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SCIENTIFIC ASSESSMENT OF OZONE DEPLETION: 2010

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
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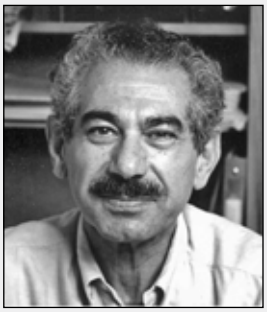
Remembrances

It is with sadness that we note the passing of the following scientists who have played leading roles in the international scientific assessments of the ozone layer.

Derek Cunnold (1940–2009). Derek Martin Cunnold was born July 10, 1940, in Reading, England. He received his B.A. and M.A. from St. John's College in Cambridge, England, and his Ph.D. in Electrical Engineering from Cornell University in 1965. He was a Professor Emeritus at the Georgia Institute of Technology at the time of his death. He was an author and/or contributor in all of the Ozone Assessments since 1988, and was a Lead Author of Chapter 1 ("Long-Lived Compounds") of the 2006 Assessment.

David Hofmann (1937–2009). David J. Hofmann was born January 3, 1937. He received his Ph.D. in Physics from the University of Minnesota in 1965. He was a scientist at the University of Wyoming for 25 years and then in NOAA for 17 years, directing the Global Monitoring Division of NOAA's Earth System Research Laboratory for a decade. Over a period of 30 years, he traveled to Antarctica 19 times for research and as director of NOAA's South Pole Station. He was a reviewer for four Ozone Assessments and Lead Author of Chapter 12 ("Predicting Future Ozone Changes and Detection of Recovery") of the 1998 Assessment.



Julius London (1917–2009). Julius London was born on March 26, 1917, in Newark, New Jersey. He received his Ph.D. in Meteorology and Oceanography from New York University in 1951. After working for several years at NYU, he moved to the University of Colorado in 1961 and remained there for his entire career, chairing the Department of Astro-Geophysics from 1966 to 1969. He was an author in NASA and WMO Assessments that predated the Montreal Protocol, including leading the chapter on "Long Period Changes in Stratospheric Parameters" in the 1979 Assessment, *The Stratosphere: Present and Future*, and chairing the Trends working group of the chapter on "Model Predictions and Trend Analysis" in the 1981 Assessment, *The Stratosphere 1981: Theory and Measurements*.

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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 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 prepared, about every 3-4 years, 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 2010 report is the latest in a series of eleven 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). This report is the seventh 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 Adjustment 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 Adjustment and Amendment	
1994		*Scientific Assessment of Ozone Depletion: 1994*. WMO No. 37.
1995	Vienna Adjustment	
1997	Montreal Adjustment and Amendment	
1998		*Scientific Assessment of Ozone Depletion: 1998*. WMO No. 44.

1999	Beijing Adjustment and Amendment	
2002		*Scientific Assessment of Ozone Depletion: 2002*. WMO No. 47.
2006		*Scientific Assessment of Ozone Depletion: 2006*. WMO No. 50.
2007	Montreal Adjustment	
2010		*Scientific Assessment of Ozone Depletion: 2010*. WMO No. 52.
2011	23rd Meeting of the Parties	

The Current Information Needs of the Parties

The genesis of *Scientific Assessment of Ozone Depletion: 2010* occurred at the 19th Meeting of the Parties to the Montreal Protocol in Montreal, Canada, at which the scope of the scientific needs of the Parties was defined in their Decision XIX/20 (4), which stated that "…for the 2010 report, the Scientific Assessment Panel should consider issues including:

(a) Assessment of the state of the ozone layer and its future evolution;

(b) Evaluation of the Antarctic ozone hole and Arctic ozone depletion and the predicted changes in these phenomena;

(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 and the likely implications for the state of the ozone layer;

(d) Assessment of the interaction between climate change and changes on the ozone-layer;

(e) Assessment of the interaction between tropospheric and stratospheric ozone;

(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 into account among other things the expected impacts of climate change;

(g) Assessment of consistent approaches to evaluating the impact of very short-lived substances, including potential replacements, on the ozone layer;

(h) Identification and reporting, as appropriate, on any other threats to the ozone layer…"

The 2010 assessment has addressed all the issues that were feasible to address to the best possible extent.

The Assessment Process

The formal planning of the current assessment was started early in 2009. The Cochairs considered suggestions from the Parties regarding experts from their countries who could participate in the process. Furthermore, an ad hoc international scientific advisory group also suggested participants from the world scientific community. In addition, this advisory 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 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 2010 assessment is contained in five chapters associated with ozone-layer topics, which are preceded by a Prologue:

Prologue. State of the Science through the 2006 WMO/UNEP Assessment
Chapter 1. Ozone-Depleting Substances (ODSs) and Related Chemicals
Chapter 2. Stratospheric Ozone and Surface Ultraviolet Radiation
Chapter 3. Future Ozone and Its Impact on Surface UV
Chapter 4. Stratospheric Changes and Climate
Chapter 5. A Focus on Information and Options for Policymakers

The initial plans for the chapters of the 2010 Scientific Assessment Panel's report were examined at a meeting that occurred on 24–25 June 2009 in London, England. The Coordinating Lead Authors and Cochairs 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 17–19 November 2009 in Fairfax, Virginia, United States, at which the Coordinating 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 122 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 28 June–2 July 2010, 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 web site on 16 September 2010) was prepared and completed by the attendees of the Les Diablerets meeting. A small science advisory group assisted the Cochairs during those Les Diablerets discussions of the Executive Summary, and also helped with advance preparations during a meeting in Toronto on 17–18 May 2010.

