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SCIENTIFIC ASSESSMENT OF OZONE DEPLETION: 2014

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
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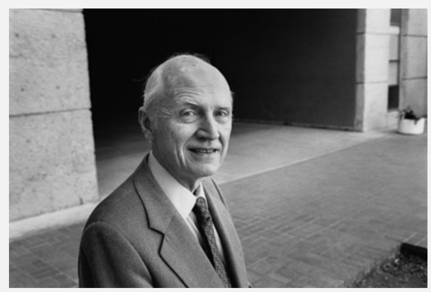
Remembrances

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

F. Sherwood "Sherry" Rowland (1927–2012) (Donald Bren research professor of chemistry in Earth system science at University of California, Irvine) passed away on 10 March 2012. Sherry was born on 28 June 1927 in Delaware, Ohio. He earned a B.A. in 1948 from Ohio Wesleyan University, his M.S. in 1951, and his Ph.D. in 1952 from the University of Chicago. In 1974, Mario Molina and Sherry warned that chlorofluorocarbons (CFCs) were increasing in the atmosphere, and were releasing chlorine in the stratosphere and thus depleting the ozone layer. Acting on this science spawned by Mario and Sherry, the nations of the world agreed in the 1985 Vienna Convention that ozone depletion was a real and serious problem. In 1987, the nations negotiated the Montreal Protocol on Substances that Deplete the Ozone Layer. The Montreal Protocol has now been strengthened to fully control the production and consumption of ozone depleting substances (ODSs), and has now been signed by every nation on Earth. In 1995, Sherry, Mario and Paul J. Crutzen shared the Nobel Prize for Chemistry "for their work in atmospheric chemistry, particularly concerning the formation and decomposition of ozone." Sherry's many other awards include the Tolman Award in 1976, the Tyler Prize for Environmental Achievement in 1983, the Japan Prize in 1989, the Peter Debye Award in 1993, the Albert Einstein World Award of Science in 1994, and the AGU Roger Revelle Medal in 1994. Sherry contributed in numerous ways to the WMO/UNEP assessments, in fact, it can be easily stated that he started the whole process with his seminal 1974 paper.



Harold "Hal" Johnston (1920–2012) died 20 October 2012 at the age of 92. He was born on 11 October 1920 in Woodstock, Georgia. He received his degree in chemistry from Emory University in 1941 and his Ph.D. from California Institute of Technology in 1948. After a few years at Stanford University, he was at UC Berkeley for his long and illustrious career. He was one of the pioneers of stratospheric research, having recognized the role of nitrogen oxides in destroying the ozone layer (simultaneously with Prof. Crutzen) and thus showing the potential impact of supersonic aircraft flying in the stratosphere. He was a major contributor to the Climatic Impact Assessment Program (CIAP) reports, an integrated assessment of the potential atmospheric impacts of the proposed American supersonic transport aircraft (SST) in the early 1970s. These reports predated the ozone layer assessments under the Montreal Protocol and laid the groundwork for stratospheric research. Hal received a number of awards and prizes, including the National Medal of Science, the Tyler World Prize for Environmental Achievement, the National Academy of Sciences Award for Chemistry in the Service to Society, and American Geophysical Union's Roger Revelle Medal.

Joseph C. Farman (1930–2013) died in Cambridge on 11 May 2013 at the age of 82. Joe led the British Antarctic Survey (BAS) team that made one of the major geophysical discoveries of the 20th century when it reported a very large decline in springtime stratospheric ozone, a phenomenon that became known as the Antarctic Ozone Hole. Joe was born on 7 August 1930 in Norwich, England. He received his M.A. in Natural Sciences from Corpus Christi College, Cambridge, where he was later a Fellow and Honorary Fellow. In 1956 he joined the Falkland Island Dependencies Survey (later British Antarctic Survey) with responsibility for establishing their geophysical measurements during the International Geophysical Year. He stayed at BAS until his retirement in 1990, then joining the European Ozone Research Coordinating Unit. He assisted directly and indirectly with a number of WMO/UNEP Ozone Assessments and played a key role in the development of the Montreal Protocol, well beyond his initial scientific input. His scientific life was characterized by a painstaking attention to detail, to the primacy of data, and for the need in geophysics for long data records.

