial sources of the CFCs, halons, and major chlorocarbons were insignificant.** Since the previous Assessment, analyses of firn air (i.e., air trapped in snow above glaciers) have revealed the abundance of long-lived atmospheric species at the time the air became trapped. As a result, trends in the atmospheric abundance for many ozone-depleting substances have been traced over the past century, to well before significant industrial sources of the compounds existed. These records show that the mixing ratios of the CFCs, halons, carbon tetrachloride (CCl_4), methyl chloroform, and HCFCs in the oldest air sampled are negligible compared with the amounts measured in today's background atmosphere. Further, the deduced 20th century records for these compounds are broadly consistent with calculated histories based on records of industrial production. The data suggest that substantial natural sources exist for atmospheric methyl bromide (CH_3Br). They also show increases throughout the 20th century, but these increases do not allow unambiguous quantification of the industrial fraction of methyl bromide emissions in recent years. The estimate of this fraction, based on an assessment of understanding of the budget of this gas, remains at 10-40%, as given in the 1998 Assessment.

- **The abundances of HCFCs in the lower atmosphere continue to increase.** HCFCs are among the gases used as transition substitutes for CFCs, halons, and chlorinated solvents. In the year 2000, HCFCs represented 6% of total chlorine abundance from anthropogenic gases in the lower atmosphere. The rate of increase in chlorine from HCFCs was constant at 10 parts per trillion per year from 1996 to 2000.

- **Observations in the stratosphere indicate that the total chlorine abundance is at or near a peak, while bromine abundances are probably still increasing.** The sum of hydrogen chloride (HCl) and chlorine nitrate ($ClONO_2$) is an effective surrogate for the abundance of stratospheric chlorine. An extended time series of ground-based measurements shows that the total stratospheric column amounts of these species, which have grown steadily for decades, have plateaued in recent years. Further, space-based measurements of HCl in the upper stratosphere indicate a broadly similar behavior. There are indications that bromine abundances in the stratosphere increased during the 1990s, but changes in stratospheric bromine are not as well characterized as those of stratospheric chlorine. These stratospheric changes are consistent with expectations based on the understanding of trace-gas trends in the troposphere, stratospheric chemistry, and atmospheric transport from the troposphere to the stratosphere.

- **Very short-lived organic chlorine-, bromine-, and iodine-containing source gases have the potential to deplete stratospheric ozone, but quantitative estimation of their potentials is more challenging than for longer-lived species like CFCs.** The very short-lived compounds reside in the atmosphere for a few months or less because they are rapidly decomposed chemically in the troposphere. Yet, a fraction of their emissions and the products from their tropospheric destruction can potentially reach the stratosphere. For example, observations suggest that non-anthropogenic bromoform ($CHBr_3$) produced largely in the oceans does make a non-negligible contribution to the total stratospheric bromine abundance. The magnitude of the ozone depletion by very short-lived compounds will depend critically on the location and season of their emissions and on the properties of their degradation products. The traditional use of a single number for their Ozone Depletion Potential (ODP), which is possible for longer-lived species, is therefore not directly applicable to the very short-lived species. Three-dimensional model simulations also suggest that very short-lived compounds emitted in the tropics would be more readily transported to the stratosphere than those emitted at higher latitudes, thus leading to greater ozone loss for tropical emissions. ODP values estimated by three-dimensional models are currently uncertain because of difficulties in modeling the complexities of transport processes and the lack of data on the products of the tropospheric degradation. A recent study on n-propyl bromide, one of the compounds proposed for possible future use, showed that for emissions that are uniform over the global land masses away from the poles, roughly 0.5% of the bromine emitted as n-propyl bromide reaches the stratosphere, resulting in an ODP of 0.04. Other ODP values reported in that study are up to 0.1 from tropical emission, and values up to 0.03 and 0.02 for emissions restricted to north of 20°N and 30°N, respectively. Therefore, the impact of very short-lived compounds can be significant if their emissions are large.

Changes in the Ozone Layer over the Poles and Globally

- **Springtime Antarctic ozone depletion due to halogens has been large throughout the last decade.** Since the early 1990s, the minimum total column (i.e., overhead) ozone amount has been ~100 Dobson units (DU). The monthly total column ozone amounts in September and October have continued to be about 40 to 50% below pre-ozone-hole values, with up to a local 70% decrease for periods of a week or so. During the last decade, the average ozone hole area in the spring has increased in size, but not as rapidly as during the 1980s. The area of the ozone hole varies from one year to another, and it is not yet possible to say whether the area of the ozone hole has maximized. In recent years, the ozone hole has also persisted into early summer, increasing its impact on ultraviolet radiation.

- **In some recent cold Arctic winters during the last decade, maximum total column ozone losses due to halogens have reached 30%.** Arctic winter/spring ozone loss is highly variable due to changes in stratospheric meteorological conditions from one winter to another, but it is now better understood because of numerous new observations and model comparisons. There is general agreement between analyses that quantify Arctic chemical ozone loss for the 1999/2000 winter/spring season. That well-studied year was distinguished by persistent low temperatures, an ozone loss reaching 70% near 20 km, and total column ozone losses greater than 80 Dobson units (~20-25%) by early spring. In contrast, during the warmer, more disturbed Arctic winter of 1998/1999, the estimated chemical loss was very small. Three of the last four Arctic winters have been warm, with little ozone loss; six of the previous nine winters were cold, with larger ozone losses.

- **Ozone remains depleted in the midlatitudes of both hemispheres.** The global-average total column ozone amount for the period 1997-2001 was approximately 3% below the pre-1980 average values. Observed changes occur primarily in midlatitudes and in polar regions; no significant trends in total column ozone have been observed in the tropics (25°N-25°S). There are differences in ozone behavior between the two hemispheres. In particular, the average amounts of total column ozone over the period 1997-2001 were 3% and 6% below the pre-1980 values in the Northern Hemisphere midlatitudes (35°N-60°N) and the Southern Hemisphere midlatitudes (35°S-60°S), respectively. The seasonality of total column ozone changes (1997-2001 relative to pre-1980) is different in the Northern Hemisphere and Southern Hemisphere. Over Northern Hemisphere midlatitudes, the largest ozone decreases are observed during winter/spring (~4%), with summer/autumn decreases approximately half as large. Over Southern Hemisphere midlatitudes, long-term ozone decreases exhibit a similar magnitude (~6%) during all seasons.

- **Models including observed changes in halocarbons, source gases, and aerosols (i.e., airborne fine particles) capture the observed long-term ozone changes in northern and southern midlatitudes.** The two-dimensional assessment models also reproduce much of the interannual ozone variations in the midlatitudes of the Northern Hemisphere, but do less well in the Southern Hemisphere. For example, observations show different ozone behavior in the Northern and Southern Hemispheres following the major eruption of the Mt. Pinatubo volcano in the early 1990s, whereas models that include aerosol-enhanced, halocarbon-ozone chemistry suggest hemispherically symmetric ozone loss during the post-eruption period. Changes in dynamical processes help to explain some of the ozone variations in Northern Hemisphere midlatitudes. They have also contributed to winter/spring trends in the Northern Hemisphere. However, because chemical and dynamical processes are coupled, their contributions to ozone changes cannot be assessed in isolation.

- **Chemistry-climate models predict that springtime Antarctic ozone levels will be increasing by 2010 because of projected decreases of halogens in the stratosphere.** A return to pre-1980 total column ozone amounts in the Antarctic is expected by the middle of this century.

- **Arctic ozone depletion is highly variable and difficult to predict, but a future Arctic polar ozone hole similar to that of the Antarctic appears unlikely.** Low ozone, as seen in some recent years, can however be expected again, and the Arctic stratosphere will be most vulnerable to other perturbations (for example, if there were to be an increase in the abundance of stratospheric aerosols from volcanic eruptions) during the next decade or so. Sustained very low Arctic ozone column amounts similar to those seen in the Antarctic are not predicted by the current chemistry-climate models. Such extreme ozone depletion during the next decade or so, when halogen abundances should still be close to their maximum, would require conditions that are unprecedented in about 40 years of Northern Hemisphere meteorological observations and, therefore, are considered highly unlikely to occur in the future.