The 2010 State-of-Understanding Report

In addition to the scientific chapters and the Executive Summary, the assessment also updates the 2006 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 and published separately in a companion booklet to 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: 2010* is the product of 312 scientists from 39 countries of the developed and developing world who contributed to its preparation and review[1] (191 scientists prepared the report and 196 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 Argentina, Australia, Belgium, Benin, Canada, Chile, Comores, Costa Rica, Czech Republic, Denmark, Egypt, Estonia, Finland, France, Germany, Greece, Hungary, India, Indonesia, Iran, Italy, Japan, Kenya, Malaysia, Mexico, New Zealand, Norway, Poland, Russia, Saudi Arabia, South Africa, Spain, Sweden, Switzerland, The Netherlands, The People's Republic of China, Togo, United Kingdom, and United States of America.

PROLOGUE

PROLOGUE: STATE OF THE SCIENCE THROUGH THE 2006 WMO/UNEP ASSESSMENT

A.R. Ravishankara, Paul A. Newman, John A. Pyle, and Ayité-Lô Ajavon

Scientists have known for many decades that the stratospheric ozone layer screens harmful ultraviolet radiation (UV) from the Earth's surface. Therefore, it has also been known that the ozone layer protects against adverse effects on humans (e.g., skin cancer and cataracts), the biosphere (e.g., inhibiting plant growth and damaging ecosystems), and physical infrastructure of the modern era (e.g., degradation of materials). In the early 1970s, scientists recognized that human actions could deplete this protective layer in connection with nitrogen oxide emissions from a proposed fleet of supersonic aircraft flying in the stratosphere. Around that time, it was shown that human-produced chlorofluorocarbons (CFCs) that had been manufactured (and emitted to the atmosphere) had remained in the atmosphere because of their stability. Soon afterward, scientists warned that these CFCs that are stable in the lower atmosphere would get to the stratosphere, where they could deplete the ozone layer. They also warned that the depletion would be large if CFC emissions continued unabated. Various national and international assessments that estimated the impact of CFCs on the ozone layer were carried out. For example, using the then-state-of-the-art models of the atmosphere, a 1981 Assessment sponsored by the World Meteorological Organization (WMO) and agencies of the United States of America estimated that up to ~15% of the column ozone would be depleted by the middle of the 21st century if the CFC emissions went unabated at 1974 emission levels under certain assumptions about other emissions and changes (WMO, 1982). Studies also predicted a decrease in ozone of 5–10% if a fleet of 500 supersonic aircraft emitting nitrogen oxides were to fly routinely in the stratosphere.

In 1985, massive ozone losses in measured column abundances during the Antarctic spring (the ozone hole) were reported and CFCs were implicated for the loss. Extensive research efforts showed that CFCs and other ozone-depleting substances (ODSs) containing chlorine and bromine were the cause. Further, measured global ozone abundances showed a decrease between 0.5% and 1.5% by 1980. Thus, ozone depletion was not just a phenomenon expected by the middle of the 21st century, but was already occurring. As a result of these findings on ozone depletion, stratospheric science rapidly evolved during the latter part of the 20th century, allowing understanding, diagnosis, and prediction of the evolution of the ozone layer; these rapid scientific developments provided a sound basis for the critical policy decisions that followed.

Faced with the potential impact of human-produced long-lived halogenated chemicals on stratospheric ozone, the Vienna Convention for the Protection of the Ozone Layer was enacted in 1985 to protect human health and the environment against adverse effects resulting from modification of the ozone layer. The recognition that CFC use was increasing, and scientific evidence that this increase would cause large ozone depletions, led in 1987 to the Montreal Protocol on Substances that Deplete the Ozone Layer, a protocol that regulated and slowed the production of designated ODSs. As new scientific knowledge became available over the next two decades, the Protocol has been amended and adjusted to provide additional protection for the ozone layer. The Montreal Protocol is now more than 20 years old and has been ratified by all of the world's nations.

The Montreal Protocol, at its inception, established three expert panels—the Scientific Assessment Panel (SAP), the Environmental Effects Assessment Panel (EEAP), and the Technology and Economic Assessment Panel (TEAP). These panels provide the basis for science-based decision making via periodic assessment reports. The SAP's primary focus is to provide an assessment of ozone layer science, including information about the abundances and emissions of ozone-depleting substances, ultraviolet radiation changes, along with additional information concerning policy options for consideration by the Parties to the Protocol. In addition, the SAP reports also aid other customers: various nations, by providing information needed for their decision making; industry, by providing a basis for technology choices; the broad science community, the EEAP, and the TEAP, with the latest information about the ozone layer science; the ozone research community, with information on the current science and gaps in knowledge; and the general public, including students and educators, with key information about this complex issue. The "Twenty Questions and Answers About the Ozone Layer" and its predecessors, which are companions to the SAP assessment reports, also help by providing clear, easy-to-understand communication of the ozone layer issues to the Parties and the general public. Further, every four years, the

Cochairs of the three Assessment Panels compile a Synthesis Report based on the findings of their individual Assessment reports. These Assessments—individual Assessments and the Synthesis Report—together provide the latest information to the Parties to the Protocol.

