Scientific Assessment of Ozone Depletion

Executive Summary

2022



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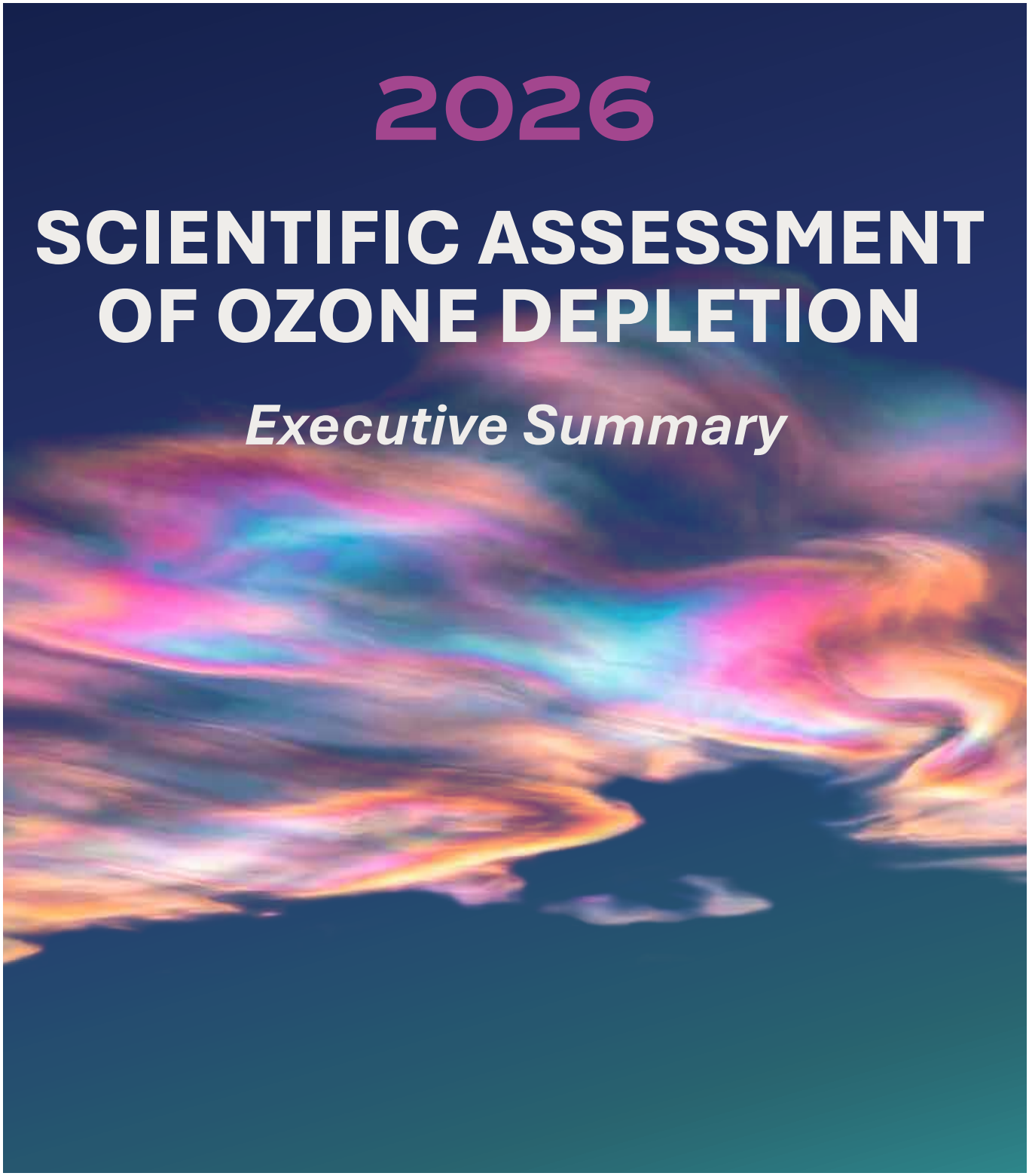
The graphic illustrations on this cover include an artistic rendering of a polar stratospheric cloud enhanced with AI tools and an adaptation of Figure ES-1 Panel A of this document.

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2026

SCIENTIFIC ASSESSMENT OF OZONE DEPLETION

Executive Summary



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

HIGHLIGHTS

of the

Scientific Assessment of Ozone Depletion: 2026

A. Achievements of the Montreal Protocol

The atmospheric abundances of chlorine and bromine contained in controlled ozone-depleting substances (ODSs) continue to decrease because of the actions taken under the Montreal Protocol. As a consequence, clear signs that the stratospheric ozone layer is beginning to recover have emerged. The decline in total atmospheric chlorine has increased in recent years due, in part, to a more rapid decline in chlorofluorocarbons (CFCs). In addition, atmospheric chlorine from all hydrochlorofluorocarbons (HCFCs) reached a peak during the last four years and has begun to decrease. The timing of this decline of HCFCs indicates that the Parties are complying with the HCFC phase-out ahead of schedule.

Total column ozone (TCO) in the Antarctic continues to recover, notwithstanding substantial interannual variability in the area, depth, and longevity of the ozone hole, primarily driven by dynamical forcings. In a middle-of-the-road greenhouse-gas scenario, Antarctic TCO is projected to return to 1980 values during the 2060s. Observations show a slightly larger annual increase in near-global (60°S–60°N) TCO compared to the previous Assessment. Near-global-mean TCO is projected to return to 1980 values around 2040. Altogether, the findings show that the Montreal Protocol is working well and is expected to meet its goals and those of the Vienna Convention provided there is continued compliance.

Global compliance with the Montreal Protocol's phaseout of ODS production has been beneficial in reducing global warming and is expected to prevent warming of 0.25–0.89 °C by 2050. Measured abundances and derived emissions of most hydrofluorocarbons (HFCs) are consistent with expectations from the production and consumption phase-down controls of the Kigali Amendment to the Montreal Protocol. Continued compliance with these Kigali Amendment provisions is estimated to prevent an additional 0.05–0.06 °C of warming by 2050 and up to 0.4 °C by 2100.

Antarctic stratospheric ozone depletion has driven substantial trends in summertime Southern Hemisphere atmospheric circulation. These trends have slowed since around 2000, indicating that the impact of ozone recovery on the circulation is already apparent. Ozone recovery will continue to drive Southern Hemisphere circulation changes that oppose those driven by increased greenhouse gases.

B. Ongoing and Emerging Issues

Atmosphere-derived global emissions of HFC-23 are substantially larger than reported emissions plus those from additional known sources. Future HFC-23 emissions could lead to warming of around a quarter of that from all HFC emissions by 2100. This projection is highly uncertain, primarily because of the poor understanding of current and future HFC-23 emissions from HCFC-22 production and other pathways for HFC-23 generation and emission.

Atmospheric observations of some ODSs used as feedstocks or produced as intermediates and by-products suggest emission factors substantially higher than those adopted in earlier Assessments. Furthermore, the production and use of ODSs as feedstock continue to rise, driven primarily by a rapidly expanding polymers industry and the chemical production of alternatives to ODSs and controlled HFCs. If ODS emissions associated with feedstock use were eliminated now, by 2100 global-mean ozone depletion of 1 Dobson unit (DU) (or about 0.4%) would be prevented, largely due to reductions of carbon tetrachloride (CCl_4), and globally averaged surface warming of about 0.01 °C would be prevented.

Emissions of chlorinated very short-lived substances (VSLSs), which are dominated by anthropogenic emissions of dichloromethane (CH_2Cl_2), continue to grow and contribute to ozone depletion. VSLSs currently contribute approximately 4.4% of the total chlorine entering the stratosphere. At their current level, CH_2Cl_2 emissions account for a reduction in global annual mean TCO of approximately 1 DU.

Ozone-depletion-weighted emissions of anthropogenic nitrous oxide (N_2O) have grown in relative importance as emissions of ODSs have been largely eliminated. Atmospheric observations indicate that the annual increase of N_2O abundance is now exceeding all projections made by the Intergovernmental Panel on Climate Change (IPCC) in its most recent assessment (2023). Future N_2O emissions are likely to have a larger impact on global stratospheric ozone and climate than future emissions of controlled ODSs.

New Earth system model projections of ozone changes in response to stratospheric aerosol injection (SAI) were assessed. Choosing a middle-of-the-road greenhouse-gas scenario and assuming an injected sulfate aerosol mass sufficient to stabilize global warming, global ozone depletion becomes 3–5 DU at mid-century, which delays the recovery of global TCO by around 15–20 years.

Currently, the known effects on ozone from aerosols and gaseous emissions attributed to space activities are minor compared to those of ODSs. The future impacts remain highly uncertain due to possible alteration of ozone depletion chemistry by particles produced during launch and reentry, dependencies on the number of launches and their location, and the fuel type used. The

expected continued rapid expansion of space activity over the coming decades will make understanding these impacts increasingly important.

Exceptional events can temporarily perturb stratospheric composition and chemistry. There is now improved understanding of how smoke particles injected into the stratosphere from the 2019–2020 Australian New Year's wildfires led to enhanced halogen-based ozone depletion and a larger Antarctic ozone hole. The meteorological conditions conducive to similarly large and intense wildfires are expected to become more common in the future. The 2022 Hunga Tonga-Hunga Ha'apai submarine volcanic eruption was sufficiently explosive that water injected at high altitude increased the global stratospheric water vapor burden by about 10%. This increase in water vapor led to stratospheric cooling and changes in circulation, while limited amounts of injected volcanic sulfur led to some additional ozone depletion.

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PREFACE

The 2026 Scientific Assessment of Ozone Depletion is the latest in a series prepared by the Scientific Assessment Panel (SAP) of the Montreal Protocol on Substances that Deplete the Ozone Layer under the auspices of the World Meteorological Organization (WMO) and the United Nations Environment Programme (UN Environment). The assessment reports contain relevant information for decisions of the Parties to the Montreal Protocol regarding controls on the production and consumption of ozone-depleting substances (ODSs) and their replacements to protect the stratospheric ozone layer and climate.

The Charge to the Assessment Panels

The mandate to prepare assessment reports is included in the articles of the Montreal Protocol with the following language:

> *Beginning in 1990, and at least every four years thereafter, the Parties shall assess the control measures provided for in Article 2 and Articles 2A to 2I on the basis of available scientific, environmental, technical and economic information.*

To provide the mechanisms whereby these assessments are conducted, the Montreal Protocol further states:

> *"...the Parties shall convene appropriate panels of experts" and "the panels will report their conclusions...to the Parties."*

To meet this mandate, the SAP, the Technology and Economic Assessment Panel (TEAP), and the Environmental Effects Assessment Panel (EEAP) each prepare quadrennial and interim assessment reports that update the state of understanding in their purview and are responsive to the terms of reference and other requests provided to each panel by formal decisions of the Parties. These reports are made available to the Parties in advance of their annual meetings at which they consider decisions related to current and emerging issues and potential amendments and adjustments to the provisions of the Montreal Protocol. The chronology of the assessment reports, along with other relevant reports and international policy decisions, is summarized in Table ES-1.