- **The global ozone layer recovery is expected to be linked mainly to decreasing chlorine and bromine loading, but other factors are likely to contribute.** The expected decrease in the amount of stratospheric chlorine and bromine over the next 50 years is predicted to lead to an increase in the global amount of total column ozone, although there are differences in the projected rate of this increase predicted by different models. Stratospheric cooling (due mainly to projected carbon dioxide (CO_2) increases) is predicted to enhance the future ozone increase in the upper stratosphere. However, a reliable assessment of this effect on total column ozone is limited by uncertainties in the lower stratospheric response to these changes. Changes in atmospheric transport are difficult to predict, and their impact on stratospheric ozone could be either positive or negative. Projected increases in methane (CH_4) and nitrous oxide (N_2O) are predicted to have small chemical effects on the rate of increase of global total column ozone in the next 50 years, but could become more significant later in the 21st century. Future changes in the ozone in the lower atmosphere are highly dependent upon the scenario adopted for future emissions of ozone precursors, but all scenarios adopted by the 2001 report of the Intergovernmental Panel on Climate Change (IPCC) lead to predicted increases in tropospheric ozone up to 2050.

Changes in Ultraviolet Radiation

- **Changes in the duration and spatial extent of the ozone hole are more important for Antarctic surface ultraviolet (UV) radiation levels than the annual ozone minimum.** Enhanced values of UV radiation continue to be observed at high latitudes in the Southern Hemisphere under the Antarctic ozone hole. The highest biologically weighted UV doses under the ozone hole are typically not observed in October when maximum ozone depletion occurs, but in November and early December when solar elevations are higher and low ozone values are still prevailing.

- **Additional measurements continue to confirm that decreases in ozone column amounts lead to increases in UV radiation.** Calculations of UV irradiance based on relationships with total ozone and total irradiance (from pyranometers) suggest that UV irradiance has increased since the early 1980s by 6-14% at more than 10 sites distributed over mid- and high latitudes of both hemispheres. These results are consistent with spectral ultraviolet irradiance measurements and with estimates from satellite measurements. The complicated spatial and temporal distributions of the predominant variables that affect ultraviolet radiation at the surface (for example, clouds, airborne fine particles, snow cover, sea ice cover, and total ozone) continue to limit the ability to describe fully surface ultraviolet radiation on the global scale, whether through measurements or model-based approaches. As was noted in the previous Assessment, the spectral surface ultraviolet data records, which started in the early 1990s, are still too short and too variable to permit the calculation of statistically significant long-term (i.e., multidecadal) trends.

The Ozone Layer and Climate Change

- **The understanding of the impact of ozone depletion on climate change has been strengthened.** There has been a global and annual-mean cooling of the stratosphere over the past two decades, which can be largely attributed to the observed stratospheric ozone depletion and increases in well-mixed greenhouse gases and water vapor. As has been noted in past assessments, cooling of the lower stratosphere leads to cooling of the Earth's climate system. The vertical profile of ozone depletion in the lowermost stratosphere, which is an important factor in the magnitude of the radiative forcing, is now more accurately estimated from additional years of observations with reduced volcanic perturbations. Averaged ozone depletion has remained close to that of the late 1990s over much of the world, and therefore the recommended globally averaged radiative forcing of the climate system implied by this Assessment is the same as that recommended by the 2001 IPCC Assessment. The stratospheric radiative forcing due to ozone decreases since 1980 offsets about 20% of the positive forcing due to the increases in abundances of well-mixed greenhouse gases over that same time period.

- **Other atmospheric changes influence both the ozone layer and the climate system.** Observations have provided stronger evidence for a widespread increase in stratospheric water vapor, which plays a role both in cooling the lower stratosphere and in depleting ozone through chemical interactions, thereby contributing to climate processes. However, the water vapor trends are not fully defined, nor are their cause understood. Methane, nitrous oxide, and carbon dioxide are all important greenhouse gases, and all exert some influence on ozone depletion. Further, surface ultraviolet radiation may be directly affected, both positively and negatively, by the effects of climate change (for example, changing cloudiness), making prediction of long-term changes in surface radiation arising from all causes quite uncertain.

- **New research has begun to explore the coupling between climate change and the recovery of the ozone layer.** A number of models have been run to explore the feedback between climate and the ozone layer. As noted earlier, they have shown that past changes in ozone have contributed, together with well-mixed greenhouse gases, to a cooling of the stratosphere. Future changes in well-mixed greenhouse gases will affect the future evolution of ozone through chemical, radiative, and dynamic processes. In this highly coupled system, attribution is difficult; studies are ongoing. Stratospheric cooling (due mainly to projected carbon dioxide increases) is predicted to enhance future ozone amounts in the upper stratosphere. However, a reliable assessment of these effects on total column ozone is limited by uncertainties in lower stratospheric response to these changes.

ADDITIONAL SCIENTIFIC EVIDENCE AND RELATED INFORMATION

Halocarbon Abundances

- Trends of ozone-depleting substances in the atmosphere have been updated, and 20th century trends have been deduced from firn air. In 2000, tropospheric mixing ratios of CFC-11 and CFC-113 declined faster than in 1996, and mixing ratios of CFC-12 were still increasing, but more slowly. The rapid drop in global methyl chloroform emission has led to an exponential decay in its mixing ratio since 1998; mixing ratios of this gas in 2000 were less than one-half of the peak observed in 1992. The rate of decline observed for methyl chloroform during 2000 was about two-thirds of what it was in 1996.

- The total effect of all ozone-depleting halogens in the atmosphere, as estimated by calculating chlorine equivalents from atmospheric measurements of chlorine- and bromine-containing gases, continues to decrease. As of mid-2000, equivalent organic chlorine in the troposphere was nearly 5% below the peak value in 1992-1994. The recent decrease is slightly slower than in the mid-1990s, owing to the reduced influence of methyl chloroform on this decline.

- Substantial reductions in the emissions of ozone-depleting substances during the 1990s as inferred from atmospheric measurements are consistent with controls on production and consumption in the fully amended and adjusted Montreal Protocol. Consumption in developing countries is now a significant contributor to global emissions. The year 1999 was the first in which production and consumption of a class of ozone-depleting substances (the CFCs) was restricted in all Parties to the Montreal Protocol. Atmospheric measurements are consistent with emissions derived from reported production data for CFCs.

- The updated, best-estimate scenario for future halocarbon mixing ratios suggests that the atmospheric burden of halogens will return to the 1980 pre-Antarctic-ozone-hole levels around the middle of the 21st century, provided continued adherence to the fully amended and adjusted Montreal Protocol. Only small improvements would arise from further reduced production allowances in the future.

- Discrepancies reported in past assessments between atmospheric observations and expectations based on industry-reported production and emissions have narrowed substantially for HCFC-142b. This improvement stems from a better description of the functions relating emissions to usage in foam applications.

Halocarbon Lifetimes

- The global lifetime of carbon tetrachloride is estimated to be about 26 years, or about 25% shorter than in the previous (1998) Assessment. This shorter lifetime stems from identification of an ocean sink that is inferred from widespread observations of carbon tetrachloride undersaturation in surface waters of the ocean. Emissions inferred from atmospheric measurements and this lifetime are about 7 times greater than the limits to global production set for 2005.

- The lifetime of methyl chloroform has been revised from 4.8 years to 5.0 years based upon new observations. The implications of this change on estimates of atmospheric hydroxyl (OH) suggest lifetimes up to 5% longer for HCFCs, hydrofluorocarbons (HFCs), methane, and all other gases removed from the atmosphere by this important oxidant. These changes affect the Global Warming Potentials (GWPs) and Ozone Depletion Potentials (ODPs) calculated for these gases.

Methyl Bromide, Methyl Chloride, and Halons

- Atmospheric histories inferred from Southern Hemisphere air archives and Antarctic firn air suggest that, assuming similar changes have occurred in both hemispheres, the sum of organic bromine from methyl bromide (CH_3Br) and halons has more than doubled since the mid-1900s.

- A substantial imbalance remains in estimates of source and sink magnitudes for both methyl bromide and methyl chloride (CH_3Cl); known sinks outweigh sources for both of these gases. New sources of methyl bromide from individual crops and ecosystems have been identified, and new sources of methyl chloride from tropical plants have been discovered. These findings have narrowed the budget imbalances for both of these gases.