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SCIENTIFIC ASSESSMENT OF OZONE DEPLETION: 2014

PREFACE

This document is part of the information upon which the Parties to the United Nations Montreal Protocol will base their future decisions regarding ozone-depleting substances, their alternatives, and protection of the ozone layer. It is the latest in a long series of scientific assessments that have informed the Parties.

The Charge to the Assessment Panels

Specifically, the Montreal Protocol on Substances that Deplete the Ozone Layer[1] 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 (SAP), the Environmental Effects Assessment Panel (EEAP), and the Technology and Economic Assessment Panel (TEAP) 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 consider the need to amend or adjust the Protocol.

The Sequence of Scientific Assessments

The present 2014 report is the latest in a series of 12 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 eighth 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*. WMO No. 16
1987	Montreal Protocol	
1988		*International Ozone Trends Panel Report 1988.* WMO No. 18
1989		*Scientific Assessment of Stratospheric Ozone: 1989*. WMO No. 20
1990	London Amendment and adjustments	
1991		*Scientific Assessment of Ozone Depletion: 1991*. WMO No. 25
1992		*Methyl Bromide: Its Atmospheric Science, Technology, and Economics* (Assessment Supplement). UNEP (1992).
1992	Copenhagen Amendment and adjustments	
1994		*Scientific Assessment of Ozone Depletion: 1994*. WMO No. 37
1995	Vienna adjustments	
1997	Montreal Amendment and adjustments	
1998		*Scientific Assessment of Ozone Depletion: 1998*. WMO No. 44
1999	Beijing Amendment and adjustments	
2002		*Scientific Assessment of Ozone Depletion: 2002*. WMO No. 47
2006		*Scientific Assessment of Ozone Depletion: 2006*. WMO No. 50
2007	Montreal adjustments	
2010		*Scientific Assessment of Ozone Depletion: 2010*. WMO No. 52
2014		*Scientific Assessment of Ozone Depletion: 2014*. WMO No. 55

[1] In this report, ozone-depleting substances (ODSs) refer to the gases listed in the Annexes to the Montreal Protocol. In addition to these gases, other chemicals also influence the ozone layer, and they are referred to as ozone-relevant gases.

The Current Information Needs of the Parties

The genesis of *Scientific Assessment of Ozone Depletion: 2014* was the 23rd Meeting of the Parties to the Montreal Protocol held during 21–25 November 2011 in Bali, Indonesia, at which the scope of the scientific needs of the Parties was defined in their Decision XXIII/13 (4), which stated that:

"*...for the 2014 report, the Scientific Assessment Panel should consider issues including:*

- *Assessment of the state of the ozone layer and its future evolution, including in respect of atmospheric changes from, for example, sudden stratospheric warming or accelerated Brewer-Dobson circulation;*
- *Evaluation of the Antarctic ozone hole and Arctic winter/spring ozone depletion and the predicted changes in these phenomena, with a particular focus on temperatures in the polar stratosphere;*
- *Evaluation of trends in the concentration in the atmosphere of ozone-depleting substances and their consistency with reported production and consumption of those substances and the likely implications for the state of the ozone layer and the atmosphere;*
- *Assessment of the interaction between the ozone layer and the atmosphere; including: (i) The effect of polar ozone depletion on tropospheric climate and (ii) The effects of atmosphere-ocean coupling;*
- *Description and interpretation of observed ozone changes and ultraviolet radiation, along with future projections and scenarios for those variables, taking into account among other things the expected impacts to the atmosphere;*
- *Assessment of the effects of ozone-depleting substances and other ozone-relevant substances, if any, with stratospheric influences, and their degradation products, the identification of such substances, their ozone-depletion potential and other properties;*
- *Identification of any other threats to the ozone layer*."

