

SCIENTIFIC ASSESSMENT OF OZONE DEPLETION: 2006

*Pursuant to Article 6 of the Montreal Protocol
on Substances that Deplete the Ozone Layer*

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

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From *Scientific Assessment of Ozone Depletion: 2006*

**Dedicated to the Memory of
Gérard Mégie
1946-2004**



This report is dedicated to the memory of our friend and colleague, Prof. Gérard Mégie of the Centre National de la Recherche Scientifique of Paris, France.

Gérard worked as a member of the Scientific Assessment Panel of the Montreal Protocol since the very beginning; he was a participant in the Les Diablerets Panel Review Meeting in 1989. Later, he became a Cochair of the Scientific Assessment Panel, cochairing the 1998 and 2002 assessment reports. To that role, he brought his rare combination of scientific excellence and leadership talent, built upon many years as a teacher, researcher, internationally acclaimed scientist, and leader in the atmospheric science community.

One mark of Gérard's insightfulness was his work to guide the Panel toward its increasing emphasis on the connections between the ozone layer and the climate system. The Panel's assessment report for 2006 does contain that emphasis, and indeed it is captured in separate chapters on these issues.

Gérard was dedicated to communicating scientific understanding at many levels, ranging from international decisionmaking to the realm of the general public and schools. This is exemplified by his thoughtful work associated with the Panel's efforts to provide a set of "frequently asked" questions and answers about the ozone layer.

Gérard's many contributions to atmospheric science, as well as his role in forging interactions of the scientific community at its interface with society, have had a lasting impact. He leaves a legacy of scientific leadership that has helped shape the world's actions on the ozone layer. This legacy will endure.

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Chapter 3. Global Ozone: Past and Present (*Martyn P. Chipperfield and Vitali E. Fioletov*)
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III. Future Expectations for Ozone, Ozone-Depleting Substances, and UV

Chapter 5. Climate-Ozone Connections (*Mark P. Baldwin and Martin Dameris*)
Chapter 6. The Ozone Layer in the 21st Century (*Greg Bodeker and Darryn W. Waugh*)
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PREFACE

The present document 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 Earth's 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 Assessment Panel, and the Technology and Economic Assessment Panel have each periodically prepared major assessment reports that updated the state of understanding in their purviews. These reports have been scheduled so as 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 present 2006 report is the latest in a series of ten 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 the United Nations Environment Programme (UNEP). This report is the sixth 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:

<u>Year</u>	<u>Policy Process</u>	<u>Scientific Assessment</u>
1981		<i>The Stratosphere 1981: Theory and Measurements.</i> WMO No. 11.
1985	Vienna Convention	<i>Atmospheric Ozone 1985.</i> Three volumes. WMO No. 16.
1987	Montreal Protocol	
1988		<i>International Ozone Trends Panel Report 1988.</i> Two volumes. WMO No. 18.
1989		<i>Scientific Assessment of Stratospheric Ozone: 1989.</i> Two volumes. WMO No. 20.
1990	London Adjustment and Amendment	
1991		<i>Scientific Assessment of Ozone Depletion: 1991.</i> WMO No. 25.
1992		<i>Methyl Bromide: Its Atmospheric Science, Technology, and Economics (Montreal Protocol Assessment Supplement).</i> UNEP (1992).
1992	Copenhagen Adjustment and Amendment	
1994		<i>Scientific Assessment of Ozone Depletion: 1994.</i> WMO No. 37.

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1995	Vienna Adjustment	
1997	Montreal Adjustment and Amendment	
1998		<i>Scientific Assessment of Ozone Depletion: 1998.</i> WMO No. 44.
1999	Beijing Adjustment and Amendment	
2002		<i>Scientific Assessment of Ozone Depletion: 2002.</i> WMO No. 47
2006		<i>Scientific Assessment of Ozone Depletion: 2006.</i> WMO No. 50
2007	19 th Meeting of the Parties	

The Current Information Needs of the Parties

The genesis of *Scientific Assessment of Ozone Depletion: 2006* occurred at the 15th Meeting of the Parties to the Montreal Protocol in Nairobi, Kenya, at which the scope of the scientific needs of the Parties was defined in their Decision XV/53 (4), which stated that "...for the 2006 report, the Scientific Assessment Panel should consider issues including:

- (a) Assessment of the state of the ozone layer and its expected recovery;
- (b) Evaluation of specific aspects of recent annual Antarctic ozone holes, in particular the hole that occurred in 2002;
- (c) Evaluation of the trends in the concentration of ozone-depleting substances in the atmosphere and their consistency with reported production and consumption of ozone-depleting substances;
- (d) Assessment of the impacts of climate change on ozone-layer recovery;
- (e) Analysis of atmospheric concentrations of bromine and the likely quantitative implications of the results on the state of the ozone layer;
- (f) 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 also into account the expected impacts of climate change..."

The Assessment Process

The formal planning of the current assessment was started early in 2005. A Scientific Steering Committee consisting of five scientists from various countries assisted the Scientific Assessment Panel's Cochairs throughout the planning, preparation, review, and finalization of the 2006 assessment. The Cochairs and Scientific Steering Committee considered suggestions from the Parties regarding experts from their countries who could participate in the process. Furthermore, an *ad hoc* international scientific group also suggested participants from the world scientific community. In addition, this group contributed to crafting the outline of the assessment report. As in previous assessments, the participants represented experts from the developed and developing world. In addition to the scientific expertise, the developing country experts bring a special perspective to the process, and their involvement in the process has also contributed to capacity building.

The information of the 2006 assessment is contained in eight chapters associated with ozone-layer topics:

I. SOURCE GASES

Chapter 1. Long-Lived Compounds

Chapter 2. Halogenated Very Short-Lived Substances

II. OZONE CHANGES

Chapter 3. Global Ozone: Past and Present

Chapter 4. Polar Ozone: Past and Present

III. FUTURE EXPECTATIONS FOR OZONE, OZONE-DEPLETING SUBSTANCES, AND UV

Chapter 5. Climate-Ozone Connections

Chapter 6. The Ozone Layer in the 21st Century

Chapter 7. Surface Ultraviolet Radiation: Past, Present, and Future

Chapter 8. Halocarbon Scenarios, Ozone Depletion Potentials, and Global Warming Potentials

A special resource for the Panel's work was the 2005 Special Report of the Intergovernmental Panel on Climate Change (IPCC) and the Technology and Economics Assessment Panel (TEAP) of the Montreal Protocol, *Safeguarding the Ozone Layer and the Global Climate System: Issues Related to Hydrofluorocarbons and Perfluorocarbons*. This report was used as a basis for many scenarios for modeling runs and hypothetical cases that are included here.

The initial plans for the chapters of the 2006 Scientific Assessment Panel's report were examined at a meeting that occurred on 26-27 July 2005 in Paris, France. The Lead Authors, Steering Committee, and Coauthors focused on the content of the draft chapters and on the need for coordination among the chapters.

The first drafts of the chapters were examined at a meeting that occurred on 30 November-2 December 2005 in Herndon, Virginia, United States, at which the Lead Authors, Steering Committee, Coauthors, 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 125 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 19-23 June 2006, the responses to these mail review comments were proposed by the authors and discussed by the 77 participants. Final changes to the chapters were decided upon at this meeting. The Executive Summary contained herein (and posted on the UNEP web site on 18 August 2006) was prepared and completed by the attendees of the Les Diablerets meeting.

The 2006 State-of-Understanding Report

In addition to the scientific chapters and the Executive Summary, the assessment also updates the 2002 assessment report's answers to 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 updated questions and answers are included in this report.

The final result of this two-year endeavor is the present assessment report. As the accompanying list indicates, the *Scientific Assessment of Ozone Depletion: 2006* is the product of 310 scientists from 34 countries who contributed to its preparation and review¹ (205 scientists prepared the report and 183 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 Participants were from Argentina, Armenia, Australia, Austria, Belgium, Bolivia, Canada, Czech Republic, Denmark, Egypt, Estonia, Finland, France, Germany, Greece, India, Israel, Italy, Japan, Kenya, Malaysia, New Zealand, Norway, Poland, Russia, South Africa, Spain, Sweden, Switzerland, The Netherlands, The People's Republic of China, Togo, United Kingdom, and United States of America.

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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 updated 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 scientific understanding were assessed by the Scientific Assessment Panel in 1989, 1991, 1994, 1998, and 2002. This information helped support discussions among the Parties that led to the subsequent Amendments and Adjustments of the 1987 Protocol. The 2006 Scientific Assessment summarized here is the sixth in that series. The information contained in this Executive Summary is based on the eight detailed chapters of the full report.

The previous Assessment presented evidence that the tropospheric abundances of most ozone-depleting substances, as well as of stratospheric chlorine, were stable or decreasing due to actions taken under the Montreal Protocol (see schematic Figure 1a, b), with the stratospheric abundances showing a time lag due to the time for surface emissions to reach the stratosphere. Based on these facts, it was stated that “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.”