- The best estimate for the global lifetime of methyl bromide remains at 0.7 (0.5-0.9) years. Additional studies directly related to estimating loss processes for methyl bromide have narrowed the uncertainties slightly, but do not suggest large revisions to this lifetime. The fraction of emissions derived from industrially produced methyl bromide is unchanged at 10-40% based upon the current understanding of source and sink magnitudes.

Very Short-Lived Ozone-Depleting Compounds

- Very short-lived natural and anthropogenic bromine and iodine source gases with surface concentrations of a few parts per trillion (ppt) could make a non-negligible contribution to the current inorganic bromine and iodine budgets, since the stratospheric concentrations of inorganic bromine and iodine are about 20 ppt and less than 1 ppt, respectively. The transport of inorganic bromine associated with very short-lived bromine source gases from the troposphere to the stratosphere may contribute to the stratospheric inorganic bromine budget.

- The most efficient route for transport of very short-lived substances and their degradation products from the surface to the stratosphere is in the tropics. In the tropics, the vertical transport times from the boundary layer to the upper troposphere are short, and air that enters the stratosphere through the tropical tropopause may remain in the stratosphere for a year or longer. A significant fraction of the emitted very short-lived substances can be expected to reach the tropical tropopause layer because current estimates indicate that air at the base of the layer is replaced by convection from the tropical boundary layer on a time scale of 10 to 30 days. A few percent of the air in the tropical tropopause layer is expected to enter the stratosphere through the tropical tropopause. Other transport pathways exist in the extratropics for the transfer of very short-lived substances and their degradation products to the extratropical lower stratosphere.

- The main uncertainties in estimating the impact of very short-lived source gases lie in the physical and dynamical processes transporting these substances into the stratosphere and in the chemistry of their degradation products. Given the complexity, three-dimensional numerical models are the preferred tools to evaluate the Ozone Depletion Potential for very short-lived source gases. Significant uncertainties exist in the treatment of dynamical and physical processes in such models.

- Two model studies simulated the atmospheric distribution of bromoform ($CHBr_3$), assuming a simplified ocean source that is uniform over space and time. The results indicate that the ocean source causes an average surface mixing of 1.5 ppt for bromoform and maintains about 1 ppt of bromine in the stratosphere. The simulation shows that one-half to three-fourths of the bromine from bromoform enters the stratosphere in the form of inorganic degradation products.

- The Ozone Depletion Potential was calculated from three separate model studies for n-propyl bromide (n-PB, $CH_3CH_2CH_2Br$). Reaction with hydroxyl (OH) removes n-PB, with local photochemical lifetimes in the tropical troposphere of about 10-20 days. Laboratory data, particularly on bromoacetone, indicate that n-propyl bromide degradation products have lifetimes shorter than a couple of days. Two of the three modeling studies provided values only for direct transport of n-PB to the stratosphere. The third study computed contributions from direct transport and the transport of degradation products to the stratosphere. In the latter study, values of the Ozone Depletion Potential are up to 0.1 for tropical emissions and 0.03 for emissions restricted to northern midlatitudes. In both cases, about two-thirds of the effect is from the transport of degradation products to the stratosphere.

- Laboratory data on iodine chemistry have led to downward revision of the efficiency of iodine for depleting ozone in the stratosphere. The revised estimated efficiency factor (~150-300) is still higher than that of bromine (~45).

Polar Ozone

Antarctic

- Springtime Antarctic ozone depletion remains very large (with daily local total column values reaching 60-70% less than pre-ozone-hole conditions), with minimum values of about 100 DU (Dobson units) seen every year since the early 1990s. These observations reflect the almost complete ozone loss in the 12-20 km range and do not imply that ozone recovery has begun. Such low ozone is consistent with current understanding of stratospheric chemistry and dynamics.

- The area enclosed by the 220 DU contour (a measure of the severity of the ozone hole) shows an increase in recent years, so that it is not yet possible to say that the ozone hole has reached its maximum. Much of the change appears to be associated with processes at the edge of the polar vortex and is consistent with meteorological variability and the almost-constant halogen loading.

- Observations show that the Antarctic polar vortex and the associated ozone hole persist later than during the 1980s. Over the last decade, the vortex has generally broken up in late November to early December, in contrast to breakup in early November during the 1980s.

- Satellite and radiosonde observations show that the springtime Antarctic lower stratosphere has cooled. During the 1979-2000 period, the linear cooling trend exceeded 1.5 K/decade at 70°S. Modeling studies reaffirm that ozone loss is the major cause of the springtime cooling and the increased persistence of the Antarctic polar vortex. Well-mixed greenhouse gas increases contribute to the annually averaged cooling. Stratospheric water vapor increases may also be contributing.

- Coupled chemistry-climate model simulations, which include the combined effects of the changes in halogens and well-mixed greenhouse gases, broadly reproduce past trends in the total column ozone over the Antarctic. These models suggest that the minimum column ozone occurs prior to 2010 and that recovery to 1980 levels may be expected in the middle of the 21st century. The model response for the past and future changes is driven mainly by the changes in stratospheric halogen loading, with ozone recovery occurring after the peak of halogen loading.

Arctic

- The magnitude of halogen-induced loss of ozone for all Arctic winters during the last decade has now been studied with a variety of observationally based approaches. There is generally good agreement between different analyses that quantify the chemical loss. In the 1999/2000 winter, for which the most comprehensive studies were conducted, agreement was better than 20% in the Arctic stratosphere at about 20 km.

- The Arctic winter/spring total column ozone amounts continue to show a high interannual variability, reflecting the variable meteorology of the Northern Hemisphere stratosphere. Low column ozone amounts were present during the cold winter of 1999/2000. That year was distinguished by persistent low temperatures, a local loss reaching 70% at 20 km, and column losses greater than 80 DU (~20-25%). In the warmer, more-disturbed winters of 1998/1999 and 2000/2001, very small ozone loss was observed. Three of the last four Arctic winters have been warm, with little ozone loss; six of the previous nine winters were cold, with larger ozone losses.

- Significant chemical loss of ozone (~0.5 parts per million) in the lower stratosphere during January has been observed in several cold Arctic winters, contributing about 25% to the overall loss of ozone over the winter. The observations indicate that the loss occurred exclusively during periods when the air masses were exposed to sunlight. Nevertheless, these January ozone losses cannot be fully explained with the current understanding of the photochemistry.

- Coupled chemistry-climate models capture the typical interannual variability of Arctic ozone levels. Because Arctic temperatures are often near the threshold for polar stratospheric cloud (PSC) formation and hence the initiation of perturbed chemistry, there is a strong sensitivity to model temperature biases of only a few degrees Celsius. This places severe limits on the ability of the models to simulate past and predict future Arctic ozone behavior in winter.

- A number of coupled chemistry-climate models run for this Assessment suggest that minimum Arctic ozone would occur within the next two decades, the timing of which will depend on the meteorology. Low ozone, as seen in some recent years, can be expected again, and the Arctic stratosphere will be most vulnerable to other perturbations (e.g., aerosols from volcanic eruptions) during the next decade or so. Total column ozone amounts in the Arctic similar to the extreme lows seen in the Antarctic are not predicted by these models (in contrast to earlier simpler calculations considered in the 1998 Assessment). These extremely low values would require conditions that are unprecedented in about 40 years of Northern Hemisphere meteorological observations.

- Satellite and radiosonde observations show that the springtime Arctic lower stratosphere has cooled. However, becuae of large variability in the Arctic spring, the magnitude of the trend is uncertain there. A linear cooling trend (exceeding 1.5 K/decade) is observed during the 1979-2000 period at 70°N. Modeling studies now suggest that stratospheric ozone depletion has exerted an important influence on the springtime cooling of the Arctic lower stratosphere over the 1979-2000 period, but the degree of attribution is hindered by the large dynamical variability in that region.

- Observations of bromine monoxide (BrO) in the winter Arctic vortex by in situ and remote detection techniques are in broad agreement and are consistent with a total bromine budget of ~20 ± 4 parts per trillion. Modeling studies of the latitudinal, seasonal, and diurnal variations in BrO column abundances agree well with observations from a number of ground sites, indicating that the processes that govern bromine partitioning and its budget in the polar regions are reasonably well understood.