The 2014 SAP Assessment has addressed all the issues that were feasible to address to the best possible extent. Further, given the change in the structure of the report and the evolution of science, the UV changes are addressed by the Environmental Effects Assessment Panel (EEAP) of the Montreal Protocol. The SAP has provided the necessary information on ozone levels, now and in the future, to EEAP as input to their assessments.

The 2014 Assessment Process

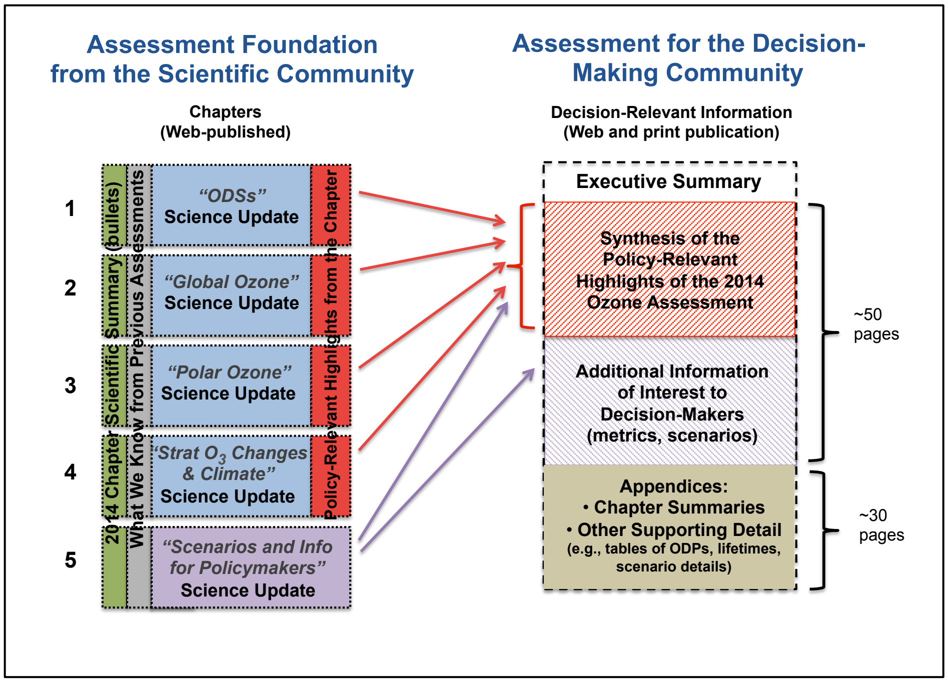
The formal planning of the current Assessment was started early in 2013. The Cochairs considered suggestions from the Parties regarding experts from their countries who could participate in the process. Two key changes were incorporated for the 2014 Assessment: (1) creation of a Scientific Steering Committee consisting of the Cochairs and four other prominent scientists; and (2) instituting Chapter Editors for each chapter to ensure that the reviews were adequately and appropriately handled by the authors and key messages were clearly enunciated to take them to the next level. For this reason, the Chapter Editors are also Coauthors of the *Assessment for Decision Makers* (ADM) of the *Scientific Assessment of Ozone Depletion: 2014*. The plan for this Assessment was vetted by an ad hoc international scientific advisory group. This group also suggested participants from the world scientific community to serve as authors of the science chapters, reviewers, and other roles. In addition, this advisory group contributed to crafting the outline of this 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 in those regions and countries.

The 2014 Scientific Assessment Panel (SAP) Report

The 2014 report of the Scientific Assessment Panel differs from the past seven reports in its structure and mode of publication. However, as in the past, it is a thorough examination and assessment of the science. The process by which this report was generated, as in the past, was also thorough; the documents underwent multiple reviews by international experts.