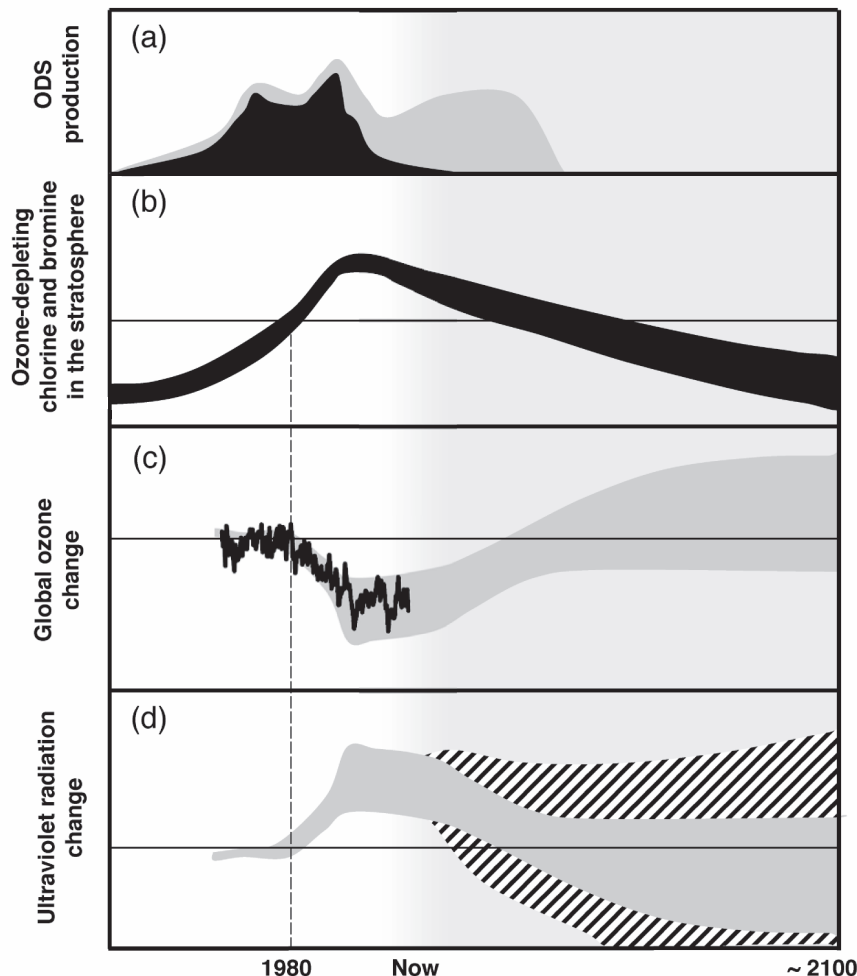


Figure 1. Ozone-Depleting Substances, the Ozone Layer, and UV Radiation: Past, Present, and Future.

(a) Production of ozone-depleting substances (ODSs) before and after the 1987 Montreal Protocol and its Amendments, from baseline scenario A1. Chlorofluorocarbons (CFCs) are shown in black; additional ODSs from hydrochlorofluorocarbons (HCFCs) are in gray. Note: HCFCs, which have been used as CFC replacements under the Protocol, lead to less ozone destruction than CFCs.

(b) Combined effective abundances of ozone-depleting chlorine and bromine in the stratosphere. The range reflects uncertainties due to the lag time between emission at the surface and the stratosphere, as well as different hypothetical ODS emission scenarios.

(c) Total global ozone change (outside of the polar regions; 60°S-60°N). Seasonal, quasi-biennial oscillation (QBO), volcanic, and solar effects have been removed. The black line shows measurements. The gray region broadly represents the evolution of ozone predicted by models that encompass the range of future potential climate conditions. Pre-1980 values, to the left of the vertical dashed line, are often used as a benchmark for ozone and UV recovery.

(d) Estimated change in UV erythemal (“sunburning”) irradiance for high sun. The gray area shows the calculated response to the ozone changes shown in (c). The hatched area shows rough estimates of what might occur due to climate-related changes in clouds and atmospheric fine particles (aerosols).

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An important next step is to ask whether stratospheric ozone and surface ultraviolet (UV) radiation are responding as expected to the controls on ozone-depleting substances imposed by the Protocol (see schematic Figure 1c, d). In addressing this question, it is necessary to consider factors other than ozone-depleting substances that also influence ozone and UV radiation. These factors include natural dynamical variability, volcanic eruptions, solar variations, aerosols (airborne fine particles), and climate change.

Pre-1980 values are often used as a benchmark for ozone and UV recovery. However, because of the above-mentioned factors, if and when ozone and UV radiation return to their pre-1980 values would not be associated solely with the return of ozone-depleting substances to their pre-1980 values (see schematic Figure 1c, d).

We address the behavior of ozone-depleting substances, the response of stratospheric ozone and UV radiation to ozone-depleting substances and other factors to date, and the future evolution of ozone and UV radiation. We first present the main findings, then the detailed supporting evidence, and finally the implications for policy formulation.

RECENT MAJOR FINDINGS AND CURRENT SCIENTIFIC UNDERSTANDING

Since the *Scientific Assessment of Ozone Depletion: 2002*, numerous laboratory investigations, atmospheric observations, and theoretical and modeling studies have produced new key findings and have strengthened the overall understanding of the ozone layer and its effect on 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, as well as the coupling between climate change and stratospheric ozone depletion.

Ozone-Depleting Substances

The previous Assessment noted that the tropospheric abundances of ozone-depleting gases were declining, whereas the stratospheric abundances were at or near their peak. Now we ask: Are the tropospheric and stratospheric abundances of ozone-depleting gases showing further changes that can be linked to policy actions, and how are they expected to evolve in the future?

- **The total combined abundances of anthropogenic ozone-depleting gases in the troposphere continue to decline from the peak values reached in the 1992-1994 time period.**
 - The shorter-lived gases (e.g., methyl chloroform and methyl bromide) continue to provide much of the decline in total combined effective abundances of anthropogenic chlorine-containing and bromine-containing ozone-depleting gases in the troposphere. The early removal of the shorter-lived gases means that later decreases in ozone-depleting substances will likely be dominated by the atmospheric removal of the longer-lived gases.
 - By 2005, the total combined abundance of anthropogenic ozone-depleting gases in the troposphere had decreased by 8-9% from the peak value observed in the 1992-1994 time period. The overall magnitude of this decrease is attributable to the estimated changes in emissions and is consistent with the known atmospheric lifetimes and our understanding of transport processes.
 - The tropospheric abundances of hydrochlorofluorocarbons HCFC-22, -141b, and -142b increased much less than projected in the previous Assessment. The implication is that emissions have been lower than anticipated.
 - The sum of bromine from halons and methyl bromide in the troposphere has decreased by 3-5% since 1998 because of decreases in methyl bromide abundance. Methyl bromide abundance has decreased by 14% between 1997 and 2004. This decrease was larger than expected and suggests that when anthropogenic emissions of methyl bromide are reduced, its atmospheric abundance decreases more than previously thought.

- **The combined stratospheric abundances of the ozone-depleting gases show a downward trend from their peak values of the late 1990s, which is consistent with surface observations of these gases and a time lag for transport to the stratosphere.**
 - Measurements of hydrogen chloride give a clear signature in the stratosphere of the decrease in stratospheric ozone-depleting gases since reaching their peak in the late 1990s.
 - Stratospheric bromine has increased in line with its tropospheric trends in preceding years. A decrease in stratospheric bromine has not yet been identified. Bromine continues to play a major role in stratospheric ozone depletion.
- **Our quantitative understanding of how halogenated very short-lived substances contribute to halogen levels in the stratosphere has improved significantly since the 2002 Assessment, with brominated very short-lived substances believed to make a significant contribution to total stratospheric bromine and its effect on stratospheric ozone.**
 - Brominated very short-lived substances (which are mainly of natural origin) contribute ~5 parts per trillion (ppt) of bromine (estimates range from 3 to 8 ppt) to current levels of total stratospheric bromine (which are about 18 to 25 ppt). These values are derived from observations of tropospheric bromine source gases and bromine monoxide in the stratosphere, based on our current understanding of chemical transformations and transport of very short-lived substances to the stratosphere.
 - Chlorinated very short-lived source gases, which are mainly of anthropogenic origin, have now been observed at levels of about 50 ppt in the tropical upper troposphere and currently may be a small source of chlorine to the stratosphere.
 - Evidence suggests that iodine is currently much less important than bromine and chlorine for stratospheric ozone destruction.

Ozone, Ultraviolet Radiation, and Other Related Changes to Date

The previous Assessment noted that stratospheric ozone depletion was expected to begin to reverse within the next decade or so. Now we ask: Are there any signs of this beginning? Have other factors influenced the behavior of ozone during this period? Has surface UV radiation responded as anticipated?