- Bromine measurements now allow for more accurate assessment of the contribution of bromine to polar ozone loss. At present, the fractional contribution of bromine to total ozone loss ranges between 30 and 60%, depending on temperature and abundances of chlorine monoxide (ClO). Considering the observed leveling off of the strength of sources of chlorine, the role of bromine in polar ozone loss will continue to increase relative to that of chlorine until the current upward trends of the bromine source gases reverse.

- Removal of nitrogen compounds (denitrification) has been observed to occur in the Arctic lower stratosphere in several cold winters. Removal of up to 70% of the total reactive nitrogen was observed at some levels of the lower stratosphere in the winter of 1999/2000. Observations and modeling results show that denitrification in the 1999-2000 Arctic lower stratosphere increased ozone loss by as much as 30% at 20 km in spring.

- The understanding of what causes denitrification has been improved considerably by the discovery in 1999-2000 of large nitric-acid-containing particles (with diameters of 10 to 20 micrometers) in the Arctic polar lower stratosphere. Sedimentation of these particles can account for observed Arctic denitrification, although the mechanism of formation of these sedimenting particles is uncertain. Therefore, sedimentation of ice containing dissolved nitric acid, which has been the generally assumed mechanism in global stratospheric models, is not the dominant mechanism in the Arctic.

- The chemical composition of liquid and solid polar stratospheric cloud particles has been measured directly for the first time. Most of the measured compositions are in agreement with model calculations for liquid particles and nitric acid trihydrate, which have been used in stratospheric models for many years. These measurements improve confidence in the particle types used in microphysical models that are central to simulations of polar ozone loss.

Global Ozone

Total Column Ozone

- Global mean total column ozone for the period 1997-2001 was approximately 3% below the 1964-1980 average. Since systematic global observations began, the lowest annually averaged global total column ozone occurred in 1992-1993 (about 5% below the pre-1980 average). These changes are evident in each available global dataset.

- No significant trends in total column ozone have been observed in the tropics (25°N-25°S) for 1980-2000. A decadal variation of total column ozone (with peak-to-trough variations of ~3%) is observed in this region, approximately in phase with the 11-year solar cycle. Total column ozone trends become statistically significant in the latitude bands 25°-35° in each hemisphere.

- There are a number of differences in total column ozone behavior between the two hemispheres:

  - Averaged over the period 1997-2001, total column ozone in the Northern Hemisphere and Southern Hemisphere midlatitudes (35°-60°) were about 3% and 6%, respectively, below their pre-1980 average values.

  - The seasonality of total column ozone changes (1997-2001 relative to pre-1980) is different in the Northern Hemisphere and Southern Hemisphere extratropics. Over Northern Hemisphere midlatitudes, larger ozone decreases are observed during winter/spring (~4%), with summer/autumn decreases approximately half as large. Over Southern Hemisphere midlatitudes, long-term ozone decreases exhibit a similar magnitude (~6%) during all seasons.

  - Pronounced negative anomalies are observed in the Northern Hemisphere midlatitudes time series during 1992-1995 in the winter/spring seasons. Similar anomalies are not seen in the Southern Hemisphere midlatitudes.

  - There is a sharp drop in ozone at Southern Hemisphere midlatitudes during 1985-1986. A similar drop is not observed in the Northern Hemisphere.

Vertical Ozone Distribution

- Ozone profile trends derived from the Stratospheric Aerosol and Gas Experiment (SAGE) satellite instrument show significant negative trends over latitudes 60°N to 60°S for altitudes ~35-50 km (with extremes near 40 km). Trend maxima of –7 to –8%/decade over the period 1979-2000 are observed in the 35°-60° latitude bands of both hemispheres, with no significant interhemispheric differences. These satellite results are in good agreement with independent Umkehr ozone measurements over the Northern Hemisphere midlatitudes.

- The updated SAGE data reveal significant negative trends extending throughout the tropics in the small amount of ozone above 30 km, a feature not observed in previous assessments based on shorter time records.

- The observed ozone depletion in the upper stratosphere is consistent with observed changes in anthropogenic chlorine. The vertical and latitudinal profiles of trends in the upper stratosphere are reproduced by photochemical models, but the magnitude of changes are sensitive to concurrent trends in temperature and methane (CH_4).

- Long-term ozonesonde measurements are primarily available for the Northern Hemisphere midlatitudes. Whereas ozone between 20 and 27 km decreased continuously during 1980-2000, ozone between 10 and 20 km decreased through the early 1990s and was relatively constant thereafter. This behavior is consistent with observed changes in Northern Hemisphere midlatitude column ozone.

EXECUTIVE SUMMARY

OZONE-RELATED CONSTITUENTS

- Stratospheric aerosol variability over the past 25 years has been dominated by the effects of episodic volcanic eruptions, with subsequent recovery. Following the large eruption of Mt. Pinatubo in 1991, relaxation to a nonvolcanic level continued to at least 1999. There is currently no evidence of a trend in the nonvolcanic aerosol loading.

- Stratospheric water vapor measurements at a single location (Boulder, Colorado, U.S., 40°N) for the period 1981-2000 show a statistically significant increase of approximately 1%/year over altitudes 15-28 km. For the shorter period 1991-2001, global satellite measurements covering latitudes 60°N-60°S show a similar trend of 0.6-0.8%/year for altitudes ~25-50 km, but no significant trend at lower altitudes. The increases in water vapor are substantially larger than can be explained by tropospheric methane trends. Characterization of stratospheric water vapor trends is limited by the lack of global long-term measurements.

- Stratospheric column nitrogen dioxide (NO_2) measurements from Lauder, New Zealand (45°S), for 1981-2000 and Jungfraujoch, Switzerland (46°N), for 1985-2001 show statistically significant positive trends of approximately 5%/decade. There are also transient decreases observed after the El Chichón and Mt. Pinatubo eruptions, which are broadly simulated by models that include heterogeneous chemistry on sulfate aerosols.

STRATOSPHERIC TEMPERATURE

- Observations indicate that, on an annual- and global-mean basis, the stratosphere has cooled over the last two decades. In the lower stratosphere, global and annual mean temperatures for the late 1990s are approximately 1 K lower than values in the late 1970s. Significant annual-mean cooling of the lower stratosphere over the past two decades is found over midlatitudes of both hemispheres (approximately 0.6 K/decade), but no significant trends are observed near the equator. The annual-mean temperature trends in the upper stratosphere are larger, with an approximately globally uniform cooling over 1979-1998 of about 2 K/decade near the stratopause (~50 km).

- Modeling studies indicate that changes in ozone, well-mixed greenhouse gases, and stratospheric water vapor can explain the major features of the observed global and annual-mean stratospheric cooling over the past two decades. Cooling due to ozone depletion dominates over the impact of well-mixed greenhouse gases in the lower stratosphere, while upper stratospheric temperature trends are due, roughly equally, to ozone and well-mixed greenhouse gas changes.

ATTRIBUTION OF PAST CHANGES IN OZONE

- The vertical, latitudinal, and seasonal characteristics of changes in midlatitude ozone are broadly consistent with the understanding that halogens are the primary cause, in line with similar conclusions from the 1998 Assessment.

- Assessment models forced by observed changes in halocarbons, source gases, and aerosols broadly reproduce the long-term changes observed in midlatitude total column ozone (35°N-60°N and 35°S-60°S) from 1980 to 2000, within the uncertainties of the observations and model range. However, the range of model results is large over Southern Hemisphere midlatitudes, which is at least partly due to their differing treatments of the Antarctic ozone hole. In addition, models suggest that the chemical signal of ozone loss following the major eruption of the Mt. Pinatubo volcano in the early 1990s should have been symmetric between the hemispheres, but observations show a large degree of interhemispheric asymmetry in midlatitudes.

- There is increased evidence that observed changes in atmospheric dynamics have had a significant influence on Northern Hemisphere midlatitude column ozone on decadal time scales. Natural variability, changes in greenhouse gases, and changes in column ozone itself are all likely to contribute to these dynamical changes. Furthermore, because chemical and dynamical processes are coupled, their contributions to ozone changes cannot be assessed in isolation.

FUTURE OZONE CHANGES

- The expected decrease in stratospheric chlorine loading over the next 50 years is predicted to lead to an increase in the global total column ozone, although there are differences in the rate of increase between different two-dimensional assessment models. Future ozone levels will also be influenced by other changes in atmospheric composition and by climate change. Because of year-to-year variability, it could take as long as a decade to demonstrate a leveling of total column ozone.