2026 SAP Assessment Terms of Reference

The terms of reference for the 2026 SAP assessment report were decided at the 35th Meeting of the Parties (MOP 35) to the Montreal Protocol convened over 23–27 October 2023, at the UNEP headquarters in Nairobi, Kenya and excerpted here from their Decision XXXV/3: *Potential areas of focus for the 2026 quadrennial reports of the Environmental Effects Assessment Panel, the Scientific Assessment Panel and the Technology and Economic Assessment Panel.*

> *"Noting with great appreciation the excellent and highly useful work of the members of the Environmental Effects Assessment Panel, the Scientific Assessment Panel and the Technology and Economic Assessment Panel of the Montreal Protocol on Substances that Deplete the Ozone Layer and their colleagues worldwide in preparing the panels' 2022 assessment reports, and in particular the efforts made to condense vast amounts of pertinent information into a concise and understandable form for better use by policymakers,*
>
> *6. That the 2026 report of the Scientific Assessment Panel should include:*
>
> *(a) An assessment of the state of the ozone layer and its future evolution;*
>
> *(b) An evaluation of global and polar stratospheric ozone, including the Antarctic ozone hole and Arctic winter and spring ozone depletion and the predicted changes in these phenomena;*
>
> *(c) An updated assessment of past and projected contributions of the Montreal Protocol to mitigating climate change in terms of total avoided CO_2-equivalent emissions and avoided temperature increase;*
>
> *(d) An evaluation of trends in the top-down derived emissions, abundances and fate in the atmosphere of trace gases of relevance to the Montreal Protocol, in particular controlled substances and other substances of importance to the ozone layer, which should include a comparison of top-down estimations and available bottom-up estimations of such emissions with a view to identifying currently unknown emission sources and explaining discrepancies between emissions derived from reported information and observed atmospheric concentrations (in cooperation with the Technology and Economic Assessment Panel);*
>
> *(e) An evaluation of consistency with reported production and consumption of those substances and the likely implications for the state of the ozone layer, including its interaction with the climate system;*
>
> *(f) An assessment of the interaction between changes in stratospheric ozone and the climate system, including consideration of related policy scenarios;*
>
> *(g) Information regarding scenarios designed to contribute further to ozone layer protection and climate change mitigation, and a presentation of their benefits in terms of impacts on total column ozone and equivalent effective stratospheric chlorine, advancing the recovery of the ozone layer, and avoiding CO_2-equivalent emissions, as relevant;*
>
> *(h) Early identification and quantification of any substances that could be of concern for the ozone layer and relevant for the implementation of the Montreal Protocol and the objectives of the Vienna Convention for the Protection of the Ozone Layer, including other halogenated gases, in particular those with high global warming potential, breakdown products of controlled substances and their alternatives that are very persistent, such as perfluoro- and polyfluoroalkyl substances, including trifluoroacetic acid, N_2O and very short-lived substances such as dichloromethane, and their main sources of emissions;*
>
> *(i) An assessment of information and research related to solar radiation modification, in particular stratospheric*

aerosol injection and its potential effects on the ozone layer and relevant information on the potential effects of supersonic aircraft, rockets, satellites, wildfires and volcanic eruptions on the stratospheric ozone layer;

(j) Identification and quantification of any other issues relevant to the objectives of the Vienna Convention for the Protection of the Ozone Layer and the Montreal Protocol;"

Interim Reports: 2023–2026

HFC-23

In addition to preparing the 2026 assessment report, the SAP responded in the interim period between quadrennial reports to requests from the parties for updated information on several topics, primarily on the emissions of HFC-23 (trifluoromethane). HFC-23 is a potent greenhouse gas having a global warming potential of 14,500 and an atmospheric lifetime of 228 years. Production and consumption of HFC-23 is controlled under the Kigali Amendment, which also stipulates that the Parties ensure that HFC-23 generated in production facilities manufacturing controlled HCFCs and controlled HFCs is destroyed to the extent practicable. Historically, HFC-23 emissions from intentional use have been small compared to those arising from by-production during the manufacture of HCFC-22. In recent years, the Parties have requested special reports from the SAP and the TEAP that assess why annual emissions derived from atmospheric abundances of HFC-23 are substantially greater than reported emissions (see **Table ES-1**).

For example, at the 35th Meeting of the Parties in Nairobi, Kenya, in October 2023, the Parties adopted Decision XXXV/7 Emissions of HFC-23, which included the following language:

"1.To request the Scientific Assessment Panel to provide an update on HFC-23 emissions into the atmosphere and atmospheric concentrations to supplement the information in the 2022 quadrennial assessment report, including by reflecting any new information regarding atmospheric monitoring and atmospheric modelling, with its underlying methodology, including in quantifiable terms, with respect to such emissions, and taking into account information reported under paragraph 3 of Article 7 by all parties that manufacture Annex C, Group I and/or Annex F substances, and to prepare a report on the matter to the Thirty-Sixth Meeting of the Parties to the Montreal Protocol;"

A similar request to update information on HFC-23 emissions was put forth in Decision XXXVI/3 at the 36th Meeting of the Parties in Bangkok, Thailand, in October 2024. In response, the SAP and the TEAP submitted separate coordinated reports in September 2024 and September 2025 to the Ozone Secretariat, with the TEAP focusing on technical aspects of production and consumption of HFC-23 and the SAP focusing on HFC-23 emissions derived from atmospheric observations and the production of HFC-23 from the atmospheric degradation of other substances. The parties requested an additional joint TEAP/SAP report updating HFC-23 information in their Decision XXXVII/2 at the 37th Meeting of the Parties in Nairobi, Kenya, in November 2025. The joint report was submitted to the Ozone Secretariat in September 2026. The 2026 SAP assessment report provides additional information responsive to this decision.

VSLSs

On the topic of very short-lived substances (VSLSs), the Parties made two requests. The first was made with a decision at the 35th Meeting of the Parties in Nairobi, Kenya, in October 2023 that included the following language:

"Decision XXXV/6 requests the TEAP, in cooperation with the SAP, to include in its 2024 progress report, for consideration by the Open-ended Working Group of the Parties to the Montreal Protocol at its forty-sixth meeting (OEWG-46): (a) Updated information on VSLS, including their ODP and the impact of each of the VSLS on the stratospheric ozone layer, in quantifiable terms; (b) Information on alternatives to VSLS in the main applications for which they are currently used, including information on availability, technical feasibility, economic viability, safety and sustainability."

In response, the TEAP, in collaboration with the SAP, included the requested information in its 2024 Progress Report.

The second VSLS request was made with Decision XXXVI/4 at the 36th Meeting of the Parties in Bangkok, Thailand, in October 2024, that includes the language:

"Noting that the Scientific Assessment Panel indicated in its 2022 quadrennial assessment report that chlorine emissions from very short-lived substances not controlled by the Montreal Protocol on Substances that Deplete the Ozone Layer, in particular from dichloromethane, continue to increase,

Noting also that any party that has information on alternatives to very short-lived substances and best practices for avoiding such emissions can provide such information to the Technology and Economic Assessment Panel, Decides:

1. To request the Technology and Economic Assessment Panel and the Scientific Assessment Panel to include the following information, as it pertains to their respective mandates, in their 2026 assessment reports, for consideration by the Open-ended Working Group of the Parties to the Montreal Protocol on Substances that Deplete the Ozone Layer at its forty-ninth meeting;

a. Updated information on dichloromethane, trichloromethane, dichloroethane, trichloroethylene and perchloroethylene, including their emissive solvent and feedstock uses and growth trends for the past five years, their ozone-depleting potential and their impact on the stratospheric ozone layer in quantifiable terms;

b. Any available relevant information on other anthropogenic very short-lived substances not mentioned in Chapter 5.2 of the 2024 progress report of the Technology and Economic Assessment Panel, along with the methodology used, growth trends for the past five years, their ozone-depleting potential and their impact on the stratospheric ozone layer in quantifiable terms;

c. Additional information on alternatives to the very short-lived substances, including of solvents with a low boiling point, referred to in subparagraphs (a) and (b) above in the emissive applications where they are currently used, including information on availability and accessibility, technical feasibility, performance, including the yield of the end product, economic viability, safety and sustainability, and penetration in parties operating under paragraph 1 of Article 5 of the Montreal Protocol, with a focus on very short-lived substances with significant emissive uses;

Table ES-1. Chronology of scientific reports and policy decisions related to ozone depletion

Year	Policy Decisions	Scientific Reports
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.
2014		Scientific Assessment of Ozone Depletion: 2014. WMO No. 55.
2016	Kigali Amendment	
2018		Scientific Assessment of Ozone Depletion: 2018. WMO No. 58.
2021		Report on Unexpected Emissions of CFC-11. WMO No. 1268.
2022		Scientific Assessment of Ozone Depletion: 2022. GAW No. 278.
2024		Report of the Technology and Economic Assessment Panel, Volume 1: Progress Report
2024		Report of the Scientific Assessment Panel in response to Decision XXXV/7: Emissions of HFC-23
2025		Report of the Scientific Assessment Panel in response to Decision XXXVI/3: Emissions of HFC-23
2026		Report of the Technology and Economic Assessment Panel in response to Decision XXXVII/2: Emissions of HFC-23 (joint with the SAP)
2026		Scientific Assessment of Ozone Depletion: 2026. GAW No. 326

d. A table providing information, to the extent possible, for each very short-lived substance identified in subparagraphs (a) and (b) above on estimated annual production and consumption, estimated annual emissions, the range of ozone-depleting potential estimated or evaluated by the Scientific Assessment Panel, the contribution of the substance to the total chlorine input to the stratosphere and its impact on the stratospheric ozone layer in quantifiable terms;"

The requested information was included in the 2026 SAP assessment report in Chapters 1, 3, 4, and 7 and the report Annex. For example, Table 7-3 in Chapter 7 on Scenarios and Information for Policymakers includes detailed VSLS information.

PFAS

The terms of reference for the 2026 SAP assessment report quoted above include the quantification of any persistent substances that can be identified as breakdown products of controlled substances and their alternatives. The Annex of the 2026 Assessment report has been expanded beyond the 2022 version to include the characterization of per- and polyfluoroalkyl substances (PFAS) and known atmospheric yields of persistent degradation products from Montreal Protocol-controlled substances. The new information is contained in Table A-4, which was developed in collaboration with TEAP and EEAP panel members and now serves as a reference for the Montreal Protocol Parties and future PFAS evaluations conducted by the panels.



The Final Author Meeting was held in Geneva, Switzerland on 20–24 July 2026. Shown is the iconic Jet d'Eau on Lake Geneva. *(Photo credit: Krystian-photos/Adobe Stock)*

The Assessment Process

The process of writing the current assessment report started in late 2024. The Co-chairs of the SAP considered suggestions from the Parties regarding experts from their countries who could participate in the process. A Scientific Steering Committee (SSC), comprising the Co-chairs and an ad-hoc international scientific advisory group, was formed to suggest authors and reviewers from the world scientific community and to help craft the report outline. As in previous reports, the participants were experts from the developed and developing world who bring scientific expertise to the process and whose involvement in the assessment report contributes to capacity building. The Authors, Contributors, and Reviewers section at the end of this document provides a listing of the approximately 230 scientists from 30 countries who contributed to the preparation and review of this assessment report.

An initial letter was sent to a number of scientists and experts in November 2024 soliciting comments on a draft outline and suggestions for authors for the 2026 report. This was followed by revisions to the outline and recruitment of Lead Authors and Co-authors. Revised chapter outlines were developed in early 2025 through a series of online meetings of the SSC and Lead Authors and an in-person meeting hosted by the University of York, UK, in April 2025. The chapter writing process produced three interim drafts between August 2025 and June 2026, aided by virtual and in-person meetings of the individual chapter author teams and a full author team meeting in April 2026 hosted by the Empa Research Institute in Zurich, Switzerland. The first order drafts of the chapters were anonymously peer-reviewed by over 90 expert reviewers. The chapters were revised by the author teams based on the extensive review comments (numbering over 3500). Review Editors for each chapter provided oversight of the revision process to assist the author teams in appropriately addressing the comments and suggestions received.