The Structure of the 2014 Report

The previous SAP reports have served well the Parties to the Montreal Protocol, the scientific community, and the managers who deal with the research activities. However, the Montreal Protocol process has matured significantly and its needs have evolved. It was clear from the discussions between the Cochairs and both the Party representatives and the people involved in decision making that the previous very lengthy assessment reports would not meet the current needs of the Parties for a short, pithy, document that is written for them and not for the scientific community. Yet, it was also clear that the integrity of and the trust in the SAP reports come from the very thorough assessment of the science. Therefore, this 2014 Assessment was restructured to serve both purposes. The new structure is shown schematically below.



First, as in the past, a major scientific assessment process was carried out and the findings from these discussions and reviews constitute the five major chapters of the assessment foundation from the scientific community. This is shown on the left hand side of the diagram. The five scientific chapters are published only on the web but *are an integral part of the 2014 SAP report to the Parties*. Also, as discussed earlier, the assessment of the surface UV changes due to past ozone depletion or to projected future ozone levels are not included in this document. Readers are referred to the 2014 Environmental Effects Assessment Panel report for the UV discussion.

Second, the findings from the SAP's five scientific chapters were then synthesized and written in a language that is accessible to the Parties to the Protocol. The contents of the *Assessment for Decision-Makers* document—an Executive Summary and three sections—are shown on the right hand side. This short document, which contains all the major scientific summary points written in a clear and accessible language, is available in print and on the web. It is hoped that this new document will be useful to and usable by the Parties to the Protocol, countries, and high-level policymakers and managers. If more scientific details are needed, the complete document can be accessed via the web.

Third, for this Assessment, the *Twenty Questions and Answers About the Ozone Layer* has been only updated. This is because the overarching scientific understanding has not changed significantly from the previous Assessment. The update will ensure that the answers include the most current data and are consistent with the 2014 Assessment. These updated questions and answers are published separately (both in print and on the web) in a companion booklet to this report.

It is hoped that these steps will enhance the usefulness of the document to the Parties, meet the needs of the multiple user communities for the information, minimize the workload of the scientific community, and reduce costs.

The Process of Preparing the 2014 Assessment

The initial plans for the scientific chapters of the 2014 Scientific Assessment Panel's report were examined at a meeting that occurred on 10–11 June 2013 in Cambridge, UK. The Lead Authors, the Scientific Steering Committee, and Chapter Editors—along with a few representatives of other assessment panels and organizations—focused on the planned content of the chapters and on the need for coordination among the chapters.

The first drafts of the scientific chapters were mailed to 213 experts for written reviews. The chapters were revised to take into account the comments of the reviewers. The revised drafts were subsequently sent to 65 reviewers who either attended a review meeting in Boulder or communicated their comments back to the group. These second drafts were reviewed by 63 experts in person in Boulder, CO, USA during 8–10 April 2014. Final changes to the chapters were decided upon at this meeting, and the final chapter summary points were agreed. Subsequently, the chapters were revised for clarity and to address specific points that were agreed to at the Boulder meeting. Final drafts of the scientific chapters were completed in May 2014.

Subsequent to the finalization of the five chapters, an author team consisting of the Scientific Steering Committee, Chapter Lead Authors, and Chapter Editors wrote a draft of the *Assessment for Decision-Makers*. This document was based on the science findings of the five chapters. The draft ADM was made available on June 13 to the attendees of a Panel Review Meeting that took place in Les Diablerets, Switzerland, on 23–27 June 2014. The overall ADM was reviewed, discussed, and agreed to by the 59 participants. The Executive Summary of the ADM, contained herein (and posted on the UNEP and WMO websites on 10 September 2014), was prepared and completed by the attendees of the Les Diablerets meeting.

The final result of this two-year endeavor is the present assessment report. As the accompanying list indicates (Appendix A), the *Scientific Assessment of Ozone Depletion: 2014* is the product of 285 scientists from 36 countries[2] of the developed and developing world who contributed to its preparation and review (133 scientists prepared the report and 220 scientists participated in the peer review process).