- Stratospheric cooling (due mainly to projected CO_2 increases) and the chemical influence of stratospheric methane increases are predicted to enhance future ozone increases in the upper stratosphere. However, a reliable assessment of these effects on total column ozone is limited by uncertainties in lower stratospheric response to these changes.

- Projected increases in methane (CH_4) and nitrous oxide (N_2O) (from the scenarios of the Intergovernmental Panel on Climate Change, 2001) are predicted to have small effects on the rate of increase of global column ozone in the next 50 years, when chlorine changes are the dominant effect. After that time, changes in CH_4 and N_2O become relatively more important.

Ultraviolet Radiation

- Annually averaged erythemal irradiance, as reconstructed from pyranometer (total irradiance), total ozone, and other meteorological measurements, increased by about 6-14% over the last 20 years at several mid- to high-latitude sites. Pyranometer and other meteorological data serve as proxies for parameters, other than ozone, that affect ultraviolet (UV) radiation. At some sites approximately half of the changes can be attributed to total ozone changes. These reconstructions are not UV measurements, and they contain several assumptions on the nature of radiative transfer. The reconstructions should be not be considered to be representative on a global scale. It is believed that the increases of UV irradiance derived from the ground-based reconstructed data are clear indicators of the long-term changes that have occurred since the 1980s.

- There is clear evidence that the long-term UV changes are not driven by ozone alone, but also by changes in cloudiness, aerosols, and surface albedo. The relative importance of these factors depends on the local conditions. Results from studies using ground-based and aircraft instruments suggest that the influence of tropospheric aerosols on UV irradiance may be larger than previously thought and may affect large areas of the globe.

- UV increases associated with the ozone decline have been observed by spectral measurements at a number of sites in Europe, North and South America, Antarctica, and New Zealand. Episodes of elevated UV irradiance associated with low total column ozone amounts continue to occur in spring in mid-to-high latitudes.

- Satellite estimates of surface UV radiation from the Total Ozone Mapping Spectrometer (TOMS) dataset have been compared with ground-based measurements at several more sites since the previous Assessment. In general the estimates capture short-term and long-term variability. However, the estimates are systematically higher than ground-based measurements at many sites. The differences in monthly average erythemal UV irradiance range from about 0% at some clean sites to 40% at one site in the Northern Hemisphere. The fact that the agreement is better at the cleaner sites suggests that the differences are caused by aerosols and/or pollutants near the ground. New UV maps that include additional influencing parameters (e.g., cloud cover and albedo) derived from other satellite data, when taken together with TOMS or Global Ozone Monitoring Experiment (GOME) ozone data, yield better agreement with ground-based data.

- In the Antarctic, ozone depletion has been the dominant factor for increases in UV irradiance. The future evolution of UV radiation is therefore expected to follow the ozone recovery. However, because of changes in other influencing factors, such as changes in cloud cover, aerosols, or snow/ice cover, UV radiation may not return exactly to pre-ozone-hole values.

- Elsewhere, including the Arctic, the impact on UV radiation of other influencing factors can be comparable to the impact of ozone depletion. The large uncertainties in future changes of these other factors prevent reliable predictions on the future evolution of UV irradiance. Furthermore, climate-change-induced trends in cloudiness and snow/ice cover are expected to be seasonally and geographically dependent, leading to differences in future UV irradiance in different parts of the world.

- A reanalysis of TOMS satellite data with respect to the influence of changes in cloudiness over Europe has confirmed that UV increases due to ozone depletion are partly masked by the increased cloudiness in some regions.

IMPLICATIONS FOR POLICY FORMULATION

The results from over three decades of research have provided a progressively better understanding of the interaction of humankind and the ozone layer. New policy-relevant insights into the roles of ozone-depleting gases have been conveyed to decisionmakers through the international state-of-understanding assessment process. The research findings in the *Scientific Assessment of Ozone Depletion: 2002* that are summarized above are direct current scientific input to governmental, industrial, and policy decisions associated with protection of the ozone layer.

- **The Montreal Protocol is working, and the ozone-layer depletion from the Protocol's controlled substances is expected to begin to ameliorate within the next decade or so.** The effectiveness of the Protocol is and will be shown by several indicators. Global observations show that the total combined effective abundances of anthropogenic chlorine-containing and bromine-containing ozone-depleting gases in the *lower atmosphere* (troposphere) peaked in the 1992-1994 time period and are continuing to decline. Furthermore, observations indicate that the *stratospheric* abundances of ozone-depleting gases are now at or near a peak. Thereafter, stratospheric ozone should increase, all other influences assumed constant, but ozone variability will make detection of the onset of the long-term recovery difficult. For example, based on assumed compliance with the amended and adjusted Protocol by all nations, the Antarctic ozone "hole," which was first discerned in the early 1980s, is predicted to disappear by the middle of this century—again with all other influences assumed constant.

- **The ozone layer will remain particularly vulnerable during the next decade or so, even with full compliance.** With the atmospheric abundances of ozone-depleting substances being near their highest, the human-influenced perturbations will be at or near their largest. Relative to the pre-ozone-hole abundances of 1980, the 1997-2001 losses in total column (i.e., overhead) ozone amounts are:
  - about 4% at northern midlatitudes in winter/spring;
  - about 2% at northern midlatitudes in summer/fall; and
  - about 6% at southern midlatitudes on a year-round basis.

  Calculations yield that such changes in ozone correspond to increases in surface erythemal radiation of at least 5, 2, and 7%, respectively, if other influences such as clouds remain constant. In Antarctica, the monthly total column ozone in September and October has continued to be about 40 to 55% below the pre-ozone-hole values, with up to a local 70% decrease for periods of a week or so. Arctic ozone is highly variable. Estimates of the cumulative winter/spring losses in the total column ozone amounts during the last 4 years range up to about 25%. Calculations of corresponding increases in surface erythemal radiation are about 70 to 150% in the Antarctic springtime, with up to 300% increases for the short-lived local ozone decreases. In the Arctic winter/spring, the corresponding calculated increases are up to 40%. Furthermore, if there were to be an increase in the abundance of stratospheric particles from a major volcanic eruption like that of Mt. Pinatubo in 1991, then the peak losses in total column ozone and the increases in ultraviolet radiation could be larger. In the highly variable Arctic, larger depletion would be expected if an unusually and persistently cold Arctic stratospheric winter like that of the 1999/2000 winter/spring were to occur; conversely, smaller depletions are expected in particularly warm years.

- **Approaches to accelerating the recovery of the ozone layer are limited.** This Assessment has made hypothetical estimates of the *upper limits* of improvements that could be achieved if global anthropogenic *production* of ozone-depleting substances were to stop in 2003 or if global anthropogenic *emissions* of ozone-depleting substances were to stop in 2003. Specifically:

  Production. Relative to the current control measures (Beijing, 1999) and recent production data, the equivalent effective stratospheric chlorine loading above the 1980 level, integrated from 2002 until the 1980 level is reattained (about 2050), could be decreased by the following amounts:
  - 5%, if production of hydrochlorofluorocarbons (HCFCs) were to cease in 2003.
  - 4%, if production of chlorofluorocarbons (CFCs) were to cease in 2003.
  - 4%, if production of methyl bromide were to cease in 2003.
  - 1%, if production of halons were to cease in 2003.
  - 0.3%, if production of methyl chloroform were to cease in 2003.

  These percentages would be about a factor of 2 smaller if the decreases were compared with the loading integrated from 1980, which is when significant ozone depletion was first detected. A hypothetical elimination of all anthropogenic production of *all* ozone-depleting substances would advance the return of stratospheric loading to the pre-1980 values by about 4 years.

  Emissions. Similarly, the equivalent effective stratospheric chlorine loading above the 1980 level, integrated from 2002 until the 1980 level is reattained (about 2050), could be decreased by the following amounts:
  - 11%, if emissions of halons were to cease in 2003.
  - 9%, if emissions of chlorofluorocarbons (CFCs) were to cease in 2003.
  - 9%, if emissions of hydrochlorofluorocarbons (HCFCs) were to cease in 2003.
  - 4%, if emissions of methyl bromide were to cease in 2003.
  - 3%, if emissions of carbon tetrachloride were to cease in 2003.
  - 2%, if emissions of methyl chloroform were to cease in 2003.