- **Our basic understanding that anthropogenic ozone-depleting substances have been the principal cause of the ozone depletion over the past few decades has been strengthened. During the recent period of near-constant abundances of ozone-depleting gases, variations in meteorology have been particularly important in influencing the behavior of ozone over much of the polar and extrapolar (60°S-60°N) regions.**

POLAR OZONE

- **Springtime polar ozone depletion continues to be severe in cold stratospheric winters. Meteorological variability has played a larger role in the observed variability in ozone, over both poles, in the past few years.**
 - Large Antarctic ozone holes continue to occur. The severity of Antarctic ozone depletion has not continued to increase since the late 1990s and, since 2000, ozone levels have been higher than in some preceding years. These recent changes, seen to different degrees in different diagnostic analyses, result from increased dynamical activity and not from decreases in ozone-depleting substances.

EXECUTIVE SUMMARY

- The Antarctic ozone hole now is not as strongly influenced by moderate decreases in ozone-depleting gases, and the unusually small ozone holes in some recent years (e.g., 2002 and 2004) are attributable to dynamical changes in the Antarctic vortex.
- The anomalous Antarctic ozone hole of 2002 was manifested in a smaller ozone-hole area and much smaller ozone depletion than in the previous decade. This anomaly was due to an unusual major stratospheric sudden warming.
- Arctic ozone depletion exhibits large year-to-year variability, driven by meteorological conditions. Over the past four decades, these conditions became more conducive to severe ozone depletion because of increasingly widespread conditions for the formation of polar stratospheric clouds during the coldest Arctic winters. This change is much larger than can be expected from the direct radiative effect of increasing greenhouse gas concentrations. The reason for the change is unclear, and it could be because of long-term natural variability or an unknown dynamical mechanism. The change in temperature conditions has contributed to large Arctic ozone losses during some winters since the mid-1990s.
- The Arctic winter 2004/2005 was exceptionally cold, and chemical ozone loss was among the largest ever diagnosed. The Arctic remains susceptible to large chemical ozone loss, and a lack of understanding of the long-term changes in the occurrence of polar stratospheric clouds limits our ability to predict the future evolution of Arctic ozone abundance and to detect the early signs of recovery.
- The role of chemical reactions of chlorine and bromine in the polar stratosphere is better quantified. Inclusion of these advances results in improved agreement between theory and observation of the timing of both Arctic and Antarctic polar ozone loss.

GLOBAL OZONE (60°S-60°N)

- **The decline in abundances of extrapolar stratospheric ozone seen in the 1990s has not continued.**
 - Ozone abundances in the extrapolar regions, 60°S-60°N, have not further declined in recent years. The mid-latitude column (i.e., overhead) ozone values for the 2002-2005 period were approximately 3% below pre-1980 values in the Northern Hemisphere and approximately 6% in the Southern Hemisphere, essentially the same as in the 1998-2001 period.
 - The contribution of polar ozone depletion to midlatitude ozone depletion is substantial; the extent of the contribution is estimated to be about one-third in the Northern Hemisphere and one-half in the Southern Hemisphere. The larger contribution in the Southern Hemisphere is to be expected, given the larger polar ozone depletion in the Antarctic relative to the Arctic region, and may explain the differences in magnitude and seasonality of the long-term ozone changes in midlatitudes between the two hemispheres.
 - Changes in tropospheric and stratospheric meteorology are partially responsible for the observed Northern Hemisphere midlatitude winter ozone decline from 1979 to the mid-1990s and the ozone increase thereafter. Quantification of these dynamical effects on long-term trends ranges from ~20% to up to 50%, depending on the study. Most of these dynamically induced ozone changes appear to occur in the lowermost stratosphere.
 - Upper stratospheric ozone declined between 1979 and the mid-1990s, with the largest decrease of about 10-15% near 40 km over midlatitudes, but has been relatively constant during the last decade. Lower stratospheric (20-25 km) ozone over midlatitudes also showed a decrease of up to 10% from 1979 to the mid-1990s and has been relatively constant thereafter.

- Ozone abundances in the Northern Hemisphere midlatitude lowermost stratosphere (12-15 km) show a strong decrease between 1979 and the mid-1990s, followed by an overall increase from 1996 to 2004, giving no net long-term decrease at this level. This lowermost stratosphere ozone change contributed significantly to the column ozone change during the last decade. Southern Hemisphere observations do not show a similar increase in the 12-15 km altitude range since the mid-1990s.
- Total column ozone over the tropics (25°S-25°N) remains essentially unchanged. This finding is consistent with the findings of the previous Assessments.
- **Observations together with model studies suggest that the essentially unchanged column ozone abundances averaged over 60°S-60°N over roughly the past decade are related to the near constancy of stratospheric ozone-depleting gases during this period.**
 - The slowing of the decline and leveling off of midlatitude upper stratospheric (35-45 km) ozone over the past decade have very likely been dominated by the corresponding changes in stratospheric ozone-depleting gases.
 - Over the past decade, changes in stratospheric ozone-depleting gases have likely contributed to the slowing of the midlatitude total column ozone decline and the general leveling off of ozone abundances. Transport has also played an important role in ozone changes, particularly in the lowermost stratosphere, making attribution of column ozone changes to changes in ozone-depleting gases more difficult than in the upper stratosphere.

STRATOSPHERIC TEMPERATURE AND SURFACE UV RADIATION

- **The stratospheric cooling observed during the past two decades has slowed in recent years.**
 - Satellite and radiosonde measurements reveal an overall decrease in the global-mean lower stratospheric temperature of approximately 0.5 K/decade over the 1979-2004 period, with a slowdown in the temperature decline since the late 1990s. The overall temperature decrease is punctuated by transient warmings of the stratosphere associated with the major volcanic eruptions in 1982 and 1991. Model calculations suggest that the observed ozone loss is the predominant cause of the global-mean cooling observed over this period.
 - The lower stratospheric cooling is evident at all latitudes, in particular in both the Arctic and Antarctic winter/spring lower stratosphere, but with considerable interannual variability in those regions.
 - Satellite observations show larger cooling trends in the upper stratosphere, with values of 1 to 2 K/decade, but little additional decline since the middle 1990s. Model calculations suggest that the upper stratosphere trends are due, about equally, to decreases in ozone and increases in well-mixed greenhouse gases.
 - The long-term cooling rate of the Antarctic stratosphere has likewise reduced compared with what was seen by the time of the previous Assessment. There has been large variability in Antarctic temperatures in recent years.
- **Measurements from some stations in unpolluted locations indicate that UV irradiance (radiation levels) has been decreasing since the late 1990s, in accordance with observed ozone increases. However, at some Northern Hemisphere stations UV irradiance is still increasing, as a consequence of long-term changes in other factors that also affect UV radiation.** Outside polar regions, ozone depletion has been relatively small, hence, in many places, increases in UV due to this depletion are difficult to separate from the increases caused by other factors, such as changes in cloud and aerosol. In some unpolluted locations, especially in the Southern Hemisphere, UV irradiance has been decreasing in recent years, as expected from the observed increases in ozone at those sites. Model calculations incorporating only ozone projections show that cloud-free UV irradiance will continue to decrease, although other UV-influencing factors are likely to change at the same time.

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- **In polar regions, high UV irradiances lasting for a few days have been observed in association with episodes of low total ozone.** Erythemat (i.e., sunburning) irradiance averaged over several days has been increased by ~70% over sub-Antarctic regions when ozone-depleted air from the polar region passes over. In Antarctica during October, instantaneous enhancements that can exceed a factor of three have been observed. Over northern Europe and Alaska, the observed enhancements were smaller.

The Future of the Ozone Layer and Surface UV Radiation

The previous (2002) Assessment noted that climate change would influence the future of the ozone layer. Now we ask: How has our understanding of this issue progressed? How has our increased understanding led to an improved estimate of the state of the future ozone layer?

Previous Assessments have relied heavily on two-dimensional models for projections of future ozone, and these models are used again here. The 2002 Assessment noted the emerging use of three-dimensional Chemistry-Climate Models; we have now used these models extensively in this current 2006 Assessment.