The final author team meeting to complete the chapters and the Executive Summary was held in-person on 20–24 July 2026 at WMO Headquarters in Geneva, Switzerland, with 74 participants. Attendees included the SSC, chapter Lead Authors, Review Editors, some chapter Co-authors, some reviewers, and some leading experts invited by the SSC. The Executive Summary was developed and revised during the meeting and approved line-by-line by the close of the meeting.

The success of the 2026 assessment report depended on the combined efforts and commitment of the large international team that wrote, edited, and managed the assessment content and on the skills and dedication of the Assessment Coordinator and the Editorial and Production staff, who are listed at the end of this report.

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Co-chairs of the Scientific Assessment Panel of the Montreal Protocol

INTRODUCTION

The 1985 Vienna Convention for the Protection of the Ozone Layer is an international agreement in which United Nations States recognized the fundamental importance of preventing damage to the stratospheric ozone layer. The 1987 Montreal Protocol on Substances that Deplete the Ozone Layer and its subsequent amendments, adjustments, and decisions were negotiated to control the consumption and production of anthropogenic ozone-depleting substances (ODSs) and some hydrofluorocarbons (HFCs). The Montreal Protocol Parties base their decisions in part on the scientific, environmental, technical, and economic information that is provided by their respective assessment panels. The Protocol requests quadrennial reports from its Scientific Assessment Panel that update the science of the depletion of the ozone layer and other matters of interest to the Parties. This Executive Summary (ES) presents the key findings of the Scientific Assessment of Ozone Depletion: 2026. The key findings of each of the chapters and annex of the report have been formulated to make the ES suitable for a broad audience. A clear message strengthened in the 2026 Assessment report is that the Montreal Protocol continues to be effective at controlling the production and consumption of ODSs and their replacements, thereby protecting the ozone layer and future climate.

Emissions of ODSs to the atmosphere lead to ozone depletion through chemical reactions which cause the release of chlorine and bromine in the stratosphere. Throughout this report, the term "ODSs" refers to controlled ozone-depleting substances. ODSs include chlorofluorocarbons (CFCs), bromine-containing halons and methyl bromide, hydrochlorofluorocarbons (HCFCs), carbon tetrachloride (CCl_4), and methyl chloroform. The substances controlled under the Montreal Protocol are listed in the various annexes to the agreement (CFCs and halons under Annex A and B, HCFCs under Annex C, and methyl bromide under Annex E). Most ODSs are long-lived (e.g., atmospheric lifetime of more than 0.5 year) and are also powerful greenhouse gases (GHGs) (e.g., CFC-12 has a 100-yr lifetime and 100-yr global warming potential (GWP) of 12,400). As a consequence of Montreal Protocol controls on global ODS production and consumption, ODS emissions and stratospheric concentrations of chlorine and bromine continue to decline.

In addition to the long-lived ODSs, there is a broad class of chlorine- and bromine-containing substances included in the report known as very short-lived substances (VSLSs) that are not controlled under the Montreal Protocol and have atmospheric lifetimes less than about six months. For example, bromoform ($CHBr_3$) has a lifetime of about 23 days, while chloroform ($CHCl_3$) has a lifetime of about 177 days. These substances are primarily destroyed in the lower atmosphere in chemical reactions. Thus, only small fractions of VSLS emissions generally reach the stratosphere, where they contribute to chlorine and bromine levels and lead to increased ozone depletion.

The Montreal Protocol's control of ODSs led to the development of replacement substances, first HCFCs and then HFCs, for a number of use sectors. While HFCs have no direct effect on stratospheric ozone, some HFCs are powerful GHGs. In 2009, HFCs were projected to increase substantially in the coming decades as economic development continued in Montreal Protocol A5 Parties. In response, the 2016 Kigali Amendment to the Montreal Protocol (see Annex F) was adopted to phase down the production and consumption of some HFCs and thereby avoid much of the projected global increase in HFCs and associated climate change. This year, 2026, is the 10-year anniversary of the adoption of the Kigali Amendment. In the last decade, it has been ratified by 172 states and the European Union (173 Parties total) and officially came into force on 1 January 2019. As a consequence of compliance with the amendment provisions, current derived emissions of most HFCs are consistent with the phase-down controls of the amendment, with HFC-23 being a notable exception.

Observations of atmospheric ozone and related species are made by instruments on the ground and onboard balloons, aircraft, and satellite platforms. This network of in situ and remote sensing observations documented the decline of ozone around the globe, with extreme depletion found over Antarctica in each austral spring and occasional large depletion in the Arctic, and, hence, provides the basis of our scientific understanding of global and polar ozone changes. Before the completion of the next SAP assessment report in 2030, key stratospheric observations of chlorine-containing gases and long-lived trace gases from aging satellite remote sensing instruments will no longer be available. There will also be a gap in satellite observations of the abundances of other important gases in the stratosphere of at least two years. The loss of these observations will impede our ability to understand how year-by-year changes in the ozone layer can be attributed to changes in the chemical and dynamical conditions in the stratosphere.

Strong declines in the emissions of ODSs starting in the late 1980s in response to Montreal Protocol controls led to a decline in the stratospheric abundances of chlorine and bromine starting around the turn of the century and the beginning of ozone layer recovery. Based on the analysis of observed trends in ozone abundances and their variability, some indications of recovery in stratospheric ozone have been communicated in previous assessment reports. Evidence of recovery is strengthened in this report based on a statistically significant positive trend found in global ozone amounts. Antarctic stratospheric ozone depletion has driven substantial trends in summertime Southern Hemisphere atmospheric circulation. These trends have slowed since around 2000, indicating that the impact of ozone recovery on the circulation is already apparent. Ozone recovery will continue to drive Southern Hemisphere circulation changes that oppose those driven by increased greenhouse gases.

In addition to ODSs, stratospheric ozone concentrations are also affected by the chemical and climate effects of greenhouse gases. Model simulations show that increasing

concentrations of the GHGs carbon dioxide (CO_2) and methane (CH_4) in some emission scenarios cause global ozone levels to increase beyond the background level of ozone observed in the 1960s, primarily because of the cooling of the upper stratosphere and changes in stratospheric circulation. On the other hand, increasing concentrations of nitrous oxide (N_2O), another GHG, lead to chemical depletion of stratospheric ozone. Thus, projected stratospheric ozone amounts in the coming decades depend on global changes in the atmospheric abundances of ODSs and GHGs, as well as changes in stratospheric conditions in response to climate forcings.

The following sections of this Executive Summary present the key messages and supporting figures on the principal topics of this assessment report: abundances and trends in ODSs, HFCs, stratospheric ozone, stratospheric ozone changes and climate, stratospheric aerosol injection and potential impacts on ozone, and policy-relevant scenarios and information. The sections following the key messages contain the summary points from each chapter as they appear in the main assessment report and a complete listing of the report author and support team.

Terminology Used in the Executive Summary

Ozone-depleting substances (ODSs)

Here and throughout this document, the term "ozone-depleting substances (ODSs)" refers to gases containing either chlorine or bromine that are released to the atmosphere as a result of human activity and are controlled under the Montreal Protocol. These include, among others, chlorofluorocarbons (CFCs), carbon tetrachloride (CCl_4), methyl chloroform (CH_3CCl_3), halons, methyl bromide (CH_3Br), and hydrochlorofluorocarbons (HCFCs). These ODSs typically have sufficiently long atmospheric lifetimes to reach the stratosphere after being emitted at the surface. Nitrous oxide (N_2O) and halogenated very short-lived substances (VSLS) also deplete stratospheric ozone. However, these are not termed ODSs because they are not controlled by the Montreal Protocol.

Ozone depletion potential (ODP) / ODP weighting

The ozone depletion potential (ODP) of a substance is a metric for quantifying its relative contribution to ozone depletion. ODP is defined as the ratio of the change in global ozone for a given mass emission of that substance to the change in global ozone for the same mass emission of CFC-11 ($CFCl_3$). In comparisons of potential impacts on stratospheric ozone from emissions of different gases, emissions are often weighted by their respective ODP and expressed as "ODP-weighted emissions" in units of "Mt CFC-11 equivalent."

Halogenated very short-lived substances (VSLSs)

Halogenated very short-lived substances (VSLSs) are substances that contain chlorine or bromine and have atmospheric lifetimes of less than 0.5 year. A large fraction of total VSLS emissions is destroyed in the troposphere, limiting the fraction of emissions that reaches the stratosphere and causes ozone depletion. VSLS emissions from tropical regions with rapid vertical transport will reach the stratosphere and contribute to stratospheric halogen levels more efficiently than emissions from higher latitudes. Hence, the ODP of a VSLS generally depends on the VSLS lifetime and assumptions about the emission source regions and the time of year of the emissions. VSLSs are not controlled substances under the Montreal Protocol.

Equivalent effective stratospheric chlorine (EESC)

EESC is a metric for representing reactive halogen levels in the stratosphere. It is calculated from surface atmospheric concentrations of individual ODSs, their number of chlorine and bromine atoms, and the relative efficiency of chlorine and bromine at depleting ozone. EESC estimates also account for the time required for ODSs to reach different stratospheric regions and the breakdown rate for each substance for releasing chlorine and bromine once in the stratosphere. As EESC continues to decrease in response to Montreal Protocol provisions, stratospheric ozone is expected to increase. In this report, EESC values do not include chlorine and bromine from very short-lived substances (VSLSs).

Hydrofluorocarbons (HFCs)

Unless otherwise stated, the term "HFC" is used throughout the report for saturated HFCs controlled under the Kigali Amendment. HFCs do not deplete ozone and some have large GWPs. At present, 18 saturated HFCs are controlled under the Kigali Amendment to the Montreal Protocol. Saturated HFCs are those with only single carbon-carbon bonds, which makes them more stable in the atmosphere than unsaturated HFCs. The latter contain carbon-carbon double bonds and are commonly referred to as hydrofluoroolefins (HFOs) and hydrochlorofluoroolefins (HCFOs). Several additional saturated HFCs and all unsaturated HFCs are not controlled under the Montreal Protocol.

Feedstocks

A feedstock is a substance used to manufacture one or more synthetic chemicals through a process of chemical transformation. Some ODSs and HFCs that are used as feedstocks are controlled by the Montreal Protocol. Feedstock use is exempted from production and consumption controls under the Montreal Protocol.

Banks

The bank of a given substance is defined as the amount of that substance that has been manufactured and is contained in equipment or products or stored for later use,

and as such has not yet been released to the atmosphere. Banks include substances contained in refrigeration and air conditioning equipment, foams, and fire protection systems. Without intervening actions, it is generally assumed that some fraction of the banks will be gradually released during the equipment's or product's lifetime, and some or all will be released at or after the end-of-life of equipment or products. With an intervention at the end of life, substances may be collected, stored, recycled, or destroyed, thereby preventing their release into the atmosphere. All releases to the atmosphere, as well as destruction, result in a decrease in the bank size.

Global warming potential (GWP) / GWP weighting

The GWP of a substance is a metric for quantifying its relative contribution to climate warming. GWP is defined as the ratio of the radiative forcing for a given mass emission of that substance to the radiative forcing for the same mass emission of CO_2 summed over a given time period (typically 20 or 100 years). In this report, a 100-yr time window is implied unless otherwise stated. As such, the GWP of CO_2 is defined to be unity. In comparisons of the potential impacts on climate from changes in the emissions of different gases, emissions are often weighted by their respective GWP and expressed as "GWP-weighted emissions" in units of "Gt CO_2-equivalent".