[2] Argentina, Australia, Austria, Belgium, Botswana, Brazil, Canada, People's Republic of China, Comoros, Costa Rica, Cuba, Czech Republic, Denmark, Finland, France, Germany, Greece, India, Israel, Italy, Japan, Korea, Malaysia, New Zealand, Norway, Poland, Russia, South Africa, Spain, Sweden, Switzerland, The Netherlands, Togo, United Kingdom, United States of America, Zimbabwe.

EXECUTIVE SUMMARY
ASSESSMENT FOR DECISION-MAKERS

[This is the Executive Summary of the *Assessment for Decision-Makers* of the 2014 Ozone Assessment. It contains the policy-relevant major findings of the Assessment's five scientific chapters, which follow.]

Actions taken under the Montreal Protocol have led to decreases in the atmospheric abundance of controlled ozone-depleting substances (ODSs), and are enabling the return of the ozone layer toward 1980 levels.

- **The sum of the measured tropospheric abundances of substances controlled under the Montreal Protocol continues to decrease.** Most of the major controlled ODSs are decreasing largely as projected, and hydrochlorofluorocarbons (HCFCs) and halon-1301 are still increasing. Unknown or unreported sources of carbon tetrachloride are needed to explain its abundance.
- **Measured stratospheric abundances of chlorine- and bromine-containing substances originating from the degradation of ODSs are decreasing.** By 2012, combined chlorine and bromine levels (as estimated by Equivalent Effective Stratospheric Chlorine, EESC) had declined by about 10–15% from the peak values of ten to fifteen years ago. Decreases in atmospheric abundances of methyl chloroform (CH_3CCl_3), methyl bromide (CH_3Br), and chlorofluorocarbons (CFCs) contributed approximately equally to these reductions.
- **Total column ozone declined over most of the globe during the 1980s and early 1990s (by about 2.5% averaged over 60°S to 60°N). It has remained relatively unchanged since 2000,** with indications of a small increase in total column ozone in recent years, as expected. In the upper stratosphere there is a clear recent ozone increase, which climate models suggest can be explained by comparable contributions from declining ODS abundances and upper stratospheric cooling caused by carbon dioxide increases.
- **The Antarctic ozone hole continues to occur each spring**, as expected for the current ODS abundances. The Arctic stratosphere in winter/spring 2011 was particularly cold, which led to large ozone depletion as expected under these conditions.
- **Total column ozone will recover toward the 1980 benchmark levels over most of the globe** under full compliance with the Montreal Protocol. This recovery is expected to occur before midcentury in midlatitudes and the Arctic, and somewhat later for the Antarctic ozone hole.

The Antarctic ozone hole has caused significant changes in Southern Hemisphere surface climate in the summer.

- **Antarctic lower stratospheric cooling due to ozone depletion is very likely the dominant cause of observed changes in Southern Hemisphere tropospheric summertime circulation over recent decades**, with associated impacts on surface temperature, precipitation, and the oceans. In the Northern Hemisphere, no robust link has been found between stratospheric ozone depletion and tropospheric climate.

Changes in CO_2, N_2O, and CH_4 will have an increasing influence on the ozone layer as ODSs decline.

- **As controlled ozone-depleting substances decline, the evolution of the ozone layer in the second half of the 21st century will largely depend on the atmospheric abundances of CO_2, N_2O, and CH_4.** Overall, increasing carbon dioxide (CO_2) and methane (CH_4) elevate global ozone, while increasing nitrous oxide (N_2O) further depletes global ozone. The Antarctic ozone hole is less sensitive to CO_2, N_2O, and CH_4 abundances.
- **In the tropics, significant decreases in column ozone are projected during the 21st century.** Tropical ozone levels are only weakly affected by ODS decline; they are sensitive to circulation changes driven by CO_2, N_2O, and CH_4 increases.