Over the past two decades, the ozone depletion assessments have provided information updates roughly every four years and have been interspersed with a few brief reports on special topics that addressed urgent needs of the Parties to the Protocol. As knowledge of ozone layer science has increased, the assessments have built a vast amount of knowledge. Now, the SAP is addressing some key remaining issues regarding the ozone layer and its future development. They include the following:

- First, the Protocol has regulated human-produced ozone-depleting substances, resulting in the reduction of their abundances in the atmosphere. This effort has brought ozone depletion science into a period of accountability. The crucial questions now have become: Does the Montreal Protocol continue to work as envisioned? Were the specific actions effective in meeting the Protocol's goals? Are the goals of the Vienna Convention also being met? How important are additional actions in returning ozone to its natural level? When will ozone levels return to preindustrial values? When will ozone levels return to the levels seen in 1980, a level that has become a benchmark for policymakers and the public? When will the ozone hole disappear? As ozone levels increase, will we observe decreases in surface ultraviolet radiation? What is our level of understanding of the workings of the stratosphere and how confident are we in our predictions for the future?
- Second, since the ozone layer is an integral part of the Earth system, other important questions have emerged: What is the influence of climate change on the stratospheric ozone layer and its future development? Specifically, how will the cooling of the stratosphere due to anthropogenic carbon dioxide (CO_2) increases and the warming of the troposphere due to the increasing abundance of greenhouse gases influence the stratospheric ozone layer? How can we disentangle the influences of climate change on stratospheric ozone levels from to the influences of ozone-depleting substances?
- Third, the changes in stratospheric ozone are but one component of stratospheric climate change, and this poses questions such as: What are the effects of changes in stratospheric climate on the global-climate system? In addition, how will decreasing concentrations of ODSs impact climate?
- Fourth, ODSs and many substitutes for the ODSs are also potent greenhouse gases. Therefore, as ODSs are phased out and new chemicals take their place, questions emerge on the suitability of the replacements. They include: How will they impact the ozone layer? Do they have appreciable effects on climate? Do they have any other unwanted effects on the environment?

The SAP's goal is to provide clear scientific answers to these questions. These questions provide the major thrust of the research in this area and are at the center of the current Assessment.

This current document provides the latest assessment of the science of the ozone layer. Below, we very briefly summarize our understanding of the science going into this Assessment. We summarize the findings of the most recent previous report of 2006 and note the key issues for the present Assessment.

Ozone-Depleting Substances (ODSs)

Emissions of ODSs were increasing at a substantial rate before the Montreal Protocol was enacted in 1987. As a result of the Protocol, emissions of most of the major ODSs—the chlorofluorocarbons (CFCs) and methyl chloroform (CH_3CCl_3)—began decreasing soon thereafter. Because of the long lifetimes of CFCs, their atmospheric abundances continued to increase in the early 1990s even as their emissions were decreasing. However the abundance of the short-lived methyl chloroform responded quickly, as expected, and started to decrease in the atmosphere. Originally, some of the CFC replacements were the so-called transition substitutes (hydrochlorofluorocarbons, HCFCs); they contained chlorine but were shorter lived than the CFCs they replaced. This substitution led to a lower accumulation of the HCFCs and a smaller fraction of their emissions being transported to the stratosphere. Subsequently, the HCFCs were also selected for phase-out, and non-chlorine containing substitutes are now being phased in. Because of these changes, the sum of the abundances of chlorine and bromine ODS species in the troposphere, as measured by equivalent chlorine (ECl), reached a peak in the 1994–1995 time period and has continued to decrease thereafter. The majority of the decrease in the ECl is attributed to the rapid decline of emissions of the short-lived methyl chloroform and, to a lesser extent, methyl bromide.

Prologue Box 1. A Clarification of the Lexicon: Ozone Destruction, Ozone Depletion, Ozone-Depleting Substances, and Montreal Gases

Ozone Destruction and Ozone Depletion

The abundance of ozone at a particular point in the stratosphere, the column abundance of ozone above a given geographical location, and the total amount of ozone in the stratosphere are controlled by a combination of production, destruction, and transport (of ozone and other chemicals into and out of the region of interest). The major mechanism for the production of ozone in the stratosphere is the breaking up of molecular oxygen (O_2) by solar UV of wavelengths less than 242 nanometers (photolysis) to make oxygen atoms (O), followed by the reaction of oxygen atoms with molecular oxygen to make ozone. The destruction of ozone occurs via the reactions of oxygen atoms (O) with ozone (O_3) (the Chapman Mechanism), as well as through cyclic chemical reactions involving naturally occurring species such the odd-hydrogen radicals (HO_x: OH and HO_2), nitrogen oxide radicals (NO_x: mostly NO and NO_2), and/or halogen radicals. The radicals are produced in the stratosphere by photolysis and oxidation of source gases (N_2O, H_2O, CH_4, and a variety of chlorine- and bromine-containing compounds). In the absence of interference from the human emissions influencing the abundance of catalysts, there is a natural balance and this balance determines the ozone abundance in a location, the column amount over a region, and the total amount of ozone in the stratosphere. The natural amounts vary on a variety of timescales: daily variations in the ozone column are driven by meteorological variability ("weather"); seasonal variations are driven by changes in stratospheric temperature and winds; multiannual variations are driven by changes in solar input, by natural variations in the emissions of the source gases, and by interannual variability in stratospheric winds.