Shared socioeconomic pathways (SSPs)

Shared socioeconomic pathways (SSPs) were developed by the climate change research community to describe a range of plausible societal futures out to the year 2100. SSPs are the main scenarios assessed in the Sixth Intergovernmental Panel on Climate Change (IPCC) report, replacing the previous generation of scenarios, the Representative Concentration Pathways (RCPs). SSPs define timelines of atmospheric emissions of GHGs expressed in units of Gt CO_2-eq. SSPs were developed based on a range of socioeconomic development trajectories, coupled with the expected global-mean radiative forcing from GHGs in 2100. The SSPs include scenarios for "Sustainability" (SSP1), "Middle of the Road" (SSP2), "Regional Rivalry" (SSP3), "Inequality" (SSP4), and "Fossil-fueled Development" (SSP5) pathways. For example, SSP2-4.5 is a "Middle of the Road" pathway that ends in 2100 with a radiative forcing of 4.5 W m^{-2}. The SSPs also include a new, very low emissions scenario which is consistent with staying below 1.5 °C of warming. Here, projections of future ozone abundances are given for specific SSPs.

1 ABUNDANCES AND TRENDS IN OZONE-DEPLETING SUBSTANCES (ODSs)



The High Altitude Observatory at Jungfraujoch in Switzerland monitors a suite of more than 50 compounds, such as chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), perfluorocarbons (PFCs), SF_6, and hydrofluorocarbons (HFCs), which are regulated under the Montreal Protocol on Substances That Deplete the Ozone Layer and the Kyoto Protocol. (Photo credit: Aerial Film Studio/Adobe Stock)

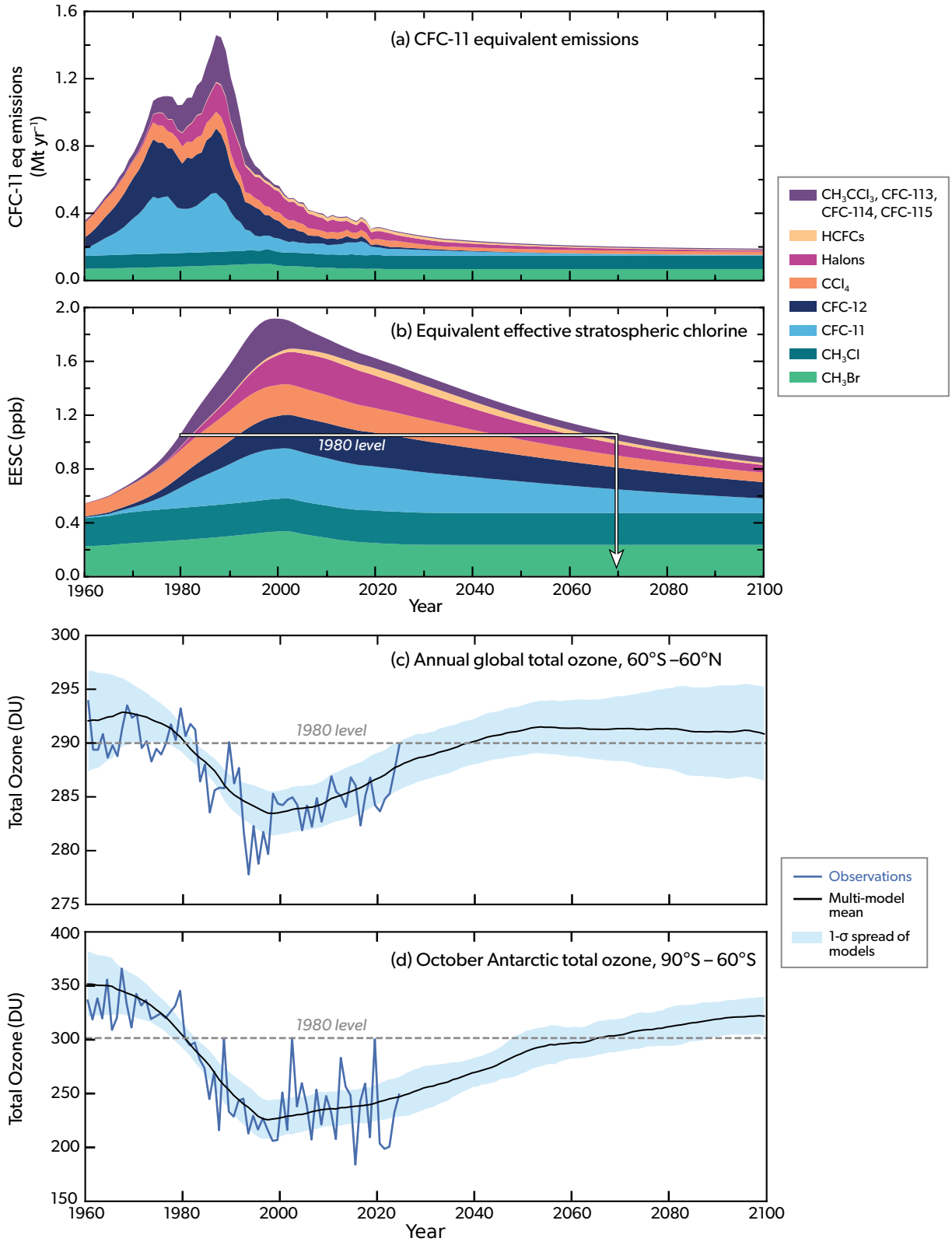
Global monitoring networks continue to deliver high-quality, consistent, ground-based, in situ observations of ozone-depleting substances, which form the basis of our knowledge on the temporal development of atmospheric mole fractions and emissions of ozone-depleting substances. Without such sustained and robust observations, quantitative information on atmospheric mole fractions and emissions of ozone-depleting substances and their long-term change, which allow the success of the Montreal Protocol to be monitored, would not be possible. The information from ground-based, in situ observations is supplemented by remote sensing observations and regional observations.

In this section, we update information on abundances, trends and emissions of ODSs and other substances of interest to the Montreal Protocol.

Changes in tropospheric chlorine and bromine over 2020–2024

- **Tropospheric chlorine (Cl) and bromine (Br) from long-lived ozone-depleting substances (ODSs) controlled under the Montreal Protocol continued to decline** (Figure ES-1).
    - **The observed rate of decline in tropospheric chlorine due to substances controlled under the Montreal Protocol was 21.5 ± 1.5 ppt Cl yr^{-1} between 2020 and 2024, which has accelerated compared to the decline of 16.0 ± 3.3 ppt Cl yr^{-1} measured between 2016 and 2020.** This accelerated decrease stems from a more rapid decline in Cl from chlorofluorocarbons (CFC) and a change from increasing to decreasing Cl from the major hydrochlorofluorocarbons (HCFCs) during this most recent four-year period. Chlorine from HCFCs declined sooner than projected in the 2022 A1 baseline scenario.
    - **The observed rate of decline in tropospheric bromine due to controlled substances was 0.13 ± 0.04 ppt Br yr^{-1} between 2020 and 2024, which is in line with the 0.1 ppt yr^{-1} decline projected in the 2022 A1 scenario.** The decline is mainly due to decreases in the abundance of halons.

ODSs and Ozone Timelines



(see caption on following page)

Figure ES-1. Timelines of: (a) CFC-11-equivalent emissions, (b) equivalent effective stratospheric chlorine (EESC), (c) global total column ozone, and (d) October Antarctic total column ozone. Panel (a): annual CFC-11-equivalent emissions for the ODSs shown in the legend computed by multiplying annual mass emissions of a substance by its ODP listed in the Annex of this report. Historical emissions are derived from the measured atmospheric abundances of individual ODSs. The future projections of emissions (after 2024) assume full compliance with the Montreal Protocol and are taken from the projections in Chapter 7 of this report. Panel (b): annual abundances of EESC for the mid-latitudes based on surface abundances (measured or derived from projected emissions and lifetimes) of the chlorine- and bromine-containing substances. The white line and arrow mark when EESC returns to its 1980 value. Panel (c): annual averages of global total column ozone over 60°S to 60°N latitudes. Panel (d): October averages of Antarctic total column ozone over 60°S to 90°S latitudes. Panels (c) and (d) include chemistry-climate model results (black line with blue shadings indicating model spread) and available observations (blue lines). The model projections assume compliance with the Montreal Protocol and an increase in greenhouse gases following the SSP2-4.5 (medium climate forcing) scenario. [Data sources. Panel (a): mixing ratios for the baseline scenario in Figure 7-5 and ODPs and lifetimes in Table A-5. Panel (b): mixing ratios for the baseline scenario in Figure 7-5 with fractional release factors in Table 7-6 and an alpha factor of 60. Panels (c) and (d): ozone timeseries derived from model results shown in Figures 3-16 and 4-18, respectively.]

- **For several ODSs, current emissions are likely dominated by losses associated with feedstock use, leakage of intermediates, or formation and release as by-products during the manufacture of other chemicals. As other sources have declined, emissions from feedstock-related processes have become better quantified. Typical emission factors for these processes are larger than assessed historically: on the order of 3–5% of production, rather than about 0.5%.** Atmospheric observations show that emissions have increased since 2010 for several controlled substances with few or no known dispersive uses, including CFC-115, CFC-113a, CFC-13, CFC-114a, and CFC-112a.
- **Tropospheric chlorine from very short-lived substances (VSLSs) increased on average by 4.1 ppt yr^{-1} (2.7% yr^{-1}) from 2020 to 2024, which was driven by increased anthropogenic sources.** This rate of increase is similar to the mean rate over the past decade. VSLSs accounted for about 4.5% of total global tropospheric chlorine in 2024.

Changes in total stratospheric chlorine and bromine

- **Total chlorine entering the stratosphere from both controlled and non-controlled substances declined by 14% between the 1993 peak (3670 ppt) and 2024 (3160 ppt) (Figure ES-2).** This long-term decrease of about 0.5% yr^{-1} is comparable with the long-term decline in upper stratospheric HCl of 0.61 ± 0.06% yr^{-1} since its peak in 1997 through 2024.
- **Total bromine entering the stratosphere from controlled and non-controlled substances declined by 16% between the 1999 peak (22.0 ppt) and 2024 (18.4 ppt) (Figure ES-2).**
- **EESC has continued to decline and was, in 2024, 18% lower than the peak values in mid-latitudes (1998) and 13% lower under polar winter conditions (2001 peak). These changes are, respectively, 44% and 28% of the decrease required to reach the 1980 reference values.** As other factors contribute to trends in stratospheric ozone, the evolution of stratospheric ozone is not expected to fully follow the evolution of EESC.

Chlorofluorocarbons (CFCs)

- **Total chlorine from CFCs has continued to decline in the atmosphere at an average rate of 16.5 ppt yr^{-1} between 2020 and 2024.** This decrease is faster than the 15.5 ppt yr^{-1} decline projected for this period in the 2022 A1 scenario and the observed 13.5 ppt yr^{-1} decline for the period from 2016 to 2020.
- **Global abundances of CFC-11, -12, -113, and -114 continued to decline in the atmosphere between 2020 and 2024.** These gases contributed 20%, 31%, 6%, and about 1%, respectively, to the chlorine entering the stratosphere in 2024.
- **Emissions of CFC-11 have continued to decline following a period of enhanced emissions between 2013 and 2018.** CFC-11 emissions were 27 ± 10 Gg yr^{-1} in 2024, 20 ± 5 Gg yr^{-1} lower than 2020 emissions. For CFC-12, the reduction in emissions between 2020 and 2024 was 13 ± 9 Gg yr^{-1}, reaching 14 ± 21 Gg yr^{-1} in 2024. Global emissions of CFC-113 have shown no detectable trend and remain around 4 ± 2 Gg yr^{-1} between 2020 and 2024.
- **Global abundances and emissions of the minor CFCs CFC-112a, CFC-113a, CFC-114a, and CFC-115 were stable or increased between 2020 and 2024.** Summed together, the minor CFCs, including also CFC-13, contributed less than 0.7% to total chlorine. Summed emissions of minor CFCs increased from 5.4 to 7.1 Gg yr^{-1} between 2020 and 2024, likely associated with feedstock usage. These emissions were dominated by CFC-113a.