- **It is unlikely that total ozone averaged over the region 60°S-60°N will decrease significantly below the low values of the 1990s, because the abundances of ozone-depleting substances have peaked and are in decline.** Two-dimensional models and three-dimensional Chemistry-Climate Models suggest that the minimum total column ozone values in this region have already occurred. This conclusion is consistent with the observation that over this region, ozone has not declined further in the 2002-2005 period.
- **The decrease in ozone-depleting substances is the dominant factor in the expected return of ozone levels to pre-1980 values. Changes in climate will influence if, when, and to what extent ozone will return to pre-1980 values in different regions.**
 - The current best estimate is that global (60°S-60°N) ozone will return to pre-1980 levels around the middle of the 21st century, at or before the time when stratospheric abundances of ozone-depleting gases return to pre-1980 levels.
 - Model simulations suggest that changes in climate, specifically the cooling of the stratosphere associated with increases in the abundance of carbon dioxide, may hasten the return of global column ozone to pre-1980 values by up to 15 years, depending on the climate-gas scenario used. However, this would not be considered a “recovery” of stratospheric ozone from ozone-depleting gases, because perceptible depletion due to anthropogenic ozone-depleting substances will still be contributing to the ozone levels.
- **The Antarctic ozone hole is expected to continue for decades. Antarctic ozone abundances are projected to return to pre-1980 levels around 2060-2075, roughly 10-25 years later than estimated in the 2002 Assessment.** The projection of this later return is primarily due to a better representation of the time evolution of ozone-depleting gases in the polar regions. In the next two decades, the Antarctic ozone hole is not expected to improve significantly.
- **Large ozone losses will likely continue to occur in cold Arctic winters during the next 15 years.** The high variability in the volume of polar stratospheric clouds in these cold winters limits our ability to predict their future occurrences. According to Chemistry-Climate Models, Arctic ozone levels are expected, on average, to return to pre-1980 levels before 2050.
- **Climate change will also influence surface UV radiation through changes induced mainly to clouds and the ability of the Earth’s surface to reflect light.** Aerosols and air pollutants are also expected to change in the future. These factors may result in either increases or decreases of surface UV irradiance, through absorption or scattering. As ozone depletion becomes smaller, these factors are likely to dominate future UV radiation levels.

ADDITIONAL SCIENTIFIC EVIDENCE AND RELATED INFORMATION

For the purpose of this report, ozone-depleting substances are considered as being either long-lived (more than 6 months in the atmosphere) or very short-lived (less than 6 months in the atmosphere), and these are considered in the next two sections. The atmospheric lifetime determines the likelihood of halogens emitted in the troposphere reaching the stratosphere, and so being able to deplete stratospheric ozone. The cumulative effective abundance of halogens in the stratosphere is quantified as equivalent effective stratospheric chlorine (EESC).¹

Long-Lived Ozone-Depleting Substances

ATMOSPHERIC TRENDS

- **The decline in the abundance of methyl chloroform and methyl bromide, which are shorter lived than chlorofluorocarbons (CFCs), contributed the most to the decline in effective equivalent tropospheric chlorine levels.** By 2005, the abundances of the total combined anthropogenic ozone-depleting gases in the troposphere had decreased by 8-9% from the peak value observed in the 1992-1994 time period. The total decline was ~120 parts per trillion (ppt) between 2000 and 2004, of which ~60 ppt was due to the decline of methyl chloroform and ~45 ppt due to methyl bromide. The CFCs together accounted for less than 23 ppt of the decline. The contribution of hydrochlorofluorocarbons (HCFCs) was to add 12 ppt.
- **Total tropospheric chlorine-containing chemicals (approximately 3.44 parts per billion (ppb) in 2004) continued to decrease.** Recent decreases (20 ppt/year or 0.59% in 2003-2004) have been at a slightly slower rate than decreases in earlier years (23 ppt/year or 0.64% in 1999-2000) primarily because of the reduced contribution from methyl chloroform. The declines in total chlorine (Cl) during 2000-2004 were slightly faster than projected for these years in the Ab scenario of the previous (2002) ozone assessment report (baseline scenario following the 1999 Beijing Amendments).
 - **Chlorofluorocarbons, consisting primarily of CFC-11, -12, and -113, accounted for 2.13 ppb (~62%) of total Cl in 2004 and accounted for a decline of 9 ppt of Cl from 2003-2004 (or nearly half of the total Cl decline in the troposphere over this period).** Atmospheric mixing ratios of CFC-12, which account for about one-third of the current atmospheric chlorine loading, have been constant within 1% (5 ppt) since 2000, and some in situ and Northern Hemisphere column (i.e., overhead) measurements show that peak values were attained in 2003. CFC-11 mixing ratios are decreasing at approximately 0.8%/year (1.9 ppt/year) and CFC-113 mixing ratios are decreasing at approximately 1%/year (0.8 ppt/year), which is twice as fast as in 1999-2000.
 - **Hydrochlorofluorocarbons (HCFCs), which are substitutes for CFCs, continue to increase in the atmosphere. HCFCs accounted for 214 ppt, or 6%, of total tropospheric chlorine in 2004 versus 180 ppt (5%) of total Cl in 2000.** HCFC-22 is the most abundant of the HCFCs and is currently (2000-2004) increasing at a rate of 4.9 ppt/year (3.2%/year). HCFC-141b and HCFC-142b mixing ratios increased by 1.1 ppt/year (7.6%/year) and 0.6 ppt/year (4.5%/year) over this same period, or at about half the rates found for these two gases in 1996-2000. The rates of increase for all three of these HCFC compounds are significantly slower than projected in the 2002 Ozone Assessment (6.6, 2.6, and 1.6 ppt/year for HCFC-22, HCFC-141b, and HCFC-142b, respectively).

¹ Equivalent effective stratospheric chlorine (EESC), a metric noted in the previous Assessment, has found widespread use. EESC is a gauge of the overall stratospheric burden of ozone-depleting halogen. It is derived from ground-based measurements of ozone-depleting substances, with consideration given to the number of chlorine and bromine atoms in ozone-depleting substances, the rates at which different ozone-depleting substances release their halogen once they reach the stratosphere, and the higher per-atom efficiency for bromine relative to chlorine in destroying ozone.

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- **Methyl chloroform has continued to decrease and contributed 13.5 ppt (or more than half) of the overall decline observed for total tropospheric Cl in 2003-2004.** It is currently still the largest contributor to the decline in tropospheric chlorine.
- **The stratospheric chlorine burden derived from ground-based total column and space-based measurements of inorganic chlorine is now in decline.** This is consistent with the decline in tropospheric chlorine from long-lived halocarbons. The burden of total stratospheric chlorine derived from satellite measurements agrees, within ± 0.3 ppb (about 12%), with the amounts expected from surface data when the delay due to transport is considered. The uncertainty in this burden is large relative to the expected chlorine contribution from shorter-lived gases.
- **Total organic tropospheric bromine from halons and methyl bromide peaked in about 1998 at 16.5 to 17 ppt and has since declined by 0.6-0.9 ppt (3-5%).** This observed decrease was solely a result of declines observed for methyl bromide. Bromine from halons continues to increase, but at slower rates in recent years (0.1 ppt Br/year in 2003-2004).
 - **Atmospheric amounts of methyl bromide declined beginning in 1999, when industrial production was reduced.** By mid-2004, mixing ratios had declined 1.3 ppt (14%) from the peak of 9.2 ppt measured before 1999. Reported production of methyl bromide for emissive uses decreased by 50% during this same period.
 - **Both the recently observed decline and the 20th century increase inferred for atmospheric methyl bromide were larger than expected.** Although industrial emissions of methyl bromide were thought to account for 20% (range 10-40%) of atmospheric methyl bromide during 1992-1998 (i.e., before production was reduced), observed concentrations are consistent with this fraction having been 30% (range 20-40%). This suggests that fumigation-related emissions could have a stronger influence on atmospheric methyl bromide mixing ratios than estimated in past Assessments, though uncertainties in the variability of natural emission rates and loss, and in the magnitude of methyl bromide banked in recent years, limit our understanding of this sensitivity.
 - **Mixing ratios calculated from updated emission estimates are in good agreement with the measurements for halon-1211, but they exceed all the halon-1301 measurements since 1980 by more than 10%.** Atmospheric increases in halon-1211 (0.06 ppt/year) in 2000-2004 were about half those in 1996-2000. It is currently unclear whether halon-1301 continues to increase.

EMISSION ESTIMATES

- **Global emissions of CFC-11 (88 Gg/yr, where 1 Gg = 10⁹ grams), CFC-12 (114 Gg/yr), and CFC-113 (6 Gg/yr) in 2003 were approximately 25%, 25%, and 3% of their maximum values around 1986.** Emissions of CFC-11, CFC-12, and CFC-113 have all continued to decrease since 2000.
- **Regional emission estimates for CFCs, methyl chloroform, and carbon tetrachloride have been reported for the first time.** Differences between developed and developing regions are indicative of the differing schedules of phase-out. However, the patchiness in the present coverage (especially in developing regions such as Southeast Asia) and the uncertainties in the regional estimates mean that useful comparisons between summed regional emissions and global emissions derived from trends cannot currently be made. Regional emission estimates of methyl chloroform indicate that global emissions after 2000 may have been roughly 22 Gg/year, which is not statistically different from the estimate of 12.9 Gg/year (for 2002) obtained from industry/United Nations Environment Programme data.
- **While emissions of HCFC-22 have remained nearly constant from 2000 to 2004, emissions of HCFC-141b and HCFC-142b decreased by approximately 15% over the same period.**

- **Hydrofluorocarbon-23 (HFC-23) emissions estimated from atmospheric measurements have increased from about 6 Gg/yr in 1990 to about 13 Gg/yr in 2001 (an increase of approximately 120%).** These emissions are a byproduct of HCFC-22 production. HFC-23 mixing ratios (18 ppt in 2004) have continued to increase, at approximately 0.7 ppt/yr (4%/yr), in 2001-2004.