The natural abundance of stratospheric ozone can be changed by human influence. This change can be brought about by changes in production, destruction, and transport. The ozone abundance arises from a balance between these terms. Human emissions, for the most part, have led to an enhancement in the destruction term, shifting the balance to lower ozone abundance. Thus, any human emission of chemicals (gases or particles) that contributes to the enhancement of the ozone destruction term in the balance leads to a lowering of ozone, i.e., ozone layer depletion, and is evidenced by changes in the amount at a location, in the column amount above a location, or the total amount in the stratosphere. Because the destruction occurs through catalytic cycles that regenerate the ozone-destroying radicals multiple times, small changes in the source gases (and hence in radical concentrations) can have a large impact on ozone.

Ozone-Depleting Substances and Montreal Gases

If there is an increase in concentrations of any of these source gases that contribute nitrogen, hydrogen, or halogen radicals to the stratosphere, there will be an increase in ozone-destroying radicals and hence in stratospheric ozone destruction. Changes in the sources gases could occur either naturally (e.g., by biogenic processes at the surface) or anthropogenically (by increased industrial emissions); some source gases are emitted both naturally and anthropogenically. The response of the stratosphere does not depend on whether the changes are natural or anthropogenic; the stratosphere does not "care." However, scientists and policymakers do care and in some circumstances it is useful to have a terminology that distinguishes the different origins of the source compounds. Therefore, ozone-depleting substances (ODSs) are those whose emissions come from human activities.

It will be important in the Assessment also to consider specifically gases that have been regulated (and which traditionally we have called ODSs). Thus, the Montreal Protocol has controlled the production (and hence their emissions into the atmosphere) of certain chemicals that are listed as controlled substances in Annexes A, B, C, and E of the Protocol. **We will continue to call the controlled substances of the Montreal Protocol as ozone-depleting substances, or ODSs for short.** This definition keeps the continuity in usage and will be clear to the Parties to the Montreal Protocol.

The above description yields a few key points. First, the ozone abundance can be changed not only by destruction but also via influence on production, transport, and stratospheric climate. There are long-standing examples of such production enhancements by hydrocarbons, in particular methane, via what is usually called smog chemistry (i.e., the chemistry that leads to the tropospheric pollutant ozone production). Second, ozone abundances can be changed by both changes in the concentrations of active agents, as well as by changes in the rates at which these chemical reactions occur. The most noteworthy way is by changes in the stratospheric climate (i.e., temperature), such as that caused by the enhancements in carbon dioxide in the atmosphere. Third, the ozone abundance can be influenced by changes in transport, such as that arising from a changing climate. And fourth, while the Montreal Protocol controls many substances that deplete ozone, not all such substances are currently controlled and, for clarity, they are not called ODSs here. Reference to such substances are clearly noted in this Assessment.

The tropospheric abundance of ECl by the end of 2005 was shown in the previous Assessment to have decreased to roughly 92% of its maximum value seen during the period between 1992 and 1994 (i.e., about a 8% decline in roughly 14 years); these values will be updated in this report.

Balloon, aircraft, and satellite observations, and the interpretation of those observational data, show clearly that stratospheric abundances of chlorine and bromine are also decreasing. The vertical and temporal variations of the ODS species are generally consistent with our understanding of atmospheric dynamics and stratospheric chemical processes, though there are some quantitative differences between observations and calculations. Improvements in quantification of these variations are expected. These improvements will enable an even better definition of the stratospheric distribution and trends of the ODSs as well as their degradation products, which will enable a better quantification of their individual role in ozone layer depletion.

The CFCs, as well as some halons (which are sources of bromine to the stratosphere), have lifetimes ranging from several decades to a few centuries. Hence, the decline of stratospheric chlorine and bromine levels to values observed before 1980 will take decades.

As noted above, CFCs have been replaced by non-ozone depleting technologies, by substitutes that deplete less ozone (e.g., hydrochlorofluorocarbons or HCFCs), and by non-ozone depleting substances (e.g., hydrofluorocarbons or HFCs). The atmospheric levels of these less-depleting and non-depleting substitutes have grown rapidly over the last decade. HCFCs typically have shorter atmospheric lifetimes and lower Global Warming Potentials (GWPs) than CFCs, but HFC substitutes for HCFCs typically have comparable, and in a few cases even longer, atmospheric lifetimes and comparable or larger GWPs; but they have Ozone Depletion Potential (ODP) values of essentially zero. The increases observed for HCFCs and HFCs reflect their widespread use as ODS replacements and our understanding of their atmospheric lifetimes.

Global Stratospheric Ozone and Its Temporal and Spatial Trends

Global atmospheric column ozone amounts decreased over the decades from the 1970s to the 1990s, with a decrease amounting to 3.5% between average 1964–1980 and 2002–2005 values. Springtime Antarctic ozone levels slowly decreased in the 1970s and exhibited rapid decreases in the 1980s and early 1990s. In the 14–20 km layer of the Antarctic stratosphere, where most of the ozone resides, virtually all of the ozone is now destroyed every year in the late August to early October period. Large Arctic ozone depletions have also been observed in the spring in some years during the last two decades, but Arctic ozone depletion is modulated strongly by variability in atmospheric dynamics, transport, and temperature. The very high levels of chlorine and bromine from ODSs directly cause the observed large polar ozone depletions (both over the Antarctic and the Arctic).