Carbon tetrachloride (CCl_4)

- **The atmospheric abundance of CCl_4 continued to decrease between 2020 and 2024.** In 2024, CCl_4 contributed about 9% of the chlorine entering the stratosphere.
- **Global CCl_4 emissions have remained approximately constant during the last 15 years at about 44 Gg yr^{-1}, with annual variability of about 3 Gg yr^{-1}.** The overall discrepancy between bottom-up and top-down emission estimates has been reduced since the previous Assessment, mainly due to an increase in feedstock-related bottom-up estimates. The two approaches agree within their uncertainty ranges, although the central top-down estimate is about 50% higher than the central bottom-up estimate.

Halogen Gases Entering the Stratosphere

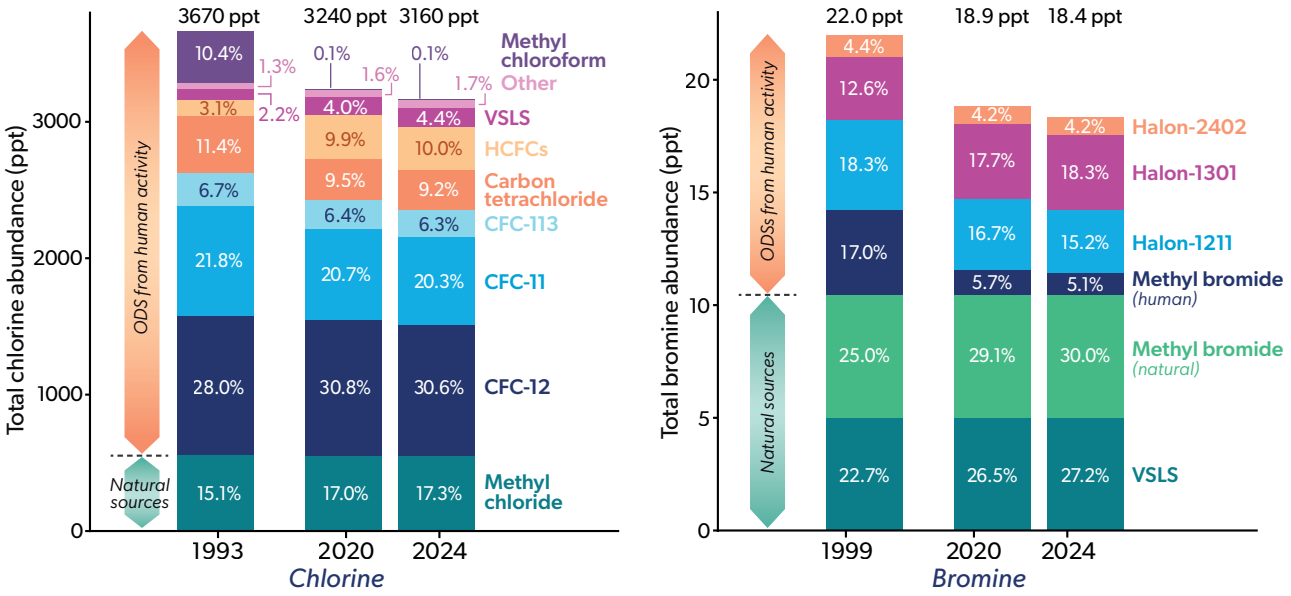


Figure ES-2. Chlorine and bromine input to the stratosphere for a reference year (1993 for chlorine and 1999 for bromine) and for 2020 and 2024, showing different species and classes of compounds. The reference years are the year of maximum chlorine or bromine loading of the troposphere, respectively. Mole fractions of long-lived gases were derived from surface observations from global networks (Advanced Global Atmospheric Gases Experiment (AGAGE), National Oceanic and Atmospheric Administration (NOAA)) along with some observations from the University of East Anglia (UEA) and the Forschungszentrum Jülich (FZJ). The VSLS contributions for bromine are included as a constant 5 ppt, as in previous Assessments. The VSLS chlorine contribution is based on the VSLS input from a model constrained by observed surface boundary conditions. Total VSLS chlorine input derived in this way is 80 ppt, 130 ppt, and 140 ppt for years 1993, 2020, and 2024, respectively. For chlorine, HCFCs include HCFC-22, HCFC-141b, HCFC-142b, and HCFC-124; "other" includes contributions from minor CFCs (CFC-13, CFC-112, CFC-113a, CFC-114, CFC-114a, and CFC-115) and halon-1211. CH_3Cl is assumed to have only natural sources, despite indications of some anthropogenic contributions. The contribution of natural sources to CH_3Br mole fractions is estimated to be a constant 5.5 ppt based on the published firn air and ice core measurements, whereas the anthropogenic contribution was estimated as the global surface mole fractions measured by AGAGE and NOAA minus 5.5 ppt. [See also Figure 1-20]

Hydrochlorofluorocarbons (HCFCs)

As a result of Montreal Protocol controls, chlorine from HCFCs has begun decreasing in the atmosphere. This decline was earlier than projected in previous assessment scenarios. While total chlorine from HCFCs had increased by 2.5 ± 0.8 ppt yr^{-1} between 2016 and 2020, it decreased by 2.6 ppt yr^{-1} between 2023 and 2024, and this change was dominated by the decline in HCFC-22. In 2024, HCFCs contributed about 10% to chlorine entering the stratosphere.

- **Global abundances of HCFC-22 peaked in 2021; those of HCFC-141b peaked between 2020 and 2021 and HCFC-142b continued to decline between 2020 and 2024.** Global emissions of HCFC-22 were 297 ± 54 Gg yr^{-1} in 2024, which is 49 ± 9 Gg yr^{-1} lower than in 2020. Emissions of HCFC-141b and HCFC-142b decreased by 7% and 13%, respectively, between 2020 and 2024.
- Emissions of several low-abundance HCFCs (e.g., HCFC-124, HCFC-133a, and HCFC-132b) remained stable or increased between 2020 and 2024, likely related to their by-production during fluorochemical manufacture.

Halons and methyl bromide (CH_3Br)

- **Bromine from halons continued to decline at an average rate of 0.1 ppt yr^{-1} between 2020 and 2024.** Halon-1211 and halon-2402 abundances declined over this period, while halon-1301 showed no significant trend. In 2024, halons contributed about 38% to stratospheric bromine, with halon-1301 comprising the largest fraction. Emissions of halon-1301 and halon-2402 remained relatively constant, while emissions of halon-1211 declined by about 25% between 2020 and 2024.
- **The atmospheric abundance of methyl bromide (CH_3Br) averaged 6.5 ± 0.1 ppt between 2020 and 2024, which is about 30% lower than its peak in 1996–1998.** CH_3Br now contributes about 35% to stratospheric bromine. Reported controlled production for critical-use exemptions of CH_3Br between 2020 and 2024 was close to zero, and quarantine and pre-shipment (QPS) consumption has been relatively stable for more than two decades at 10 ± 1 Gg yr^{-1}. Gaps remain in the understanding of the global budget of CH_3Br, with sinks outweighing known sources.

Table ES-2. Contributions of ODSs controlled under the Montreal Protocol to tropospheric chlorine and bromine in 2024, and annual average trends between 2020 and 2024.

	Contribution to tropospheric chlorine and bromine in 2024 (ppt Cl or Br)	Changes in tropospheric chlorine and bromine (ppt Cl or Br per year) from 2020 to 2024
Controlled chlorine substances by group		
Chlorofluorocarbons (CFCs)	1859	−16.5 ± 0.7
Methyl chloroform (CH_3CCl_3)	2.7	−0.4 ± 0.05
Carbon tetrachloride (CCl_4)	292	−3.5 ± 0.5
Hydrochlorofluorocarbons (HCFCs)	317	−1.0 ± 1.3
Halon-1211	2.8	−0.1 ± 0.0
Total chlorine from controlled substances	*2474*	*−21.5 ± 1.5*
Controlled bromine substances by group		
Halons	6.9	−0.10 ± 0.01
Methyl bromide (CH_3Br)	6.5	−0.03 ± 0.05
Total bromine from controlled substances	*13.3*	*−0.13 ± 0.04*

Halogenated very short-lived substances (VSLSs)

- **CH_2Cl_2 is the most abundant of the four regularly monitored and most important chlorinated VSLSs (C_2Cl_4, $CHCl_3$, CH_2Cl_2, and CH_2ClCH_2Cl). Its surface abundance increased from 41 to 50 ppt between 2020 and 2024.** The global mean surface mole fraction of $CHCl_3$ declined from 8.4 ppt in 2020 to 7.8 ppt in 2024, and this change continued the downward trend previously reported for 2016–2020. Surface mole fractions of both CH_2ClCH_2Cl and C_2Cl_4 showed no detectable trend between 2020 and 2024.
- **The VSLS chlorine input to the stratosphere from the four most important chlorinated VSLS source gases and from product gases is estimated from atmospheric measurements and modeling at 140 ± 30 ppt in 2024, compared to the 2020 value of 130 ± 30 ppt reported in the previous Assessment.** In 2024, chlorine from VSLSs contributed about 4.4% to the chlorine entering the stratosphere.
- **The overall estimates of the bromine and iodine inputs to the stratosphere from VSLSs remain unchanged since the last Assessment.** Brominated VSLSs, with mainly natural sources, contribute 5 ± 2 ppt to stratospheric bromine, which is 27% of the bromine entering the stratosphere in 2024.

Other gases that influence stratospheric ozone and climate

- **The global mean mole fraction of nitrous oxide (N_2O) continued to increase since the previous Assessment, reaching 338.0 ± 0.9 parts per billion (ppb) in 2024.** The average annual growth rate between 2020 and 2024 was 1.2 ± 0.1 ppb yr^{-1}, which is higher than the 2016–2020 annual increase of 1.0 ± 0.1 ppb yr^{-1} reported in the previous Assessment and about 50% higher than rates of increase during the beginning of the century. The 2020–2024 increase exceeds all of the IPCC projected pathways.
- **Anthropogenic N_2O emissions (ODP-weighted) in 2024 were 18–36% of CFC peak emissions in 1988. With the substantial decline in CFC emissions as a result of Montreal Protocol controls, ODP-weighted emissions of N_2O have become relatively more important and in 2024 were 4–8 times the sum of all CFCs.**
- **The global mean mole fraction of methane (CH_4) continued to increase, reaching 1929 ± 5 ppb in 2024.** This increase corresponds to an average annual growth rate of 13 ± 5 ppb yr^{-1} for CH_4 during the period 2020–2024 —higher than the 2016–2020 mean growth rate of 9 ± 2 ppb yr^{-1}.
- **The atmospheric abundances of most non-ODS, non-HFC, fluorinated substances (e.g., SF_6, PFCs, SO_2F_2, NF_3) have continued to increase.** Total direct radiative forcing from these species increased from 0.013 W m^{-2} in 2020 to 0.015 W m^{-2} in 2024. This contribution corresponds to approximately 30% of the radiative forcing attributable to HFCs in 2024.