  Again, these percentages would be about a factor of 2 smaller if the decreases were compared with the loading integrated from 1980, which is when significant ozone depletion was first detected. A hypothetical elimination of all emissions derived from industrial production of *all* ozone depleting substances would advance the return of stratospheric loading to the pre-1980 values by about 10 years.

- **Failure to comply with the Montreal Protocol would delay or could even prevent recovery of the ozone layer.** For example, continued constant production of ozone-depleting substances at the 1999 amount would likely extend the recovery of the ozone layer well past the year 2100. The total atmospheric abundance of ozone-depleting gases will decline to pre-Antarctic-ozone-hole amounts only with adherence to the Montreal Protocol's full provisions on production of ozone-depleting substances.

- **Estimating the impacts of very short-lived ozone-depleting substances on depletion of the ozone layer requires new approaches, and, as requested by the Parties, this Assessment has described one such scientific approach.** The traditional concept of a *single-valued* Ozone Depletion Potential (ODP) is not directly applicable for these very short-lived ozone-depleting substances, because their impacts on the ozone layer will depend on the season and location of their emissions. These impacts would need to be assessed on a case-by-case basis, taking into account how much, when, and where they are emitted. Such estimates can provide insight into the stratospheric contribution of natural emissions of these very short-lived substances (for example, bromoform) and can provide scientific input into decisions associated with their industrial production/uses (for example, n-propyl bromide).

- **The issues of ozone depletion and climate change are interconnected.** The ozone-depletion phenomenon and the greenhouse-warming phenomenon share many common chemical and physical processes. For example, as the atmospheric abundances of the CFCs decline because of the Montreal Protocol's provisions, their greenhouse-warming contributions will decline. On the other hand, use of hydrofluorocarbons (HFCs) and HCFCs as substitutes for CFCs would cause the greenhouse-warming contributions of these new compounds to increase. Indeed, global observations of many HFCs and HCFCs, as well as of hydrogen fluoride, confirm that these contributions are currently increasing. As other examples, potential decisions associated with methane, nitrous oxide, and carbon dioxide stemming from their greenhouse roles will also have direct and indirect effects on stratospheric ozone. And, because ozone depletion acts to cool the climate system, recovery of the ozone layer over coming decades would tend to warm the climate system.

List of International Authors, Contributors, and Reviewers

Assessment Cochairs

Ayité-Lô Nohende Ajavon, Daniel L. Albritton, Gérard Mégie, and Robert T. Watson

Chapters and Lead Authors

Chapter 1. Controlled Substances and Other Source Gases (*Stephen A. Montzka and Paul J. Fraser*)
Chapter 2. Very Short-Lived Halogen and Sulfur Substances (*Malcolm K.W. Ko and Gilles Poulet*)
Chapter 3. Polar Stratospheric Ozone: Past and Future (*Paul A. Newman and John A. Pyle*)
Chapter 4. Global Ozone: Past and Future (*Martyn P. Chipperfield and William J. Randel*)
Chapter 5. Surface Ultraviolet Radiation: Past and Future (*James B. Kerr and Gunther Seckmeyer*)

Twenty Questions and Answers About the Ozone Layer (*David W. Fahey*)

Authors, Contributors, and Reviewers

Alberto Adriani	Consiglio Nazionale delle Ricerche Istituto di Fisica dell'Atmosfera	Italy
Ayité-Lô Nohende Ajavon	Université de Lomé	Togo
Daniel L. Albritton	NOAA Aeronomy Laboratory	US
Douglas R. Allen	Naval Research Laboratory	US
Georgios T. Amanatidis	European Commission	Belgium
Stephen O. Andersen	Environmental Protection Agency	US
James Anderson	Harvard University	US
Gustavo A. Argüello	Universidad Nacional de Córdoba	Argentina
Antti Arola	Finnish Meteorological Institute	Finland
Roger Atkinson	University of California at Riverside	US
Pieter J. Aucamp	Ptersa Environmental Consultants	South Africa
John Austin	UK Meteorological Office	UK
Linnea M. Avallone	University of Colorado	US
Alkiviadis F. Bais	Aristotle University of Thessaloniki	Greece
Mark P. Baldwin	NorthWest Research Associates, Inc.	US
Stephen R. Beagley	York University	Canada
Pranvera Bekteshi	Hydrometeorological Institute	Albania
Germar Bernhard	Biospherical Instruments, Inc.	US
Donald R. Blake	University of California at Irvine	US
Nicola J. Blake	University of California at Irvine	US
Mario Blumthaler	Universität Innsbruck	Austria
Greg E. Bodeker	National Institute of Water and Atmospheric Research (NIWA)	New Zealand
Rumen D. Bojkov	Centre for International Postgraduate Studies of Environmental Management	Germany
Olivier Boucher	CNRS-Université des Sciences et Technologies de Lille	France
Michel Bourqui	University of Reading	UK
Geir O. Braathen	Norwegian Institute for Air Research (NILU)	Norway
Peter Braesicke	University of Cambridge	UK
Guy P. Brasseur	Max-Planck-Institut für Meteorologie	Germany
Bram Bregman	Royal Netherlands Meteorological Institute	The Netherlands
Christoph Brühl	Max-Planck-Institut für Chemie	Germany

William Brune	Pennsylvania State University	US
James H. Burkholder	NOAA Aeronomy Laboratory	US
Neal Butchart	UK Meteorological Office	UK
James H. Butler	NOAA Climate Monitoring and Diagnostics Laboratory	US
James Calm	Engineering Consultant	US
Pablo O. Canziani	CONICET/Universidad de Buenos Aires	Argentina
Ken S. Carslaw	University of Leeds	UK
Marie-Lise Chanin	Service d'Aeronomie du CNRS	France
Mian Chin	Georgia Institute of Technology/NASA Goddard Space Flight Center	US
Martyn P. Chipperfield	University of Leeds	UK
John Christy	University of Alabama at Huntsville	US
Peter S. Connell	Lawrence Livermore National Laboratory	US
Brian Connor	National Institute of Water and Atmospheric Research (NIWA)	New Zealand
David B. Considine	NASA Langley Research Center	US
R. Anthony Cox	University of Cambridge	UK
Derek M. Cunnold	Georgia Institute of Technology	US
Martin Dameris	DLR Institut für Physik der Atmosphäre	Germany
John S. Daniel	NOAA Aeronomy Laboratory	US
Richard G. Derwent	UK Meteorological Office	UK
Susana B. Diaz	Centro Austral de Investigaciones Cientificas (CADIC)	Argentina
Ed Dlugokencky	NOAA Climate Monitoring and Diagnostics Laboratory	US
Anne R. Douglass	NASA Goddard Space Flight Center	US
Katja Drdla	NASA Ames Research Center	US
Thomas Duafala	Tri-Cal Research Division	US
Ellsworth S. Dutton	NOAA Climate Monitoring and Diagnostics Laboratory	US
Victor L. Dvortsov	PacifiCorp	US
Ezequiel Echer	Instituto Nacional de Pesquisas Espaciais (INPE)	Brazil
Stephen Eckermann	Naval Research Laboratory	US
Kalju Eerme	Tartu Observatory	Estonia
James W. Elkins	NOAA Climate Monitoring and Diagnostics Laboratory	US
Andreas Engel	Universität Frankfurt	Germany
Christine A. Ennis	NOAA Aeronomy Laboratory/CIRES	US
David W. Fahey	NOAA Aeronomy Laboratory	US
Joe Farman	European Ozone Research Coordinating Unit	UK
Vitali E. Fioletov	Meteorological Service of Canada	Canada
Eric L. Fleming	NASA Goddard Space Flight Center	US
Ian Folkins	Dalhousie University	Canada
Piers M. de F. Forster	University of Reading	UK
Paul J. Fraser	CSIRO Division of Atmospheric Research	Australia
Randall R. Friedl	NASA Jet Propulsion Laboratory	US
Ru-Shan Gao	NOAA Aeronomy Laboratory	US
Rolando R. Garcia	National Center for Atmospheric Research	US
Marvin A. Geller	State University of New York, Stony Brook	US
Melvyn Gelman	NOAA NWS Climate Prediction Center	US
Christian George	Laboratoire d'Application de la Chimie à l'Environnement/ University of Lyon	France
Sophie Godin-Beekmann	Service d'Aeronomie du CNRS	France
Marco González	United Nations Environment Programme	Kenya
Florence Goutail	Service d'Aeronomie du CNRS	France
Michael Graber	United Nations Environment Programme	Kenya
Hans-F. Graf	Max-Planck-Institut für Meteorologie	Germany
Volker Grewe	DLR Institut für Physik der Atmosphäre	Germany