Atmospheric ozone levels (often measured as a column amount) exhibit well-known and understood variations in space and time. Ozone amounts are influenced not only by the concentrations of ODSs but also by atmospheric transport (winds), incoming solar radiation, aerosols (fine particles suspended in the air), and other natural compounds. Given natural variability, methods used to measure stratospheric ozone must be consistent and very stable over decades if they are to be used to detect the changes expected over these long periods due to the changes in ODS abundances. Based on observations from ground-based instruments and satellites, it is clear that global ozone levels reached a minimum in the mid-1990s. Since then the levels have not decreased further nor have they increased substantially. Similarly, the Antarctic ozone hole continues to be no worse than in the mid-1990s but there also has been no discernible improvement, consistent with predictions from previous assessments. Both annual global ozone and the springtime Antarctic ozone levels continue to vary from year to year because of meteorological variability. There is no discernible ozone depletion over the tropics outside of the natural background variations. Vertically, ozone depletion is most evident in the lower and upper stratosphere, with minimal changes in the mid-stratosphere.

In the last few decades, ozone levels in the stratosphere have responded to volcanic eruptions that have injected large amounts of sulfur dioxide into the stratosphere, which then forms sulfate aerosols in this region. These sulfate aerosols enhance the ozone depletion by chlorine from ODSs. The very large ozone depletions induced by the presence of aerosols following the eruptions of Mt. Pinatubo (1991) and El Chichón (1982) are very clearly seen in the records in the Northern Hemisphere. The influence of these eruptions persisted for several years. As the stratosphere recovered from the volcanic emissions, there were corresponding changes in ozone. The ozone response depends on the effective abundances of chlorine and bromine in the stratosphere. Thus, response to future volcanic eruptions will likely be smaller because

chlorine/bromine concentrations will be smaller (see Figure P-1). The mechanisms for these changes are qualitatively understood, but some uncertainties remain in their quantification.

The observed levels of ozone described above and the vertical, latitudinal, and seasonal structure of their temporal trends, as well as the spatial and temporal variability, are consistent with our combined understanding of the atmospheric motions (transport), the chemistry, and the level of ODSs in the atmosphere. Even though some details of chemical and dynamical processes are uncertain, atmospheric models have been largely successful in reproducing observed ozone levels and their temporal and spatial variations. The link between ODSs and ozone depletion was clearly established in the 1989 Ozone Assessment (WMO, 1991) and that conclusion has only been strengthened since then.

Surface UV Changes

Ultraviolet radiation (UV) from the Sun is divided into wavelength bands. UV-B is the band that leads to serious medical problems. Fortunately, the majority of the UV-B is absorbed by ozone. The surface UV-B and UV-A levels (expressed as the UV Index) are directly related to the amount of overhead ozone. Other factors such as clouds, aerosols, ground reflectivity, and other tropospheric pollutants also influence surface UV-B. The data outside of the polar regions shows that, consistent with the observed small ozone depletion, there have not been large increases in surface UV-B over the last few decades. The relatively small increases of surface UV-B in the midlatitudes, which are expected based on the observed ozone decline, are responsible for small changes in the UV background level, which are superposed by other strong effects, such as changes in cloudiness. However, since medical impacts are UV-dose related, the UV changes due to ozone depletion are nonetheless important. In contrast, over Antarctica, and on occasion in other parts of the high latitudes in the Southern Hemisphere, large increases in UV-B have been seen; they are clearly associated with the ozone hole or the remnants of the ozone hole passing over the measurement sites.

The changes in UV-B levels are consistent with our understanding of UV transmission and the other factors that influence UV-B at the surface.

Factors that Influence Stratospheric Ozone and Its Future

The change in the atmospheric ODS concentrations is the most important factor in the ozone layer changes that have occurred over the past half a century and also in the predicted return of the ozone layer to levels that existed prior to 1980. However, many other aspects of the Earth system are also changing. These include changes in climate and tropospheric composition.

Climate change influences the stratosphere in many ways. The primary influence is a cooling of the mid- to upper stratosphere due to increases in carbon dioxide (CO_2) via radiation to space, which is a well-understood process. This cooling has been clearly seen in measured temperatures. The cooling influences the ozone loss rates in the stratosphere—increasing it in the lower stratosphere and decreasing it in upper stratosphere. At the same time the warming in the troposphere accelerates processes of ozone formation. Further, climate change has an effect on transport between the stratosphere and the troposphere and within the stratosphere, and in turn, climate will influence the recovery of ozone layer from the effects of ODSs.

Tropospheric changes also influence stratospheric ozone levels. For example, an increased abundance of methane (CH_4) in the troposphere will result in more methane being transported to the stratosphere, where methane interacts with chlorine compounds, converting active chlorine that destroys ozone to inactive hydrogen chloride (HCl) that does not destroy ozone. Changes in methane also lead to changes in water vapor in the stratosphere, with important consequences. Similarly, changes in nitrous oxide (N_2O) also influence ozone destruction. Other tropospheric changes of interest include processes leading to increases in sulfur in the stratosphere. In some cases, changes of these tropospheric processes may be related to climate change. For instance, climate change may affect biogeochemical cycles and cause an increase in tropospheric concentrations of certain species as well as the transport rate between the troposphere and the stratosphere. The latter may be particularly important for the very short-lived species.

The timeline of the ozone evolution from the pre-ODS era to roughly 2100 was presented in the 2006 Assessment to facilitate discussion on recognition and attribution of the recovery of the ozone layer. This approach provided a pathway for interim conclusions on this issue, but many issues remained unresolved. They include: How should recovery be defined? What time period is appropriate as a baseline against which we can measure recovery? How do we separate ozone changes

due to ODSs from those due to changes in climate and tropospheric composition? How do we describe and attribute future changes in levels of ozone? Given the natural variability, at which point will one be confident of the recovery from ODS effects? This Assessment addresses some of these issues and concepts (see Prologue Box 2 on Recovery Issues).