Halogenated Very Short-Lived Substances

- **Observations show that the total inorganic bromine (Br_y) in the stratosphere is more abundant than can be accounted for by the sum of bromine delivered to this region by “long-lived” brominated source gases.** Very short-lived substances (VSLS) are defined as trace gases whose local tropospheric lifetimes are comparable to or shorter than tropospheric transport time scales, such that their tropospheric distributions are non-uniform. Here, VSLS are considered to have atmospheric lifetimes of less than 6 months.
- **Various lines of evidence show that brominated VSLS contribute about 5 ppt (with estimates ranging from 3 to 8 ppt) to total stratospheric Br_y :**
 - The estimate of total stratospheric Br_y abundance existing in the late 1990s is about 18-25 ppt. This value is derived from different observations of bromine monoxide (BrO). This is greater than the 16-17 ppt of bromine delivered to the stratosphere by “long-lived” brominated source gases (i.e., the halons and methyl bromide, CH_3Br) during this period.
 - Measurements of organic brominated very short-lived source gases in the tropical upper troposphere amount to about 3.5 ppt. Compounds resulting from source gas degradation and other sources of tropospheric inorganic bromine may contribute comparable amounts.
- **Levels of total stratospheric bromine continue to show evidence for a trend that is consistent with that of tropospheric total bromine.** Further studies are required to determine if the recent decline in tropospheric bromine will be reflected in stratospheric bromine abundance.
- **It is unlikely that iodine is important for stratospheric ozone loss in the present-day atmosphere.** There is little evidence for measurable iodine in the form of iodine oxide (IO) in the lower stratosphere (i.e., about 0.1 ppt). This difference in behavior compared with bromine may be partly attributed to the short photochemical lifetime and lower abundances of iodine source gases, and aerosol uptake of iodine in the stratosphere.
- **The sum of the chlorine content from very short-lived source gases in the tropical upper troposphere is now estimated to be about 50 ppt.** While 50 ppt of inorganic chlorine (Cl_y) from VSLS would represent only 1-2% of Cl_y from long-lived source gases (~3500 ppt), it would represent a significant contribution to background Cl_y due only to naturally occurring methyl chloride (550 ppt). The value of 100 ppt for Cl_y from short-lived species in the previous Assessment also included a contribution of 50 ppt from phosgene.
- **The majority of known brominated and iodinated very short-lived source gases are predominantly of natural origin and are nearly unchanged in the past few decades,** as indicated by firn air studies. Some have small anthropogenic sources and have increased slightly in the Northern Hemisphere (e.g., certain brominated trihalomethanes) and a few are almost exclusively anthropogenic (notably n-propyl bromide (n-PB)).
- **Chlorinated very short-lived source gases originate largely from anthropogenic emissions,** although natural sources also contribute. There is evidence for significant recent declines in concentrations of some chlorinated very short-lived source gases, notably chloroform, dichloromethane, and tetrachloroethene.

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- **The route by which VSLs are most likely to reach the stratosphere is transport out of the boundary layer by deep convection in tropical regions (particularly if co-located with regions of high emissions over tropical oceans) followed by quasi-horizontal transport into the lower stratosphere.** The fraction of source gas and product gas transported into the stratosphere also depends on the local chemical lifetime, where source gases decompose, and the loss of product gases by heterogeneous processes involving aerosols and clouds.

Global Ozone (60°S-60°N)

TOTAL COLUMN OZONE

- **Global mean total column (i.e., overhead) ozone values for 2002-2005 were 3.5% below 1964-1980 average values.** The 2002-2005 values are similar to the 1998-2001 values. This behavior is evident in all available global datasets, although differences of up to 1% between annual averages exist between some individual sets.
- **There are differences between the two hemispheres in the evolution of total column ozone at midlatitudes:**
 - Averaged for the period 2002-2005, total column ozone for the Northern Hemisphere (NH) and Southern Hemisphere (SH) midlatitudes (35°-60°) are about 3% and 5.5%, respectively, below their 1964-1980 average values and are similar to their 1998-2001 values. The NH shows a minimum around 1993 followed by an increase. The SH shows an ongoing decrease through the late 1990s followed by the recent leveling off.
 - There are seasonal differences between the NH and the SH in ozone changes over midlatitudes. Changes since the pre-1980 period over northern midlatitudes (35°N-60°N) are larger in spring, whereas those over southern midlatitudes (35°S-60°S) are nearly the same throughout the year.
- **Total column ozone over the tropics (25°S-25°N) remains essentially unchanged.** These findings are consistent with the findings of the previous Assessments.

VERTICAL OZONE DISTRIBUTION

- **Upper stratospheric ozone declined during 1979-1995, but has been relatively constant during the last decade.** Measurements from Stratospheric Aerosol and Gas Experiment (SAGE I+II) and Solar Backscatter Ultraviolet spectrometer (SBUV(2)) satellite instruments show significant declines through 1995 when averaged over 60°N-60°S and altitudes of 35 to 50 km. The net ozone decrease was ~10-15% over midlatitudes, with smaller, but significant changes over the tropics. Available independent Umkehr, lidar, and microwave ozone measurements confirm these findings.
- **Lower stratospheric ozone declined over the period 1979-1995, but has been relatively constant with significant variability over the last decade.** At midlatitudes of both the Northern and Southern Hemispheres, measurements by the SAGE I+II and SBUV(2) satellite instruments showed declines of up to 10% by 1995 between 20 and 25 km altitude. These decreases did not continue in the last decade.
- **In the lowermost stratosphere of the Northern Hemisphere, between 12 and 15 km, a strong decrease in ozone was observed between 1979 and 1995, followed by an overall increase from 1996 to 2004 leading to no net long-term decrease at this level.** These changes in the lowermost stratosphere have a substantial influence on the column. The Southern Hemisphere midlatitude data do not show similar increases since 1995 at these altitudes.

UNDERSTANDING PAST CHANGES IN GLOBAL OZONE

- **There is good overall agreement between observed long-term changes in extrapolar ozone and model simulations that include the effects of increasing halogens.** The models generally reproduce the observed ozone changes as a function of altitude, latitude, and season, confirming our understanding that halogen changes are the main driver of global ozone changes. This link is supported by the statistical fit of globally averaged ozone observations with equivalent effective stratospheric chlorine (EESC; see footnote at the beginning of this section of the Executive Summary). However, there are discrepancies between the modeled and observed changes. Notably, the models tend to perform less well in simulating changes in the SH compared with the NH.
- **Empirical and model studies have shown that changes in tropospheric and stratospheric dynamics have been partially responsible for the observed NH midlatitude winter ozone decline from 1979 to the mid-1990s and the ozone increase thereafter.** Whether this is due to dynamical variability or results from a long-term trend in stratospheric circulation is not yet clear. Estimates of these dynamical effects on long-term trends range from ~20% up to 50% for the winter period.
- **The inclusion of additional inorganic bromine (Br_y) from very short-lived substances (VSLS) in models yields simulations with larger ozone destruction at midlatitudes and polar regions, compared with studies including only long-lived bromine source gases.** In both regions, the enhanced ozone loss occurs in the lower stratosphere via interactions of this bromine with anthropogenic chlorine. Midlatitude ozone loss is most enhanced during periods of high aerosol loading. Ozone loss through chemical reactions involving bromine and odd-hydrogen (HO_x) is also enhanced at midlatitudes under all conditions. The impact on long-term midlatitude ozone trends (1980-2004), assuming constant VSLS Br_y , is calculated to be small because aerosol loading was low at the start and end of this time period.
- **Several independent modeling studies confirm that dilution of ozone-depleted polar air makes a substantial contribution to midlatitude ozone depletion, especially in the Southern Hemisphere, where polar ozone loss is much larger.** Long-term annually averaged model-based estimates indicate that about one-third of the depletion in the Northern Hemisphere (with large interannual variation), and about one-half in the Southern Hemisphere, results from polar loss. This is supported by the observation that polar ozone depletion in the Antarctic spring is strongly correlated with southern summer midlatitude ozone depletion.
- **Identification of the solar cycle signal in observed ozone has been improved because of the absence of major volcanic eruptions over the past 15 years.** The deduced solar cycle variation in column ozone has a mean amplitude of 2-3% (from minimum to maximum) in low to midlatitudes from the extended data series.