2 HYDROFLUOROCARBONS (HFCs)



2026 marks the 50th anniversary of the Cape Grim Baseline Air Pollution Station in Tasmania, Australia. The station maintains the most comprehensive baseline measurements for ozone-depleting substances in the Southern Hemisphere, tracking over 30 distinct ODSs and related halogenated gases. (Photo credit: Paul Krummel, CSIRO)

Hydrofluorocarbons (HFCs), controlled under the Kigali Amendment, have been used as replacements for ODSs because their impact on stratospheric ozone depletion is negligible. Many HFCs have large GWPs that are comparable to or even larger than those of many HCFCs and smaller than those of most CFCs. HFOs and HCFOs have been introduced to replace HFCs in many applications because they have low-GWPs. Some of these HFOs and HCFOs (as well as HFCs and HCFCs) degrade at least partly to trifluoroacetic acid (TFA) and other persistent compounds. Table A-4 of the Annex summarizes the molar yields of these breakdown products, as well as example categorizations of Montreal Protocol-controlled and related compounds based on a small subset of definitions for per- and polyfluoroalkyl substances (PFAS).

Kigali Amendment

- **Global HFC emissions are aligned with the phase-down schedule of HFC production and consumption under the Kigali Amendment, based on projections from earlier Assessments.** Abundances and global emissions are still increasing, as expected, for most HFCs. Restrictions on HFC production and consumption, including under the Kigali Amendment, are now reflected in measured abundances and emissions.
- **Adherence to the limits on HFC production and consumption in the Kigali Amendment is projected to prevent up to 0.4 °C of global temperature rise by 2100.** HFCs were estimated to have contributed 0.02 °C to global temperature increases through 2024, and their contribution is projected to remain below 0.06 °C through the 21st century (see Figure ES-3).

Changes in emissions and abundances

- **As expected, annual CO_2-equivalent HFC emissions have surpassed emissions of all ODSs combined since the last Assessment, following the transition from ODSs to HFCs.** Total HFC emissions were 1.4 ± 0.1 Pg CO_2-eq yr^{-1} in 2024, 17% higher than in 2020 (1.2 ± 0.1 Pg CO_2-eq yr^{-1}). As projected in the last Assessment, HFC-125 has become the largest contributor to CO_2-eq emissions from all HFCs, surpassing HFC-134a.
- **The radiative forcing from HFCs has increased, as expected, by 27% between 2020 and 2024, which follows the projection from the last Assessment.**
- **Reported HFC emissions by Annex I countries classified under the UNFCCC account for less than one third of the global CO_2-eq emissions derived from measurements**

in 2022, the last year for which all Annex I countries reported. Current reporting frameworks do not capture most global HFC emissions derived from measurements. HFC production and consumption based on reported data has recently become available through ratification of the Kigali Amendment by countries dominating production and consumption of controlled HCFCs and HFCs.

Emissions of HFC-23

- **HFC-23 emissions have decreased from 16 ± 1 Gg yr^{-1} in 2020 to 14 ± 1 Gg yr^{-1} in 2024. Emissions decreased despite an increase in HCFC-22 production, the process thought to be primarily responsible for HFC-23 generation.** The decrease may reflect increased mitigation of HFC-23 and/or a decrease in emissions of other lesser-understood sources. The ongoing increase in HCFC-22 production is driven by feedstock production.
- **More than three quarters of HFC-23 emissions in 2024 derived from atmospheric measurements cannot be explained by reported emissions and other known sources.** The unexplained emissions emerged around 2015 and coincide with an increase in reported abatement of HFC-23.

Emerging uses

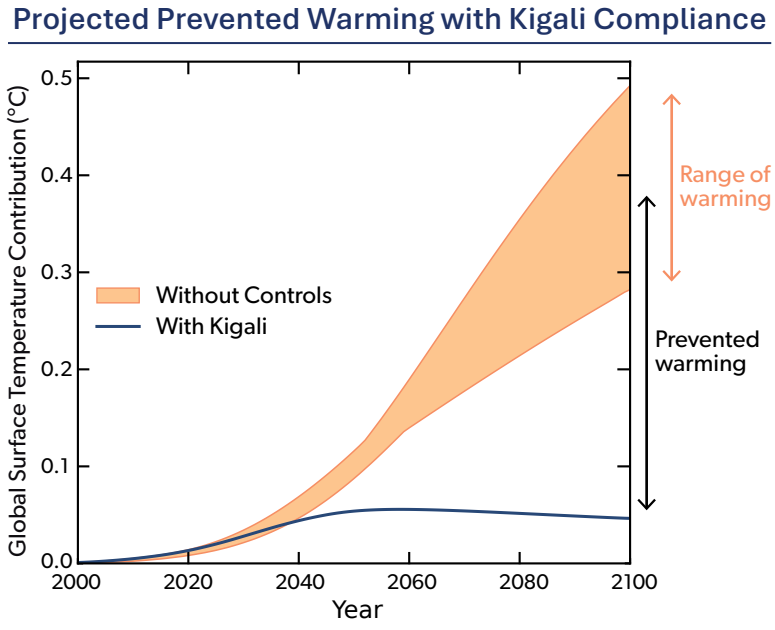
- **Production of some HFCs for feedstock is increasing, primarily driven by use of HFC-152a in the polymer industry (over 100 Gg yr^{-1}).**
- **Emerging applications of HFCs, for example in air conditioning and refrigeration, include mixtures of HFCs with low-GWP alternatives (e.g., HFOs) to lower their climate impact.**
- **Available observations of short-lived HFOs and HCFOs show that their emissions are increasing rapidly around the world. This increase is consistent with the adoption of these next-generation alternatives.** Atmospheric measurements in Europe, East Asia, and the USA show that HFO-1234yf, HFO-1234ze(E), and HCFO-1233zd(E) emissions are increasing. Despite their short atmospheric lifetimes, these compounds have become detectable far from major emissions regions, e.g., in the Arctic.

Atmospheric by-products

The breakdown of some HFCs, HFOs, and HCFOs in the atmosphere can form very persistent products. For example, HFC-23, CFC-13, PFC-14, trifluoroacetic acid (TFA), and others are formed in the atmospheric degradation of Montreal Protocol-controlled substances and some alternatives. Yields for these persistent compounds are summarized in Table A-4 of the Annex.

- **The breakdown of some HFCs, HFOs, and HCFOs in the atmosphere forms HFC-23. This source is less than 2% of current global HFC-23 emissions and is projected to remain under 20% throughout the 21st century relative to current emissions of HFC-23.**
- **Levels of persistent TFA in precipitation and inland water bodies are measurably increasing, in part because of the breakdown in the atmosphere of some HCFCs and HFCs controlled under the Montreal Protocol, as well as HFOs and HCFOs. The atmospheric formation of TFA is expected to increase in the coming decades due to increased use of HFOs and HCFOs.** Certain pesticides and industrial or wastewater discharges could also contribute to the increase of TFA in surface waters.
- **Some definitions of per- and polyfluoroalkyl substances (PFAS) include substances controlled by the Montreal Protocol and their alternatives.** Example definitions of PFAS and substance categorization are included in Table A-4 of the Annex. As such, some substances may become subject to regulation outside of the Montreal Protocol.

Figure ES-3. HFC contributions to global average surface temperature change during the 21st century in two scenarios. In the first scenario, the HFC contribution is derived assuming full compliance with the 2016 Kigali Amendment and other control measures (dark blue line). In the second scenario, the HFC contribution is derived assuming no past or future controls on HFC production and consumption (orange shaded area, unchanged from the 2022 report). The prevented warming in the first scenario and the range of estimated warming in the second scenario are indicated to the right of the figure. Uncertainties arise primarily from the range of assumed HFC production volumes. The contributions from HFC-23 emissions are not included here. All projections assume a constant climate sensitivity.



Global Estimates of HFC-23 Emissions and Generation

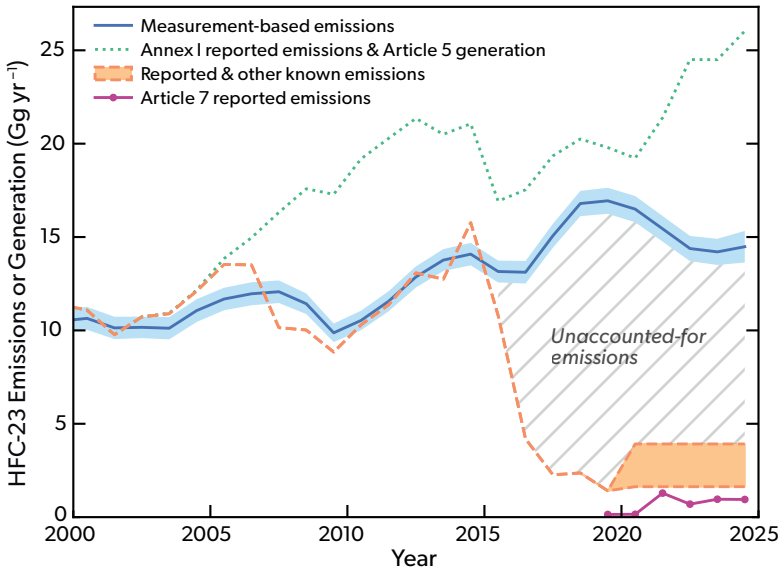


Figure ES-4. Global estimates of emissions and generation of HFC-23. The blue line shows the measurement-derived global emissions of HFC-23. The green dotted line shows estimated HFC-23 generation from by-production associated with HCFC-22 manufacture in A5 countries plus UNFCCC-reported emissions from Annex 1 countries; these totals are similar to A7 reporting of total generation in 2023 (within 0.1 Gg) and 2024 (within 2.2 Gg), years when that reporting was considered complete. The orange dashed line and shading show reported and estimated emissions from all known sources, including secondary atmospheric production. Emissions of HFC-23 reported under Article 7 of the Montreal Protocol are shown by a pink line with circle markers. The hatched area shows the global emissions that cannot be accounted for from all known sources. See Chapter 2 for more details.

Additional mitigation

- **Emissions from appliances could be reduced by nearly half through lifecycle refrigerant management of HFCs and HCFCs between 2025 and 2050, relative to no management.** Lifecycle refrigerant management can reduce emissions of refrigerants and lower demand for new refrigerant production through measures including leakage prevention, refrigerant recovery, recycling, reclamation and reuse, and destruction at end of life.
- **Additional climate benefits could be achieved through improving energy efficiency of equipment containing HFCs and their alternatives.**

3 STRATOSPHERIC OZONE



NOAA's Mauna Loa Observatory in Hawaii serves as a primary baseline station for monitoring ozone-depleting substances and related trace gases tracking nearly 60 atmospheric compounds, including CFCs, HCFCs, HFCs, halons, PFCs, methyl bromide, and methyl chloride. (Photo credit: Jonathan Kingston)

The Montreal Protocol and its Amendments and Adjustments have been effective in decreasing the abundance of ODSs in the atmosphere. As in recent Assessments, the clearest signs of corresponding ozone recovery are seen in the upper stratosphere and in the Antarctic lower stratosphere in spring. Southern Hemisphere mid-latitude TCO also continues to show a positive trend. As expected, ozone recovery remains difficult to detect in other regions because of large variability on interannual-to-decadal timescales and confounding factors such as GHG-driven circulation changes. Episodic events such as volcanic eruptions and intense wildfires have temporarily affected stratospheric ozone both by inducing circulation changes and by enhancing chemical depletion.

Changes to date in polar ozone

The response of polar ozone to chemical and dynamical processes is well understood. Polar ozone depletion is driven by anthropogenic chlorine and bromine, with year-to-year variability in the severity of the chemical loss in both hemispheres primarily controlled by meteorological conditions.