Influence of Stratospheric Ozone and ODS Changes on Climate

As noted above, increases in CO_2 in the atmosphere have led to a clear decrease in upper stratospheric temperature. This temperature trend is a very clear signature of the radiative influence of increasing CO_2 abundances. Changes in the stratosphere—be it the temperature decrease due to CO_2 increases or ozone layer depletion due to ODSs—are an integral part of the changes to the Earth system. Further, these changes in the stratosphere influence what happens at the surface. Therefore, the influence of stratospheric changes on surface climate is an important issue.

Ozone is a greenhouse gas that greatly influences the Earth's energy budget. Therefore, ozone changes—depletion in the stratosphere due to ODSs, recovery from the depleted state as ODSs decline, and tropospheric ozone changes—also influence climate. Further, many of these ODSs that deplete the ozone layer are also greenhouse gases. Consequently, they influenced Earth's climate in the past as their abundances increased and will continue to do so, albeit to a lesser extent, as their abundances decrease in response to compliance with the Montreal Protocol. Furthermore, many of the substitutes for CFCs and HCFCs are also potent greenhouse gases and their contribution to climate change will depend on the their potency for warming and their emission rates.

These are some of the emerging issues that have been covered only briefly in the past due to a primary focus on ozone depletion issues. As research on the influence of stratospheric changes on the overall climate has emerged, the current Assessment is devoting more attention to this topic.

Major Findings of the Previous Assessment in 2006

The major findings of the 2010 Assessment are given in the Executive Summary that follows this Prologue. To place these findings in context and show the changes in our knowledge over the past four years, we provide below the summary of the 2006 Assessment (WMO, 2007). Further, for ease of comparison, the findings from the 2006 Assessment are grouped according to where they are covered in the 2010 Assessment; i.e., the 2006 Assessment is mapped on to the 2010 Assessment's structure.

A major finding of the previous Assessment in 2006, the tenth in a series of Assessments dating back to 1981, was that the Montreal Protocol was working as intended. Some specific findings of the 2006 Assessment are summarized in the schematic shown as Figure P-1.

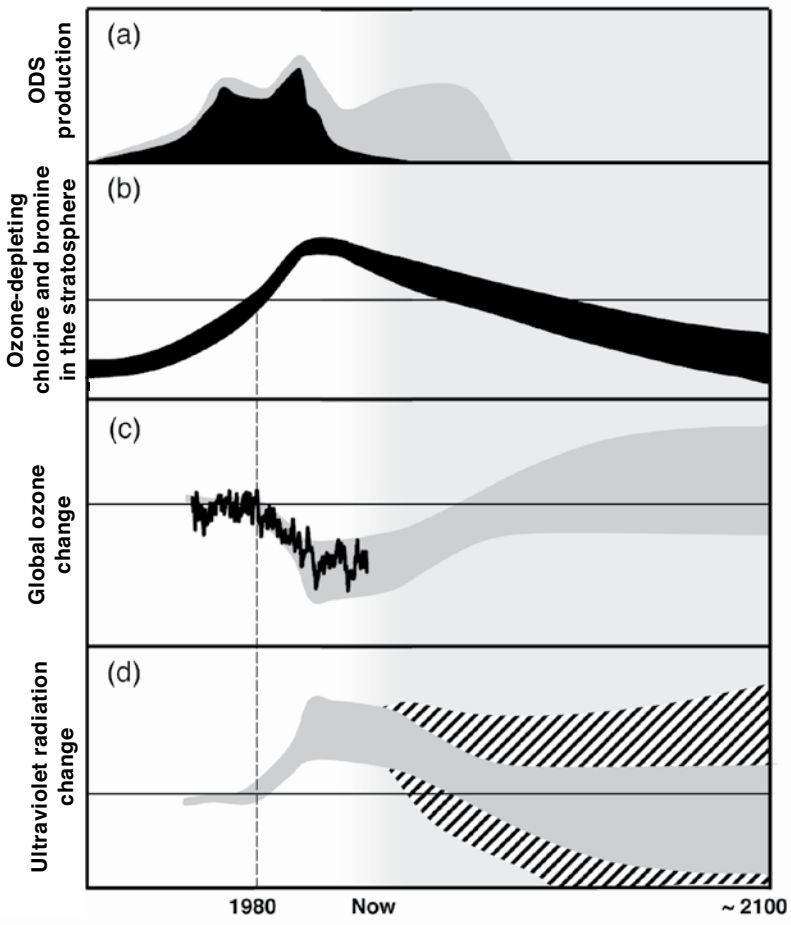
The high-level findings of the previous Assessment (WMO, 2007) include the following.

Findings of the 2006 Assessment that are related to "Ozone-Depleting Substances (ODSs) and Related Chemicals" covered in ***Chapter 1 of the 2010 Assessment***:

1. 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.
2. The combined stratospheric abundances of the ozone-depleting gases show a downward trend from their peak values of the 1990s, which is consistent with surface observations of these gases and a time lag for transport to the stratosphere.
3. Our quantitative understanding of how halogenated very short-lived substances contribute to halogen levels in the stratosphere has improved significantly since the 2002 Assessment (WMO, 2003), with brominated very short-lived substances believed to make a significant contribution to total stratospheric bromine and its effect on stratospheric ozone.