Polar Ozone

ARCTIC

- **Arctic spring total ozone values over the last decade are lower than values observed in the 1980s, but somewhat larger than those in the 1990s; they are highly variable depending on dynamical conditions.** For current halogen levels, anthropogenic chemical loss and variability in ozone transport are about equally important for year-to-year Arctic ozone variability. Lower-than-average Arctic vortex temperatures result in larger halogen-driven chemical ozone losses.
- **For the “coldest” Arctic winters, the volume of air with temperatures low enough to support polar stratospheric clouds (called “ V_{PSC} ”) has increased significantly since the late 1960s.** This change is much larger than expected from the direct radiative effect of increasing greenhouse gas concentrations. The reason for the change is not clear, and it could be due to long-term natural variability or an unknown dynamical mechanism.

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- **Column ozone chemical loss in the 2004/2005 Arctic winter was among the largest ever diagnosed.** The 2004/2005 Arctic stratosphere was exceptionally cold, particularly at altitudes below 18 km, leading to a value of V_{PSC} 25% larger than the previous record value. Various independent studies and methods suggest that the chemical column ozone loss in 2004/2005 was among the largest ever observed.
- **The chemical loss of column ozone for Arctic winters exhibits a near-linear relation with V_{PSC} during each winter.** A similar relation between ozone loss and V_{PSC} is now seen for two independent analyses of chemical ozone loss, increasing our confidence in the robustness of this relation. Observations of the large Arctic ozone loss in 2004/2005 are in line with the relationship established for prior winters.

ANTARCTIC

- **Large Antarctic ozone holes continue to occur. The severity of Antarctic ozone depletion has not continued to increase since the late 1990s and, since 2000, ozone levels have been higher in some years.** These recent changes, evident to different degrees in different diagnostic measures, result from increased dynamical wave activity and not from decreases in ozone-depleting substances.
- **In September 2002, the first-ever observed major stratospheric sudden warming occurred in the Southern Hemisphere. This early spring warming caused a drastic reduction of the ozone hole area and resulted in a less severe ozone hole.** This warming resulted from anomalously strong dynamical wave activity in the Southern Hemisphere. The Antarctic winter of 2004 was also dynamically very active and had higher ozone levels than in previous years.

GENERAL

- **Large interannual variability in polar stratospheric temperatures complicates the interpretation of temperature trends.** Previously reported estimates of temperature trends in polar regions have differed from assessment to assessment. In retrospect, it is evident that temperature trends derived over time scales of 1-2 decades, though they may appear statistically significant, are not robust because of large interannual and decadal variability in observed temperatures. Therefore, changes in reported temperature trends do not necessarily indicate systematic changes in physical or chemical processes.
- **Calculated chemical loss rates of polar ozone substantially increase in models that assume: 1) more efficient ozone destruction by reactions involving two chlorine monoxide (ClO) molecules (referred to as the ClO dimer cycle) and 2) higher concentrations of bromine.** The higher concentrations of bromine are assumed because of new evidence that natural bromocarbons play a considerable role in the stratospheric bromine budget. More efficient ozone destruction by the ClO dimer cycle is supported by analyses of the first stratospheric observations of the ClO dimer. These two changes to models improve the comparison between measured and modeled Arctic ozone loss rates that was noted in the past Assessment. These changes also improve comparison between theory and observation of the timing of ozone loss over Antarctica.
- **For the first time, measurements show unambiguously that nitric acid trihydrate (NAT) polar stratospheric cloud (PSC) particles can nucleate above the ice frost point, and there is additional evidence of their widespread occurrence.** Widespread, low-number-density NAT clouds can lead to denitrification and enhanced ozone loss. Incorporating NAT nucleation above the ice frost point into chemical transport models has improved denitrification simulations, but discrepancies in interannual variability remain, probably because the NAT nucleation mechanisms are not fully understood.

Impact of Climate Change

- **The stratospheric cooling observed during the past two decades has slowed in recent years.**
 - Satellite and radiosonde measurements reveal an overall decrease in the global-mean lower stratospheric temperature of approximately 0.5 K/decade over the 1979-2004 period, with a slowdown in the temperature decline since the late 1990s. The overall temperature decrease is punctuated by transient warmings of the stratosphere associated with the major volcanic eruptions in 1982 and 1991. Consistent with the previous Assessment, model calculations indicate that the observed ozone loss is the predominant cause of the global-mean lower stratospheric cooling observed over this period.
 - The cooling of the lower stratosphere is evident at all latitudes. The annual-mean temperature in the Arctic lower stratosphere has decreased by approximately 1 K over the 1979-2004 period. There continues to be a large interannual variability in the winter and springtime, which makes it difficult to determine reliable trends in the Arctic lower stratosphere.
 - A considerable interannual variability in the temperature of the Antarctic lower stratosphere has become evident in recent years; this has reduced the estimate of the decadal-scale cooling trend in that region from that in the previous Assessment.
 - Satellite observations show large global-mean cooling trends in the upper stratosphere (1 to 2 K/decade over 1979-2004), but there is little additional decline since the middle 1990s. The conclusion of the previous Assessment, that the observed upper stratosphere trends are due to approximately similar contributions from decreases in ozone and increases in well-mixed greenhouse gases, is reaffirmed.
- **Future increases of greenhouse gas concentrations will contribute to the average cooling in the stratosphere.** Estimates derived from climate models (AOGCMs, coupled ocean-atmosphere general circulation models) and Chemistry-Climate Models (CCMs) with interactive ozone consistently predict continued cooling of the global average stratosphere. The predicted cooling rate within the next two decades is dependent on the prescribed scenario and the type of model used for the Assessment. At 50 hPa (an altitude of about 20 km), an average of all AOGCMs gives approximately 0.1 K/decade, while CCMs predict a larger cooling of about 0.25 K/decade caused by the interactive consideration of ozone changes. All models calculate a stronger cooling at 10 hPa (about 30 km), averaging approximately 0.5 K/decade. Simulations of polar temperatures in the future are less certain than global mean temperatures because of greater interannual variability.
- **Chemical reaction rates in the atmosphere are dependent on temperature, and thus the concentration of ozone is sensitive to temperature changes.** Decreases in upper stratospheric temperature slow the rate of photochemical ozone destruction in this region. Hence the concentration of upper stratospheric ozone increases in response to cooling. Cooling of the polar lower stratosphere would lead to more efficient chlorine activation on aerosols and polar stratospheric clouds, and enhanced ozone destruction. Therefore, the concentration of ozone in the springtime polar lower stratosphere would decrease in response to cooling.

INTERACTIONS BETWEEN STRATOSPHERE AND TROPOSPHERE

- **Changes to the temperature and circulation of the stratosphere affect climate and weather in the troposphere.** Consistent evidence for this coupling comes from both observational analyses and models, but the mechanisms responsible are not well understood. The dominant tropospheric response comprises changes in the strength of the midlatitude westerlies (the prevailing winds from the west). Observations and models suggest that Antarctic ozone depletion, through its effects on the lower stratospheric vortex, has contributed to the observed strengthening of tropospheric winds and Antarctic surface cooling during December-February.

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- **Updated datasets of stratospheric water vapor concentrations now show differences in long-term behavior.** Recent trend analyses, which are based on only two available multiyear datasets, cast doubt on the positive stratospheric water vapor trend that was noted in the previous Assessment. Balloonborne water vapor measurements at Boulder, Colorado, for the period 1980-2005 show a significant increase of 5-10% per decade over altitudes of 15-28 km. Global water vapor measurements from the Halogen Occultation Experiment (HALOE) satellite instrument for 1991-2005 do not show a corresponding positive lower stratospheric trend. Interannual water vapor changes derived from HALOE data exhibit quantitative agreement with temperature variations near the tropical tropopause. In contrast, the long-term increases inferred from the Boulder data are larger than can be explained by observed tropopause temperature changes or past increases in tropospheric methane.

The Ozone Layer in the 21st Century

- **The slowing of the decline and leveling off of midlatitude upper stratospheric (35-45 km) ozone over the past 10 years has very likely been dominated by changes in equivalent effective stratospheric chlorine (EESC).** Gas-phase chemistry, modulated by changes in temperature and other gases such as methane, directly controls ozone in this region, and observed ozone increases are similar to those modeled from EESC decreases.
- **Over the past 10 years, changes in EESC have likely contributed to the slowing of midlatitude total column ozone decline and the leveling off of column ozone.** Transport also has played an important role, particularly in the lowermost stratosphere, making attribution of ozone changes to solely EESC difficult. For northern midlatitudes, increases in ozone have been greater than expected from EESC decreases alone; whereas over southern midlatitudes, ozone changes are more consistent with the range expected from EESC decreases.
- **The decline in EESC has not caused the large annual variations observed in Arctic ozone depletion.** Indeed, the onset of ozone recovery in the Arctic has not been detected. The large interannual variations driven by changes in meteorology are likely to preclude the detection of the first stage of recovery.