Joanna D. Haigh	Imperial College of Science, Technology, and Medicine	UK
Patrick Hamill	San Jose State University	US
David B. Harper	The Queen's University of Belfast	UK
Neil R.P. Harris	European Ozone Research Coordinating Unit	UK
Didier Hauglustaine	CNRS-Laboratoire des Sciences du Climat et de l'Environnement	France
Peter H. Haynes	University of Cambridge	UK
Jay R. Herman	NASA Goddard Space Flight Center	US
David J. Hofmann	NOAA Climate Monitoring and Diagnostics Laboratory	US
James R. Holton	University of Washington	US
Robert D. Hudson	University of Maryland	US
Drusilla Hufford	Environmental Protection Agency	US
Abdelmoneim A. Ibrahim	Egyptian Meteorological Authority	Egypt
Mohammad Ilyas	University of Science Malaysia	Malaysia
Takashi Imamura	National Institute for Environmental Studies	Japan
Ivar S.A. Isaksen	University of Oslo	Norway
Charles H. Jackman	NASA Goddard Space Flight Center	US
Daniel J. Jacob	Harvard University	US
Mauricio Jaramillo-Ayerbe	Pontificia Universidad Javeriana-Cali	Colombia
Paul Johnston	National Institute of Water and Atmospheric Research (NIWA)	New Zealand
David Karoly	Monash University	Australia
Nozomi Kawamoto	National Space Development Agency	Japan
Jack A. Kaye	NASA Office of Earth Science	US
James B. Kerr	Meteorological Service of Canada	Canada
M.A.K. Khalil	Portland State University	US
Peter W. Kiedron	State University of New York at Albany	US
Dieter Kley	Institut für Chemie und Dynamik der Geosphäre Forschungszentrum Jülich	Germany
Bjørn M. Knudsen	Danmarks Meteorologiske Institut	Denmark
Malcolm K.W. Ko	Atmospheric and Environmental Research, Inc.	US
Yutaka Kondo	University of Tokyo	Japan
Yuri Koshelkov	Central Aerological Observatory	Russia
Karin Kreher	National Institute of Water and Atmospheric Research (NIWA)	New Zealand
Nickolay A. Krotkov	University of Maryland	US
Janusz W. Krzyścin	Polish Academy of Sciences	Poland
Lambert Kuijpers	Technical University Pav	The Netherlands
Michael J. Kurylo	NASA Headquarters	US
Karin Labitzke	Freie Universität Berlin	Germany
Murari Lal	Indian Institute of Technology	India
Shyam Lal	Physical Research Laboratory	India
Ulrike Langematz	Freie Universität Berlin	Germany
Kathleen O. Lantz	NOAA Air Resources Laboratory	US
Neils Larsen	Danish Meteorological Institute	Denmark
Katherine S. Law	University of Cambridge	UK
Mark G. Lawrence	Max-Planck-Institut für Chemie	Germany
J. Ben Liley	National Institute of Water and Atmospheric Research (NIWA)	New Zealand
Roger Lin	NOAA National Centers for Environmental Prediction/ RS Information Systems	US
Shaw Liu	Academia Sinica	Taiwan R.O.C.
Jennifer A. Logan	Harvard University	US
Craig S. Long	NOAA NWS Climate Prediction Center	US
Daniel Lubin	Scripps Institution of Oceanography	US
A. Robert MacKenzie	Lancaster University	UK
Sasha Madronich	National Center for Atmospheric Research	US

Emmanuel Mahieu	Université de Liège	Belgium
Gloria L. Manney	NASA Jet Propulsion Laboratory/New Mexico Highlands University	US
Elisa Manzini	Max-Planck-Institut für Meteorologie	Germany
Céline Mari	Laboratoire d'Aérologie, Observatoire Midi Pyrénées	France
Timothy J. Martin	Universität Graz	Austria
W. Andrew Matthews	National Institute of Water and Atmospheric Research (NIWA)	New Zealand
Konrad Mauersberger	Max-Planck-Institut für Kernphysik	Germany
Archie McCulloch	Marbury Technical Consulting	UK
Gordon McFadyen	Scottish Environment Protection Agency	UK
Mack McFarland	E.I. DuPont de Nemours & Company	US
Daniel S. McKenna	National Center for Atmospheric Research	US
Richard L. McKenzie	National Institute of Water and Atmospheric Research (NIWA)	New Zealand
Richard D. McPeters	NASA Goddard Space Flight Center	US
Ralf Meerkötter	DLR-Institut für Physik der Atmosphäre	Germany
Gérard Mégie	Centre National de la Recherche Scientifique	France
Inna A. Megretskaia	Harvard University	US
Davit Melkonyan	Department of Hydrometeorology	Armenia
Abdelwahid Mellouki	CNRS-Laboratoire de Combustion et Systèmes Réactifs	France
Pauline M. Midgley	M&D Consulting	Germany
Alvin J. Miller	NOAA NWS Climate Prediction Center	US
Stephen A. Montzka	NOAA Climate Monitoring and Diagnostics Laboratory	US
Rolf Müller	Forschungszentrum Jülich GmbH	Germany
Nzioka John Muthama	University of Nairobi	Kenya
Tatsuya Nagashima	National Institute for Environmental Studies	Japan
Hideaki Nakane	National Institute for Environmental Studies	Japan
Eric R. Nash	Science Systems and Applications, Inc.	US
John Nash	UK Meteorological Office	UK
Patrick J. Neale	Smithsonian Environmental Research Center	US
Paul A. Newman	NASA Goddard Space Flight Center	US
Samuel J. Oltmans	NOAA Climate Monitoring and Diagnostics Laboratory	US
Alan O'Neill	University of Reading	UK
Michael Oppenheimer	Princeton University	US
David E. Oram	University of East Anglia	UK
Eduardo Palenque	Instituto de Investigaciones Físcias, Universidad Mayor de San Andres	Bolivia
Panos Papagiannakopuolos	University of Crete	Greece
David Parker	Hadley Centre Met Office	UK
Steven Pawson	Goddard Earth Sciences and Technology Center/University of Maryland	US
Stuart A. Penkett	University of East Anglia	UK
Sunil Kumar Peshin	India Meteorological Department	India
Thomas Peter	Institute for Atmospheric and Climate Science ETH-Zurich	Switzerland
Klaus Pfeilsticker	Universität Heidelberg	Germany
Giovanni Pitari	Università L'Aquila	Italy
Ulrich Platt	Universität Heidelberg	Germany
Ian Plumb	CSIRO Telecommunications and Industrial Physics	Australia
Jean-Pierre Pommereau	Service d'Aéronomie du CNRS	France
Lamont R. Poole	NASA Langley Research Center	US
Robert W. Portmann	NOAA Aeronomy Laboratory	US
Gilles Poulet	CNRS-Université d'Orléans	France
Michael J. Prather	University of California at Irvine	US
Margarita Préndez	Universidad de Chile	Chile
Ronald Prinn	Massachusetts Insititute of Technology	US
Michael H. Proffitt	World Meteorological Organization	Switzerland