Findings of the 2006 Assessment that are related to "Stratospheric Ozone and Surface Ultraviolet Radiation" in the past and our understanding of its changes covered in ***Chapter 2 of the 2010 Assessment***:

1. 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.



[Figure reproduced from the 2006 Ozone Assessment (WMO, 2007).]

Figure P-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).

2. 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.
3. The decline in abundances of extrapolar stratospheric ozone seen in the 1990s has not continued.
4. Observations together with model studies suggest that the essentially unchanged column ozone abundances averaged over 60°S–60°N over roughly the 1995–2005 period are related to the near constancy of stratospheric ozone-depleting gases during this period.
5. Measurements from some stations in unpolluted locations indicate that UV irradiance (radiation levels) has been decreasing since the late 1990s. 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.
6. In polar regions, high UV irradiances lasting for a few days have been observed in association with episodes of low total ozone.

Findings of the 2006 Assessment that are related to "Future Ozone and Its Impact on Surface UV" covered in ***Chapter 3 of the 2010 Assessment***:

1. 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.

2. 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.
3. 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.
4. Large ozone losses will likely continue to occur in cold Arctic winters during the next 15 years.
5. Chemical reaction rates in the atmosphere are dependent on temperature, and thus the concentration of ozone is sensitive to temperature changes caused by climate change.

Findings of the 2006 Assessment that are related to the influence of "Stratospheric Changes and Climate" covered in ***Chapter 4 of the 2010 Assessment***:

1. The stratospheric cooling observed during the past two decades has slowed in the recent years up to 2005.
2. Changes to temperature and circulation of the stratosphere affect climate and weather in the troposphere.
3. Updated datasets of stratospheric water vapor concentrations show differences in long-term behavior.
4. Future increases in greenhouse gas concentrations will contribute to the average cooling in the stratosphere.
5. 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.

Findings of the 2006 Assessment that are related to "A Focus on Options and Information for Policymakers" covered in ***Chapter 5 of the 2010 Assessment***:

1. 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.
2. The dates for the return of the global ozone layer and the Antarctic ozone hole to 1980 levels were provided based on the best available information to be around, respectively, 2049 and 2065.
3. Many potential options for accelerating the recovery of the ozone layer were evaluated and presented.

Organization of the Current Assessment

Much new information has been generated since the 2006 Assessment. Further, the information needs of the Parties to the Protocol have also changed. The specific requests of the Parties to the SAP are given in the Preface of this Assessment. Of particular note are the questions related to the influence of stratospheric changes on Earth's climate. This is somewhat of a new issue to the SAP and thus demands a chapter of its own.

This Assessment is an update to previous Assessments, and in particular the 2006 Assessment. However, as noted above, the changes in ozone and UV are not rapid and there are no new major findings in this area. To reflect this updating approach and consolidation of information, the structure of this Assessment differs from the most recent reports. In this Assessment, Chapter 1 deals with all issues related to ODSs; they include long-lived and very short-lived halocarbons as well as the replacements for the ODSs. In particular, it covers the trends and abundances of the replacements for ODSs that are greenhouse gases (but not ODSs), such as HFCs that are being discussed by the Parties to the Protocol for regulation. Chapter 2 deals with all observations of ozone and surface UV to date and our understanding of these observations, including a discussion of the current state of polar ozone. Chapter 3 focuses primarily on the future response of the ozone layer and UV-B radiation to reduced halocarbon emissions and other changes in an effort to focus on the question: What should one anticipate for ozone layer depletion and its consequences? It also picks up the issue of the definition and recognition of the recovery of the ozone layer first discussed in the 2006 Assessment. Of particular note are the issues related to the influence of stratospheric changes on climate. This issue was briefly described in the 2006 Assessment, which mostly focused on the influence of climate change on the recovery of the ozone layer. Because of the emergence of information on the influence of the stratospheric changes on Earth's climate, we have added a new chapter—Chapter 4—to address this topic. Chapter 4 focuses on the two-way connection between stratospheric changes and climate changes. This places the effects of halocarbon-induced ozone depletion on climate in the broader context of other stratospheric changes. Chapter 5 is expanded to include not only the policy options, often posed in hypothetical terms, available for further action but also other information relevant to the Parties to the Protocol.

Prologue Box 2. Recovery of the Ozone Layer: Concepts and Practical Issues

A conceptual diagram of the behavior of stratospheric ozone between 1960 and 2100 was presented in Chapter 6 of the 2006 Assessment (Bodeker and Waugh et al., 2007: "The Ozone Layer in the 21st Century"). A slightly modified version of this diagram is shown below.

As noted in the 2006 Assessment, stratospheric ozone abundances should change in response to decreases of ODSs and in response to other factors that influence ozone levels in the stratosphere. The other major factors are changes in temperature of the stratosphere because of increases in CO_2, changes in transport associated with climate change, and changes in tropospheric composition.

The ODS increases in the past few decades depleted the ozone layer. In the future, as ODSs decrease, the atmosphere in general—and the stratosphere in particular—should have decreasing amounts of ozone-destroying halogen catalysts. This decrease will follow the emissions of ODSs but will be shifted to later times because ODSs generally have long atmospheric lifetimes.