MODEL PROJECTIONS

Two-dimensional models and three-dimensional coupled Chemistry-Climate Models (CCMs), both of which incorporate many of the factors that affect ozone as well as their feedbacks, have been used in this Assessment to make projections of the evolution of ozone throughout the 21st century. The model projections guiding the conclusions below were based on the surface time series of halocarbons from the “Ab” scenario (baseline scenario following the Beijing Amendments) from the 2002 ozone assessment, as well as the well-mixed greenhouse gas concentrations from the Third Assessment Report of the Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis*. To focus on long-term changes, the projected ozone anomalies have been decadal smoothed.

- **The CCMs used to project future ozone abundances have been critically evaluated and more emphasis has been given to those models that best represent the processes known to strongly affect column ozone abundances.** The CCMs vary in their skill in representing different processes and characteristics of the atmosphere. However, there is sufficient agreement between the majority of the CCMs and the observations, so that some confidence can be placed in their projections.
- **Averaged over 60°S to 60°N, total column ozone is projected to increase by 1% to 2.5% between 2000 and 2020, reaching 1980 values at the same time or before EESC in that region declines to 1980 values (2040-2050). By 2100, ozone should be up to 5% above 1980 values.** Both two-dimensional models and CCMs suggest that minimum total column ozone values have already occurred in this region. Ozone exceeds pre-1980 values at the time EESC returns to 1980 values in nearly all models that include coupling between well-mixed greenhouse gases and temperature (interactive two-dimensional models and the CCMs). Similarly the elevated ozone levels in 2100 are observed in all interactive two-dimensional models and in the one CCM that extended to 2100.

- **Antarctic springtime ozone is projected to increase by 5% to 10% between 2000 and 2020, reaching 1980 values close to when Antarctic EESC decreases to 1980 values (2060-2075), and changing little thereafter.** Different diagnostic indicators of ozone depletion show different sensitivities to EESC. The most rapid change (decrease) occurs in the ozone mass deficit and the slowest change (increase) occurs in ozone minimum values and October ozone anomalies. Minimum ozone values remain roughly constant between 2000 and 2010 in many models. The projected onset of decreases in the ozone mass deficit occurs between 2000 and 2005, whereas the projected onset of increases in minimum Antarctic ozone does not occur until after 2010 in many models.
- **Arctic springtime ozone is projected to increase by 0% to 10% between 2000 and 2020, reaching 1980 values much earlier than when Arctic EESC decreases to 1980 values (2060-2070). By 2100, Arctic ozone is projected to be substantially above 1980 values.** While the large interannual variability in projected Arctic ozone obscures the date when the ozone turnaround due to decreasing EESC occurs, this is projected to occur before 2020. The increase in Arctic ozone does not follow EESC as closely as in the Antarctic, and in the majority of CCMs, Arctic ozone exceeds 1980 values before the Antarctic. There is no indication of future large decreases in Arctic column ozone in any of the model simulations. There is large uncertainty in predictions of Arctic ozone because of the smaller ozone depletion and the larger interannual variability in the Arctic stratosphere.
- **The projected ozone in 2100 is sensitive to future levels of the well-mixed greenhouse gases.** For example, expected future increases in nitrous oxide (N_2O) will increase stratospheric nitrogen oxides (NO_x), which may exacerbate ozone depletion. However, the expected stratospheric cooling induced by increasing concentrations of greenhouse gases, primarily carbon dioxide (CO_2), is expected to slow gas-phase ozone depletion reactions and, thereby, increase ozone. The net effect on ozone amounts will depend on future levels of the different well-mixed greenhouse gases. The importance of this temperature feedback is demonstrated by the non-interactive two-dimensional models, which predict that extrapolar column ozone will be less than or near 1980 values through the latter half of the century.
- **Human activities are expected to affect stratospheric ozone through changes in tropospheric emissions of trace gases.** Enhanced methane (CH_4) emission (from wetter and warmer soils) is expected to enhance ozone production in the lower stratosphere, whereas an increase in nitrous oxide emission (from extended use of artificial fertilizer) is expected to reduce ozone in the middle and high stratosphere. Also, changes in non-methane hydrocarbons and NO_x emissions are expected to affect the tropospheric concentrations of hydroxyl radical (OH) and, hence, impact the lifetimes and concentrations of stratospheric trace gases such as CH_4 and organic halogen species.
- **Future changes of stratospheric water vapor concentrations are uncertain.** If water vapor concentrations increase in the future, there will be both a radiative and a chemical effect. Modeling studies suggest increased water vapor concentrations will enhance odd hydrogen (HO_x) in the stratosphere and subsequently influence ozone depletion. Increases in water vapor in the polar regions would raise the temperature threshold for the formation of polar stratospheric clouds, potentially increasing springtime ozone depletion.

UV Radiation and Its Changes

- **Some unpolluted sites show that UV radiation has been decreasing since the late 1990s. However, at some midlatitude stations in the Northern Hemisphere, surface UV irradiance continued to increase at rates of a few percent per decade.** The observed increases and their significance depend on location, wavelength range, and the period of measurements. These increases cannot be explained solely by ozone depletion and could be attributed to a decreasing tendency in aerosol optical extinction and air pollution since the beginning of the 1990s and partly to decreasing cloudiness, as estimated from satellites.

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- **Tropospheric aerosols are responsible for the overestimation of UV irradiance from satellite instruments (e.g., TOMS, the Total Ozone Mapping Spectrometer) that use solar backscattered ultraviolet radiation to derive surface UV irradiance.** At clean sites the agreement with ground-based measurements is good. However, over more polluted locations the bias can be as large as 40%, because the lowermost atmosphere containing the absorbing aerosols is not adequately probed by the measurements. The presence of clouds and snow or ice cover can also lead to significant biases. New algorithms have been developed to improve the parameterization of aerosol, snow, and ice effects on satellite-derived surface UV irradiance, as well as of cloud effects using Advanced Very High Resolution Radiometer (AVHRR) and Meteosat images, showing on average good agreement with ground-based UV observations. Although the TOMS instrument is no longer available, the continuity of satellite-derived global UV data is maintained with the new Ozone Monitoring Instrument (OMI) onboard the Aura satellite.
- **Clouds are the major factor limiting the detectability of long-term changes in UV radiation due to ozone changes or other factors.** Even if ozone trends were linear, at least 10-15 years of measurements would be needed for detecting a trend in UV radiation. At most extrapolar locations, the effects on UV-B radiation from ozone depletion are relatively small, and the influence of clouds is dominant.
- **Air pollutants may counterbalance the UV radiation increases resulting from ozone depletion.** Observations confirm that UV-absorbing air pollutants in the lower troposphere, such as ozone, nitrogen dioxide (NO₂) and sulfur dioxide (SO₂), attenuate surface UV irradiance by up to ~20%. This effect is observed at locations near the emission sources. Air pollution exerts stronger attenuation in UV compared with attenuation in total solar irradiance.

Ozone Depletion Potentials and Global Warming Potentials

- **The effectiveness of bromine compared with chlorine for global ozone depletion (on a per-atom basis), typically referred to as α , has been re-evaluated upward from 45 to a value of 60.** The calculated values from three independent two-dimensional models range between 57 and 73, depending on the model used and depending on the assumed amount of additional bromine added to the stratosphere by very short-lived substances.
- **Ozone Depletion Potentials (ODPs) have been re-evaluated, with the most significant change being a 33% increase for bromocarbons due to the update in the estimate for the value of α .** A calculation error in the previous ozone assessment leading to a 13% overestimate for the ODP of halon-1211 has been corrected.
- **Direct and indirect Global Warming Potentials (GWPs) have been updated. The direct GWPs were revised for changes in radiative efficiencies of HFC-134a, carbon tetrafluoride (CF₄), HFC-23, HFC-32, HFC-227ea, and nitrogen trifluoride (NF₃), as well as changes in the lifetimes of trifluoromethylsulfurpentafluoride (SF₅CF₃) and methyl chloride (CH₃Cl).** In addition, the direct GWPs for all compounds are affected by slight decreases in the CO₂ absolute Global Warming Potentials for various time horizons. Indirect GWPs have been updated primarily to reflect the later return of ozone-depleting substances to 1980 levels estimated in this Assessment compared with the earlier Assessment and to account for the increased bromine efficiency factor.