The climate benefits of the Montreal Protocol could be significantly offset by projected emissions of HFCs used to replace ODSs.

The Montreal Protocol and its Amendments and adjustments have made large contributions toward reducing global greenhouse gas emissions. In 2010, the decrease of annual ODS emissions under the Montreal Protocol is estimated to be about 10 gigatonnes of avoided CO_2-equivalent emissions per year, which is about five times larger than the annual emissions reduction target for the first commitment period (2008–2012) of the Kyoto Protocol (from the Executive Summary of the *Scientific Assessment of Ozone Depletion: 2010*).[3]

- The sum of the hydrofluorocarbons (HFCs) currently used as ODS replacements makes a small contribution of about 0.5 gigatonnes CO_2-equivalent emissions per year. These emissions are currently growing at a rate of about 7% per year and are projected to continue to grow.
- If the current mix of these substances is unchanged, increasing demand could result in HFC emissions of up to 8.8 gigatonnes CO_2-equivalent per year by 2050, nearly as high as the peak emission of CFCs of about 9.5 gigatonnes CO_2-equivalent per year in the late 1980s.[4]
- Replacements of the current mix of high-Global Warming Potential (GWP) HFCs with low-GWP compounds or not-in-kind technologies would essentially avoid these CO_2-equivalent emissions.
- Some of these candidate low-GWP compounds are hydrofluoro-olefins (HFOs), one of which (HFO-1234yf) yields the persistent degradation product trifluoroacetic acid (TFA) upon atmospheric oxidation. While the environmental effects of TFA are considered to be negligible over the next few decades, potential longer-term impacts could require future evaluations due to the environmental persistence of TFA and uncertainty in future uses of HFOs.
- By 2050, HFC banks are estimated to grow to as much as 65 gigatonnes CO_2-equivalent. The climate change impact of the HFC banks could be reduced by limiting future use of high-GWP HFCs to avoid the accumulation of the bank, or by destruction of the banks.

Additional important issues relevant to the Parties to the Montreal Protocol and other decision-makers have been assessed.

- Derived emissions of carbon tetrachloride (CCl_4), based on its estimated lifetime and its accurately measured atmospheric abundances, have become much larger than those from reported production and usage over the last decade.

[3] GWP-weighted emissions, also known as CO_2-equivalent emissions, are defined as the amount of gas emitted multiplied by its 100-year Global Warming Potential (GWP). Part of the effect of ODSs as greenhouse gases is offset by the cooling due to changes in ozone.

[4] This is equivalent to about 45% of the fossil fuel and cement emissions of CO_2 in the late 1980s.

- As of 2009, the controlled consumption of methyl bromide declined below the reported consumption for quarantine and pre-shipment (QPS) uses, which are not controlled by the Montreal Protocol.
- Increased anthropogenic emissions of very short-lived substances (VSLS) containing chlorine and bromine, particularly from tropical sources, are an emerging issue for stratospheric ozone. The relative contribution of these emissions could become important as levels of ODSs controlled under the Montreal Protocol decline.
- As the atmospheric abundances of ODSs continue to decrease over the coming decades, N_2O, as the primary source of nitrogen oxides in the stratosphere, will become more important in future ozone depletion.
- Emissions of HFC-23, a by-product of HCFC-22 production, have continued despite mitigation efforts.
- While ODS levels remain high, a large stratospheric sulfuric aerosol enhancement due to a major volcanic eruption or geoengineering activities would result in a substantial chemical depletion of ozone over much of the globe.

While past actions taken under the Montreal Protocol have substantially reduced ODS production and consumption, additional, but limited, options are available to reduce future ozone depletion.

Emissions from the current banks are projected to contribute more to future ozone depletion than those caused by future ODS production, assuming compliance with the Protocol.

- Possible options to advance the return of the ozone layer to the 1980 level (analyses based on midlatitude EESC) are shown graphically. The cumulative effect of elimination of emissions from all banks and production advances this return by 11 years.