The past and future timeline of ozone behavior has been categorized as: stage I—slowing of ozone decline; stage II—onset of ozone increases; and stage III—full recovery of ozone from ODSs. In this idealization it is assumed that ozone production is not altered significantly, and that the climate and tropospheric changes are sufficiently small that the influence of ODSs is the predominant factor that controls the rate of depletion of the ozone layer. Of course, because of natural interannual variability, the ozone abundances do not show sufficiently clear changes to allow precise identification of these timeline stages. *(Continued on following page.)*

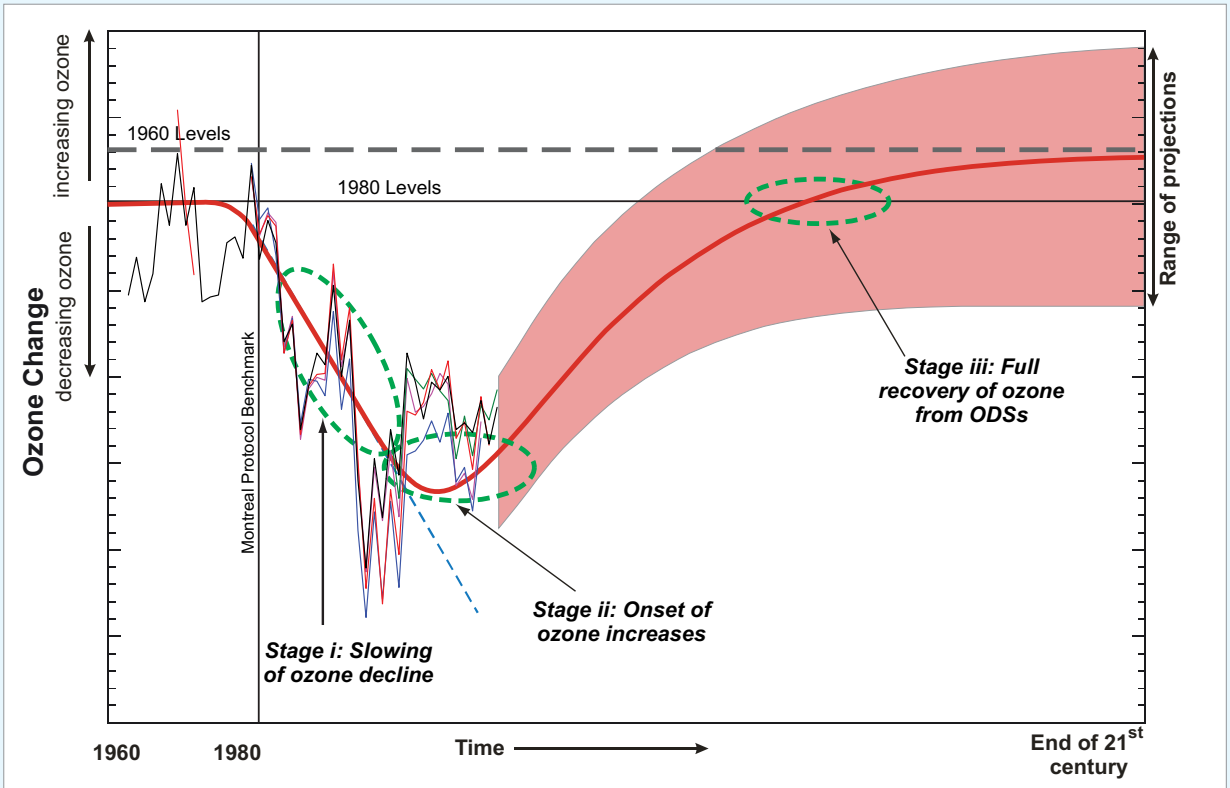


Figure P-2. A conceptual diagram of the evolution of column ozone between 60°N and 60°S between 1960 and 2100 (the x-axis is not to scale) adapted from Fig. 6-1 in the 2006 Assessment. The observations are discussed in Chapter 2. The thick red line is a representation of the ozone amounts observed to date and projected for the future. The red-shaded region represents the model results predicted for the future. The Montreal Protocol 1980 ozone level benchmark is shown as the horizontal line. The dashed thick gray line represents the somewhat uncertain 1960 levels. The three recovery stages are shown by green dashed ellipses.

Prologue Box 2, continued.

This three-stage timeline is a very useful conceptual picture for understanding ozone changes, diagnosing the current and future trends, and attempting to predict future ozone levels. However, as noted above, the ozone timeline is also influenced by other changes—climate change, volcanic eruptions that introduce sulfate aerosols in the stratosphere, and tropospheric composition changes. Further, the natural (and forced) variability in the Earth system will lead to difficulties in identifying as well as attributing these changes. These variabilities occur not only in the ozone abundances but also in the ODS levels, as climate change and other changes will alter when the ODS levels will reach values seen prior to 1980.

For all practical purposes, the Montreal Protocol has used 1980 levels as the time when there was little perturbation of the ozone layer by ODSs. This does not mean that there was no ozone depletion in 1980. Indeed, retroactive analyses of observations show that the ozone hole was growing prior to 1980. Yet we use 1980 levels of ODSs as the level when the ozone layer was not significantly influenced by ODSs and we will continue to use this date as a benchmark in this Assessment.

Because of factors other than ODSs, the ozone levels in the future could easily go above the values that were present either in the 1980s or even the 1960s. This situation was described in the previous Assessment as a "super-recovery." Of course, this is not recovery from the influence of ODSs but due to other factors, primarily CO_2. Therefore, the use of the term "super-recovery" differs from references to recovery from ODS-forced ozone depletion.

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