IMPLICATIONS FOR POLICY FORMULATION

The results from over three decades of research have provided a progressively better understanding of the interaction of human activity and the ozone layer. New policy-relevant insights into the roles of ozone-depleting gases have been conveyed to decisionmakers through a series of international state-of-understanding assessment reports. The research findings in the *Scientific Assessment of Ozone Depletion: 2006* that are given above and are summarized here provide direct current scientific input to governmental, industrial, and other policy decisions associated with protection of the ozone layer:

- **Our basic understanding that anthropogenic ozone-depleting substances have been the principal cause of the ozone depletion over the past decades has been strengthened.**
- **The Montreal Protocol is working: There is clear evidence of a decrease in the atmospheric burden of ozone-depleting substances and some early signs of stratospheric ozone recovery. As noted earlier in this Executive Summary:**
 - Abundances of ozone-depleting substances, taken together, are clearly decreasing in the lower atmosphere. Nearly all the abundances of individual ozone-depleting substances are also decreasing.
 - There are clear indications that the equivalent effective stratospheric chlorine (which is a standardized measure of ozone-depleting capacity of bromine and chlorine in the stratosphere; see footnote in the previous section of this Executive Summary) has also started to decrease.
 - In the last decade, the depletion of the global ozone layer has not worsened.
 - Measurements from some unpolluted locations show that UV radiation has decreased since the late 1990s, in accordance with observed ozone increases at those sites.
- **The unusually small 2002 Antarctic ozone hole was characterized by a smaller area and higher ozone levels than observed during the past decade.** This was due to an unusually strong meteorological event (a “major stratospheric sudden warming”) and was not due to changes in ozone-depleting gases. The 2003 and 2005 ozone holes exhibited severe depletions as observed since the early 1990s. Severe Antarctic ozone losses will very likely continue to be observed for at least the next 10-20 years because of the expected slow decline of the long-lived ozone-depleting gases.
- **Bromine is now estimated to be approximately 60 times as effective as chlorine in global ozone depletion, on a per-atom basis.** This value is larger than the effectiveness of 45 used in the 2002 Assessment. This increase in the effectiveness of bromine increases the Ozone Depletion Potential of bromine-containing compounds, evaluated using the semi-empirical method that has been used in previous Assessments.
- **Long-term recovery of the ozone layer from the effects of ozone-depleting substances is expected to span much of the 21st century and is estimated to occur later than projected in the previous Assessment (2002).** An important milestone in the recovery process is the time when combined chlorine and bromine amounts (equivalent effective stratospheric chlorine, EESC) decline to pre-1980 values.
 - The date when equivalent effective stratospheric chlorine at midlatitudes returns to pre-1980 levels is now calculated to be 2049, for the case of global compliance with the Montreal Protocol with no significant exceptions (Scenario A1). This date is about 5 years later than projected in the previous (2002) Assessment. This projected later date primarily results from (i) an increase in CFC-11 and CFC-12 emissions due to the larger recent estimates of amounts currently contained in equipment and products (banks) and (ii) an increase in HCFC-22 emissions due to larger estimated future production, as reported in the 2005 Intergovernmental Panel on Climate Change/Technology and Economic Assessment Panel (IPCC/TEAP) Special Report on *Safeguarding the Ozone Layer and the Global Climate System: Issues Related to Hydrofluorocarbons and Perfluorocarbons*.
 - The return to pre-1980 conditions of equivalent effective stratospheric chlorine for the Antarctic vortex is projected to occur around 2065, more than 15 years later than the return of midlatitude equivalent effective stratospheric chlorine to pre-1980 levels. This projected later recovery is because, unlike in previous Assessments, we now recognize that the age of air is greater in the Antarctic lower stratosphere, which affects the amount of ozone-depleting gases available for ozone depletion. The equivalent effective stratospheric chlorine evaluation for the Antarctic vortex has not been presented in previous Ozone Assessments.

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- Potential options for accelerating the recovery of the ozone layer have been evaluated.** The table provided below shows hypothetical estimates of the *upper limits* of improvements that could be achieved if global anthropogenic *production* of ozone-depleting substances were to stop after 2006, if emissions were eliminated from existing banks at the end of 2006, or if global anthropogenic *emissions* of ozone-depleting substances were to stop after 2006. Some options show greater effectiveness for accelerating recovery of the ozone layer than in previous Assessments, for reasons noted below.

Table 1. Percentage reductions in integrated equivalent effective stratospheric chlorine relative to the baseline (A1) scenario that can be achieved in the hypothetical cases.¹

Compound or Compound Group	Column A: All Emissions Eliminated from Production after 2006	Column B: All Emissions Eliminated from Existing Banks at End of 2006	Column C: All Emissions Eliminated after 2006
Chlorofluorocarbons (CFCs)	0.3	11	11
Halons	0.5	14	14
Carbon tetrachloride (CCl ₄)	3	(a)	3
Methyl chloroform (CH ₃ CCl ₃)	0.2	(a)	0.2
Hydrochlorofluorocarbons (HCFCs)	12	4	16
Methyl bromide (CH ₃ Br) (anthropogenic)	5	(a)	5

¹ Column A corresponds to a hypothetical elimination of all emissions from production after 2006. Column B corresponds to a hypothetical elimination of all emissions from banks existing at the end of 2006 (for example, capture and destruction). Column C corresponds to a hypothetical elimination of all emissions after 2006 and is approximately equal to the sum of columns A and B.

(a) For these compounds, banks are uncertain and therefore emissions are equated to production in these calculations.

- The percentage cumulative (integrated) reductions in equivalent effective stratospheric chlorine for halons and CFCs, integrated from 2007 until the 1980 level is reattained (shown in Column B), are larger than previously reported. This is because recent bank estimates from the 2005 Intergovernmental Panel on Climate Change/Technology and Economic Assessment Panel (IPCC/TEAP) Special Report on *Safeguarding the Ozone Layer and the Global Climate System: Issues Related to Hydrofluorocarbons and Perfluorocarbons* are significantly larger and likely more reliable than values presented in previous Assessments for CFC-11, CFC-12, and halon-1211.
- The percentage reduction in integrated equivalent effective stratospheric chlorine for HCFCs shown in Column A is larger than previously reported. This is because of significantly larger estimates of future HCFC-22 production in Article-5 countries.
- The percentage reduction in integrated equivalent effective stratospheric chlorine for methyl bromide in Column A is larger than previously reported. This is because of the upward revision of the fraction of anthropogenic emissions relative to total methyl bromide emissions, as well as being due to the upward revision in the ozone-depletion effectiveness of bromine atoms compared with chlorine atoms mentioned earlier.
- In addition to the percentage reductions in integrated equivalent effective stratospheric chlorine, these scenarios can reduce the time for equivalent effective stratospheric chlorine to drop below 1980 values. A hypothetical elimination of all emissions of ozone-depleting substances after 2006 (Column C) would advance this time by about 15 years, from 2049 to 2034. A hypothetical elimination of all emissions from production of ozone-depleting substances after 2006 (Column A) would advance it by about 6 years, to 2043.

- A methyl bromide phase-out has been in effect since 2005 in developed countries, with critical-use exemptions granted in 2005 and 2006 at levels that are 30-40% of the 2003-2004 production levels. Two additional hypothetical cases of critical and quarantine and pre-shipment (QPS) exempted uses of methyl bromide were considered. In the analysis of both cases, equivalent effective stratospheric chlorine is integrated above the 1980 level from 2007 until it returns to the 1980 level. The size of the critical use exemptions is similar to the estimated use of methyl bromide for QPS use.
 - > If critical-use methyl bromide exemptions continue indefinitely at the 2006 level compared to a cessation of these exemptions in 2010 or 2015, midlatitude integrated equivalent effective stratospheric chlorine would increase by 4.7% or 4.0%, respectively.
 - > If production of methyl bromide for QPS use were to continue at present levels and cease in 2015, midlatitude integrated equivalent effective stratospheric chlorine would decrease by 3.2% compared with the case of continued production at present levels.
- **Failure to comply with the Montreal Protocol would delay, or could even prevent, recovery of the ozone layer.** Emissions associated with continued or expanded exemptions, QPS, process agents, and feedstocks may also delay recovery.
- **The role of very short-lived halogenated substances in stratospheric ozone depletion is now believed to be of greater importance than previously assessed.** This suggests that significant anthropogenic production of such substances could enhance ozone depletion. Current understanding of the Ozone Depletion Potentials of these classes of substances is:
 - The Ozone Depletion Potentials of n-propyl bromide are 0.1 for tropical emissions and 0.02-0.03 for emissions restricted to northern midlatitudes. These are unchanged from the previous Assessment.
 - New analyses suggest upper-limit Ozone Depletion Potentials for CF₃I of 0.018 for tropical emissions and 0.011 for midlatitude emissions. The previous Assessment had an upper limit of 0.008.
 - Any chlorinated very short-lived source gas with a lifetime of ~25 days, one chlorine atom, and a similar molecular weight to CFC-11, has an Ozone Depletion Potential of about 0.003.
- **Understanding the interconnections between ozone depletion and climate change is crucial for projections of future ozone abundances.** The ozone-depleting substances and many of their substitutes are also greenhouse gases; changes in ozone affect climate; and changes in climate affect ozone. These issues were recently the subject of the IPCC/TEAP 2005 Special Report on *Safeguarding the Ozone Layer and the Global Climate System: Issues Related to Hydrofluorocarbons and Perfluorocarbons*, and some aspects of the coupling between ozone depletion and climate change have been considered in this 2006 Ozone Assessment. An important development has been the emerging use of three-dimensional models that incorporate the interaction between chemistry and climate.