- **Recovery of Antarctic stratospheric ozone continues to progress.** New lines of evidence and analyses since the 2022 Assessment strengthen previous findings that the Antarctic ozone hole has generally diminished in area and depth since the year 2000.
- **Antarctic ozone holes observed between 2022 and 2025 exhibited substantial variability in area, depth, and longevity.** The variability during recent years is consistent with our understanding and was primarily driven by dynamical forcings and radiative feedbacks.
- **In the Arctic, observed trends in ozone remain small compared to the large year-to-year variability, precluding confident diagnosis of recovery over the 2000–2025 period.**

Changes to date in global ozone

Total column ozone

- **Aggregated ground- and space-based observations indicate an increase of 0.5% decade^{-1} (with a 2-sigma uncertainty of ±0.3% decade^{-1}) in near-global (60°S–60°N) average TCO over the 1996–2024 period.** This trend is statistically significant and is consistent with model simulations and our scientific understanding of the

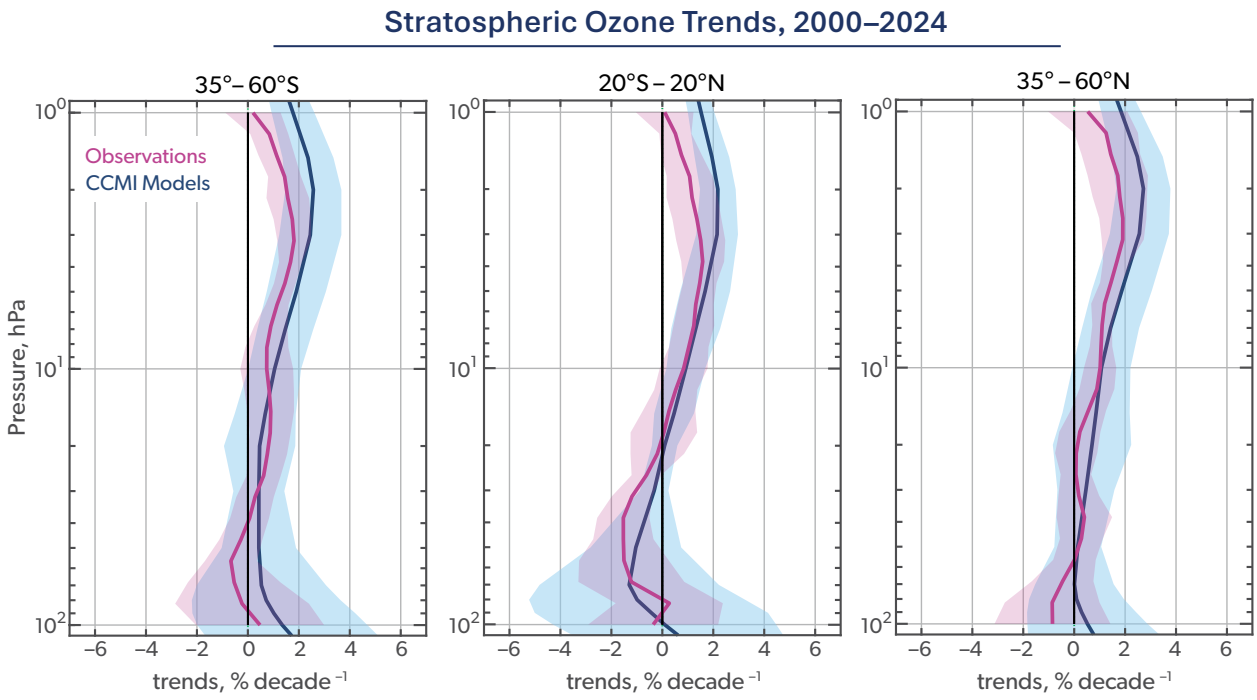


Figure ES-5. Ozone trends in the stratosphere from 2000 to 2024 for three latitude bands. Ozone trends derived from satellite observations (magenta lines, with uncertainty ranges given by the magenta shading) are compared with trends from chemistry-climate models (blue lines, with uncertainty ranges given by the blue shading). The largest increase in ozone has occurred in the upper stratosphere across all three regions, where observations and models are in best agreement. The maximum positive trends of about 2% per decade occur near 40-km altitude. Uncertainties in the trends become larger below 25 km, where observations in the mid-latitudes show a slight decrease while models show a slight increase. [See also Figures 3-9 and 3-10]

processes controlling ozone. Whether this significance will remain robust through the next Assessment cycle is uncertain because TCO exhibits large variability on interannual-to-decadal timescales. Present-day (2021–2024) annual mean near-global TCO remains about 2% lower than the 1964–1980 average.

- **Over the same 1996–2024 period, the TCO trends averaged over broad latitude bands are positive, with signs of recovery in SH mid-latitudes. Present-day (2021–2024) TCO is lower than or matches the baseline (1964–1980) period:**
  - SH mid-latitude (60°S–35°S) TCO has changed by +1.1% decade^{-1}, with a 2-sigma uncertainty of ±0.9% decade^{-1}, and is about 6% lower than the baseline period.
  - NH mid-latitude (35°N–60°N) TCO has changed by +0.1% decade^{-1}, with a 2-sigma uncertainty of ±0.8% decade^{-1}, and is about 2% lower than the baseline period.
  - Tropical (20°S–20°N) TCO has changed by +0.2% decade^{-1}, with a 2-sigma uncertainty of ±0.4% decade^{-1}, and matches the abundance from the baseline period. In this region, lower stratospheric ozone is decreasing primarily due to transport changes, while tropospheric ozone is increasing due to changes in precursor emissions.

The latitudinal pattern of these TCO trends is largely consistent with our scientific understanding and is reproduced by the latest set of chemistry-climate models (CCMs).

Vertically resolved ozone

Vertically resolved trends remain positive in the upper stratosphere, while trends in the lower stratosphere are less negative than those reported in the previous Assessment (Figure ES-5).

- **Measurements continue to show unambiguous increases in upper stratospheric ozone for 2000–2024.** Positive trends have a range of ~1–3% decade^{-1} at mid-latitudes in both the Northern and Southern Hemispheres and ~0.5–2.5% decade^{-1} in the Tropics.
- **Lower stratospheric ozone shows a small and uncertain decrease for 2000–2024 of 0.5–2.5% decade^{-1} in the Tropics and ~0.5% decade^{-1} in mid-latitudes.** The tropical decrease is consistent with climate change–driven acceleration of the large-scale stratospheric circulation. Observed mid-latitude trends are less negative than those reported in the previous Assessment. Lower stratospheric mid-latitude ozone has large variability, and measurements of this region are more uncertain than in the middle and upper stratosphere. Thus, the trends have large uncertainties and are not robust across all datasets. As in the last Assessment, most CCMs indicate a positive trend in mid-latitudes. The magnitude of the model trends is now

smaller, such that the measurement-model disagreement is reduced and appears to be primarily associated with dynamics.

- **Zonally averaged TCO trends are broadly consistent with those in the integrated stratospheric column and thus primarily reflect ozone changes in the stratosphere.** However, in some locations tropospheric ozone trends over the past two to three decades are of the same order of magnitude as stratospheric column trends. As a result, attribution of TCO trends in those locations requires understanding ozone trends in both the stratosphere and troposphere.

Future ozone changes

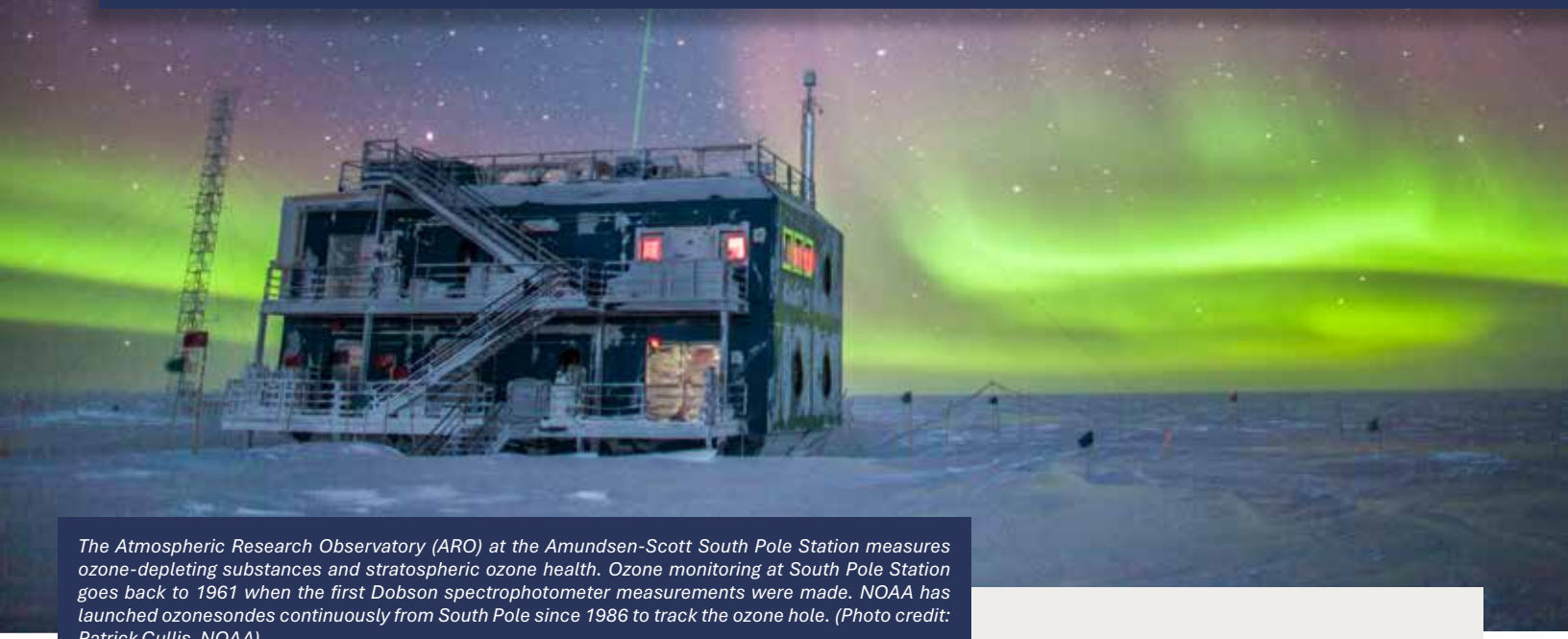
As in the previous Assessment, the key drivers of future stratospheric ozone abundances continue to be declining ODS concentrations coupled with the effects of increasing GHGs (e.g. CO_2-driven cooling in the upper stratosphere). TCO will also be affected by changes in the tropospheric ozone burden.

Return dates are defined as the return of decadally smoothed TCO time series to a historical benchmark. As a result, projected return dates can only be evaluated against those from observations several years after the nominal return date has passed. Given the large variability in Arctic ozone (particularly in recent years) and the slow rate of ODS decline, it has become clearer that the concept of the date of return to 1980 levels is not appropriate for this region. In contrast to previous Assessments, a projected Arctic return date is not highlighted in this Executive Summary.

The new CCM simulations used to estimate the return dates reported here still follow a "middle of the road" climate scenario (SSP2-4.5) and the WMO 2018 A1 ODS scenario. The most recent ODS scenario produced for this Assessment (described in Chapter 7) has an EESC return date that is approximately a decade later than the one used here.