John A. Pyle	Centre for Atmospheric Science, University of Cambridge	UK
S. Ramachandran	Physical Research Laboratory	India
V. Ramaswamy	NOAA Geophysical Fluid Dynamics Laboratory	US
William J. Randel	National Center for Atmospheric Research	US
Lakshman Randeniya	CSIRO Telecommunications and Industrial Physics	Australia
Philip J. Rasch	National Center for Atmospheric Research	US
A.R. Ravishankara	NOAA Aeronomy Laboratory	US
Claire E. Reeves	University of East Anglia	UK
Markus Rex	Alfred Wegener Institute for Polar and Marine Research	Germany
Brian A. Ridley	National Center for Atmospheric Research	US
Curtis P. Rinsland	NASA Langley Research Center	US
Henning Rodhe	University of Stockholm	Sweden
José M. Rodríguez	University of Miami	US
Bjørg Rognerud	Universitetet I Oslo	Norway
Joan E. Rosenfield	NASA Goddard Space Flight Center	US
Martin N. Ross	Aerospace Corporation	US
Eugene Rozanov	World Radiation Center and Institute for Atmospheric and Climate Science ETH	Switzerland
James M. Russell III	Hampton University	US
Nelson A. Sabogal	United Nations Environment Programme	Kenya
Ali A. Sabziparvar	University of Bou-Ali Sina	Iran
Ross J. Salawitch	California Institute of Technology/NASA Jet Propulsion Laboratory	US
Eugenio Sanhueza	Instituto Venezolano de Investigaciones Cientificas	Venezuela
Michelle L. Santee	NASA Jet Propulsion Laboratory	US
Toru Sasaki	Japan Meteorological Agency	Japan
Yasuhiro Sasano	National Institute for Environmental Studies	Japan
Sue M. Schauffler	National Center for Atmospheric Research	US
Ulrich Schmidt	Universität Frankfurt	Germany
Christina Schnadt	DLR Institut für Physik der Atmosphäre	Germany
Ulrich Schumann	DLR Institut für Physik der Atmosphäre	Germany
M. Daniel Schwarzkopf	NOAA Geophysical Fluid Dynamics Laboratory	US
Paul W. Seakins	University of Leeds	UK
Gunther Seckmeyer	Universität Hannover	Germany
Dian J. Seidel	NOAA Air Resources Laboratory	US
Dudley E. Shallcross	University of Bristol	UK
Theodore G. Shepherd	University of Toronto	Canada
Drew T. Shindell	NASA Goddard Institute for Space Studies	US
Keith P. Shine	University of Reading	UK
Masanori Shitamichi	Japan Meteorological Agency	Japan
Peter G. Simmonds	University of Bristol	UK
Paul C. Simon	Institut d'Aeronomie Spatiale de Belgique	Belgium
Harry Slaper	National Institute of Public Health and the Environment (RIVM)	The Netherlands
James R. Slusser	Colorado State University	US
Claire A. Smith	Imperial College of Science, Technology, and Medicine	UK
Sergei Smyshlyaev	Russian State Hydrometeorological University/ State University of New York	Russia
Susan Solomon	NOAA Aeronomy Laboratory	US
Johannes Stähelin	Swiss Federal Institute of Technology-Zurich	Switzerland
L. Paul Steele	CSIRO Division of Atmospheric Research	Australia
Andreas Stohl	Technical University Munich	Germany
Richard S. Stolarski	NASA Goddard Space Flight Center	US
Susan E. Strahan	University of Maryland	US

B.H. Subbaraya	Indian Space Research Organization Headquarters	India
Christine C. Sweet	Science and Technology Corporation	US
Petteri Taalas	Finnish Meteorological Institute	Finland
Azadeh Tabazadeh	NASA Ames Research Center	US
David W. Tarasick	Meteorological Service of Canada	Canada
Gary Taylor	Taylor/Wagner, Inc.	Canada
Manfred Tevini	Botanisches Institut	Denmark
Christiane Textor	Max-Planck-Institut für Meteorologie	Germany
Larry W. Thomason	NASA Langley Research Center	US
David Thompson	Colorado State University	US
Claudia Timmreck	Max-Planck-Institut für Meteorologie	Germany
Darin W. Toohey	University of Colorado	US
Geoffrey C. Toon	NASA Jet Propulsion Laboratory	US
Adrian F. Tuck	NOAA Aeronomy Laboratory	US
Jan C. van der Leun	Ecofys	The Netherlands
Michel Van Roozendael	Institut d'Aeronomie Spatiale de Belgique	Belgium
Michiel van Weele	Koninklijk Nederlands Meteorologisch Instituut (KNMI)	The Netherlands
Guus J.M. Velders	National Institute of Public Health and the Environment (RIVM)	The Netherlands
Jean Verdebout	European Commission Joint Research Centre	Italy
Mario Visca	Ausimont S.p.A.	Italy
C. Michael Volk	Universität Frankfurt	Germany
Peter von der Gathen	Alfred Wegener Institute for Polar and Marine Research	Germany
Ray Wang	Georgia Institute of Technology	US
Joe W. Waters	NASA Jet Propulsion Laboratory	US
Robert T. Watson	World Bank	US
Darryn W. Waugh	Johns Hopkins University	US
Elizabeth C. Weatherhead	NOAA Air Resources Laboratory	US
Philipp Weihs	Universität für Bodenkultur	Austria
Debra K. Weisenstein	Atmospheric and Environmental Research, Inc.	US
Ray F. Weiss	University of California at San Diego/Scripps Institution of Oceanography	US
Paul O. Wennberg	California Institute of Technology	US
Fei Wu	National Center for Atmospheric Research	US
Donald J. Wuebbles	University of Illinois	US
Yoko Yokouchi	National Institute for Environmental Studies	Japan
Vladimir Yushkov	Central Aerological Observatory	Russia
Rodolphe J. Zander	Université de Liège	Belgium
Francesco Zaratti	Instituto de Investigaciones Físicas, Universidad Mayor de San Andres	Bolivia
Joseph M. Zawodny	NASA Langley Research Center	US
Christos S. Zerefos	Aristotle University of Thessaloniki	Greece
Xiuji Zhou	Chinese Academy of Meteorological Sciences	China
Tong Zhu	Peking University	China

Chapter Editorial Contributors

Chapter 1: Controlled Substance and Other Source Gases

Nada Derek	CSIRO Division of Atmospheric Research	Australia

Chapter 3: Polar Stratospheric Ozone: Past and Future

Rose Kendall	Computer Sciences Corporation	US
Kathy A. Thompson	Computer Sciences Corporation	US

Sponsoring Organizations and Liaisons

Michael H. Proffitt World Meteorological Organization Switzerland
Marco González United Nations Environment Programme Kenya
Daniel L. Albritton National Oceanic and Atmospheric Administration US
Michael J. Kurylo National Aeronautics and Space Administration US
Georgios T. Amanatidis European Commission Belgium

Coordinating Editor

Christine A. Ennis NOAA Aeronomy Laboratory/CIRES US

Technical Editing

Christine C. Sweet Science and Technology Corporation US
Christine A. Ennis NOAA Aeronomy Laboratory/CIRES US

Publication Design and Layout

Debra Dailey-Fisher (*Lead*) NOAA Aeronomy Laboratory US
Albert D. Romero (*Consulting and Support*) NOAA Mountain Administrative Support Center US
Dennis Dickerson (*Graphics Design, "Twenty Questions"*) Concepts 3 US

Editorial Assistance

Jeanne S. Waters NOAA Aeronomy Laboratory US
Barbara A. Keppler NOAA Aeronomy Laboratory US

Conference Coordination and Documentation

Michael H. Proffitt World Meteorological Organization Switzerland
Marie-Christine Charriére World Meteorological Organization Switzerland
Christine A. Ennis NOAA Aeronomy Laboratory/CIRES US
Jeanne S. Waters NOAA Aeronomy Laboratory US
Kathy A. Thompson Computer Sciences Corporation US

Conference Support

Jeanne S. Waters NOAA Aeronomy Laboratory US
Kathy A. Thompson Computer Sciences Corporation US
Catherine A. Burgdorf NOAA Aeronomy Laboratory/CIRES US
Debra Dailey-Fisher NOAA Aeronomy Laboratory US
Rose M. Kendall Computer Sciences Corporation US
Randy Soderholm Computer Sciences Corporation US
Chantal Renaudot World Meteorological Organization US
Barbara A. Keppler NOAA Aeronomy Laboratory US
Suzie Milano-Schoser NOAA Aeronomy Laboratory US
Gordon McFadyen Scottish Environment Protection Agency UK
Neil R.P. Harris European Ozone Research Coordinating Unit UK

Computing and Networking Support

Catherine A. Burgdorf NOAA Aeronomy Laboratory/CIRES US
Walter J. Harrop NOAA Aeronomy Laboratory US
Gabrielle Accatino NOAA Aeronomy Laboratory US
Ken Jamieson NOAA Aeronomy Laboratory US
Richard J. Tisinai NOAA Aeronomy Laboratory US