- **Estimates of the year in which near-global (60°S–60°N) TCO returns to 1980 levels (~2040) are consistent with those in previous Assessments.** The NH mid-latitudes are projected to return before the near-global mean date, while the SH mid-latitudes are expected to return after the near-global mean date.
- **Near-global (60°S–60°N) TCO is projected to return to 1980 values more than two decades before stratospheric total reactive chlorine (Cl_y) is projected to reach its 1980 values.** This difference reflects the influence of changes in stratospheric composition, temperature, and circulation associated with changing GHG concentrations, and tropospheric ozone precursor emissions.
- **Projections of TCO are dependent on which future scenario of GHG and tropospheric ozone precursor concentrations is used.** While near-global (60°S–60°N) stratospheric column ozone is projected to increase over the coming decades under all scenarios, the magnitude of this increase varies between scenarios. In contrast, both the magnitude and the sign of tropospheric column ozone projections differ substantially between future emissions scenarios.
- **The Antarctic ozone hole is expected to gradually close because of declining ODSs. Springtime polar cap TCO is expected to return to 1980 values during the 2060s.** This return date is similar to that in previous Assessments.
- **Arctic ozone depletion is expected to continue to occur during cold stratospheric winters/springs.** As ODS abundances decline, later years with similarly cold conditions are expected to experience less severe depletion.
- **Exceptional events can temporarily perturb stratospheric composition.** The Australian New Year's (ANY) wildfires and the Hunga volcanic eruption both caused reductions in SH mid-latitude TCO of around 5% during the 2020–2024 period; these reductions were driven by both circulation changes and halogen-driven chemical loss. Chemistry on ANY smoke particles increased the area of the 2020 ozone hole by about 10%. Although Hunga also affected polar chemical processing, the impact on Antarctic ozone was small compared to typical interannual variability. The impact on Arctic ozone was negligible. While the Hunga eruption was unusual due to the submarine nature of the volcano, eruptions without excess water vapor have occurred frequently over the past two decades, and several previous eruptions have had a larger impact on ozone. The meteorological conditions conducive to large wildfires capable of perturbing stratospheric composition are expected to become more common in the future.
- **Emerging technologies such as a hydrogen economy, rocket launches/space debris, and supersonic aviation have so far had only minor effects on stratospheric ozone depletion compared to those from ODSs.** Even under very large leakage scenarios, current projections suggest that a potential future hydrogen economy will have little impact on ozone recovery. New studies also confirm previous findings that the impact on ozone from both supersonic and hypersonic aircraft fleets is expected to be small, with some dependence on fuel mixtures and flight corridors. The impacts of a growing rocket industry are highly uncertain due to dependencies on fuel type, the number of launches and their location, and the possible alteration of ozone chemistry by particles emitted during launch and reentry. The expected continued rapid expansion of space activity over the coming decades will make understanding these impacts increasingly critical.
- **By the time of the next Assessment, daily global vertically resolved spaceborne measurements of ozone-related atmospheric constituents (e.g., chlorine-containing gases and long-lived transport tracers) that underpin much of our understanding of the chemical and dynamical processes controlling ozone changes will no longer be available, impeding the ability to attribute changes in the stratospheric ozone layer to ODSs.** A multi-year gap in these trace gas observations is expected between the end of current capabilities (no later than 2028) and the earliest planned future mission (no earlier than 2030). Moreover, there are no plans to replace current spaceborne measurements of the largest chlorine reservoir (HCl). Daily global measurements of ozone and aerosol are expected to continue outside of polar night through the gap period.

4 STRATOSPHERIC OZONE CHANGES AND CLIMATE



The Atmospheric Research Observatory (ARO) at the Amundsen-Scott South Pole Station measures ozone-depleting substances and stratospheric ozone health. Ozone monitoring at South Pole Station goes back to 1961 when the first Dobson spectrophotometer measurements were made. NOAA has launched ozonesondes continuously from South Pole since 1986 to track the ozone hole. (Photo credit: Patrick Cullis, NOAA)

The stratosphere is the home of the ozone layer, and its chemical, radiative, dynamical, and transport processes control changes in ozone. Changes in stratospheric temperature and circulation under continued greenhouse gas (GHG) increases and declines in ozone-depleting substances (ODSs) are key drivers of future ozone evolution. In turn, changes in stratospheric ozone and ODSs have important impacts on climate from the stratosphere to the ocean.

Impacts of changes in stratospheric ozone and ODSs on climate

- **ODSs have exerted a positive net effective radiative forcing (ERF) on climate, contributing to observed global warming. New model evidence indicates that the net ERF of ODSs as of the early 21st century is between 0.09 and 0.22 W m^{-2}, which is a smaller contribution of ODSs to global warming than previously assessed.**
  - The direct ERF of ODSs is around +0.35 W m^{-2} in 2024, which is about 15% of the CO2 radiative forcing over 1750–2024.
  - The indirect ERF of ODSs is mainly from ozone depletion and leads to a net ERF of ODSs that is approximately 25–65% of the direct ERF. While uncertainty remains, the indirect effect has been better quantified since the last Assessment.
  - The ERF of HFCs is around 0.054 W m^{-2} in 2024.
- **The control of ODS emissions due to the implementation of the Montreal Protocol and its Amendments has prevented additional global warming, and these benefits will grow over the 21st century. The expected reduction in HFC emissions due to the Kigali Amendment will prevent additional warming in the future.**
  - The prevented global warming from ODSs due to the Montreal Protocol is estimated to be 0.09–0.41 °C by 2025, and 0.25–0.89 °C by 2050.
  - The prevented global warming from HFCs due to the Kigali Amendment is projected to be 0.05–0.06 °C by 2050 and 0.2–0.4 °C by 2100.
- **Antarctic stratospheric ozone depletion and recovery have caused substantial changes in Southern Hemisphere atmospheric and oceanic circulation.**
  - Observed changes in the Southern Hemisphere atmospheric and oceanic circulation attributed to ozone depletion include a delay of the springtime polar vortex breakdown, which drives a poleward shift of the summertime mid-latitude tropospheric jet stream and a poleward expansion of the summertime southern Hadley cell edge (Figure ES-6). These circulation changes have led to regional shifts in precipitation and surface temperatures.

Effects of Stratospheric Ozone Depletion and Recovery on Climate

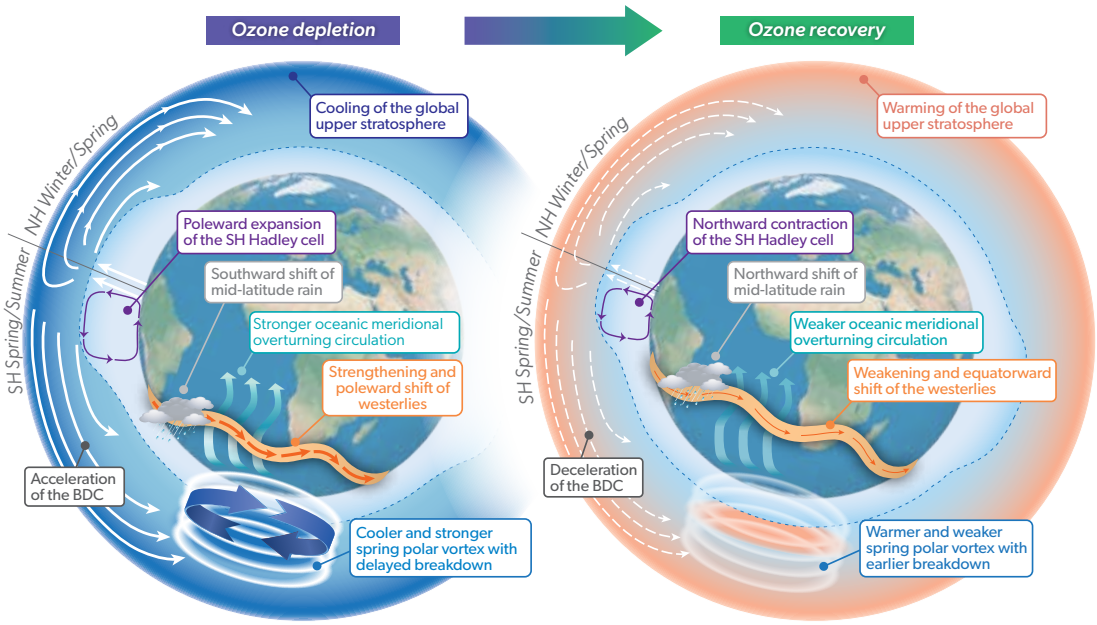


Figure ES-6. Schematic of the aspects by which stratospheric ozone depletion (left) and ozone recovery (right) influence stratospheric temperature and atmospheric and oceanic circulation for conditions in the Southern Hemisphere spring/summer and Northern Hemisphere winter/spring. The aspects described in the figure text boxes document how stratospheric ozone depletion followed by recovery affects stratospheric circulation through radiative-dynamical feedbacks, and in turn alter conditions in the troposphere, surface, and ocean via dynamical downward coupling. As stratospheric ozone recovers, the changes due to depletion are reversed. See more detail in Box 5-1.

- Changes in surface winds associated with the poleward shift in the tropospheric jet stream have driven a stronger meridional overturning circulation (MOC) in the Southern Ocean (Figure ES-6). While changes in the MOC have been partly attributed to ozone depletion along with the radiative effect of ODSs in some model studies, observed warming of the upper ocean is primarily attributed to increasing greenhouse gases.
- Consistent with the influence of ozone recovery, Southern Hemisphere atmospheric circulation trends attributed to ozone depletion have slowed since around 2000. Ozone recovery will continue to drive circulation changes (Figure ES-6) that oppose those driven by increased greenhouse gases.

Observed and simulated changes in stratospheric climate

- **The mid-to-upper stratosphere has cooled globally by about 0.5 °C decade^{-1} from 1979 to 2024. This cooling is primarily because of continued increases in carbon dioxide (CO_2) abundances. Ozone depletion contributed to this cooling over the last decades of the 20th century. Mid-to-upper stratospheric cooling is projected to continue as CO_2 increases, contributing to ozone recovery.**
  - The Hunga eruption cooled the global mid-to-upper stratosphere by an additional 0.5–1 °C between 2022 and 2024 due to the injection of a vast amount of water vapor into the stratosphere. This anomalous cooling is expected to diminish as stratospheric water vapor returns to pre-Hunga levels by 2027–2031.
- **The stratospheric circulation is changing in response to increasing greenhouse gases and to ozone depletion and recovery. These circulation changes will in turn impact the future evolution of the ozone layer.**
  - The Brewer-Dobson circulation has accelerated in the lower stratosphere by a few percent per decade over the last four decades. Climate models attribute this acceleration to ozone depletion through the end of the 20th century and ongoing increases in GHGs.
  - There continues to be large uncertainty in the response of the Northern Hemisphere polar vortex to increasing GHGs, with some models projecting a strengthening and others a weakening. The Southern Hemisphere polar vortex is robustly projected to strengthen in the winter, while in the spring the sign of future changes is uncertain primarily due to the offsetting effect of Antarctic ozone recovery.
  - The amplitude of the Quasi-Biennial Oscillation (QBO), the main mode of variability in the tropical stratosphere, is expected to decline because of increasing GHGs. This decline suggests an increased likelihood of disruptions to the regularity of the QBO, with global impacts on ozone variability.

5 STRATOSPHERIC AEROSOL INJECTION AND POTENTIAL IMPACTS ON OZONE



Earth's limb (the Earth's horizon from orbit) at sunset taken August 8, 1991 by astronauts on the Space Shuttle STS-43 mission, less than two months after the Mt. Pinatubo eruption. Two dark layers of volanic aerosols make distinct boundaries in the stratosphere. The estimated altitude of the aerosol layers in this view is 20 to 25 km. (Photo credit: NASA)

A substantial amount of research has been conducted on potential technological methods to counteract a portion of human-caused surface warming. One such method, stratospheric aerosol injection (SAI), proposes to intentionally enhance stratospheric aerosol loading to reflect more incoming solar radiation back to space, similar to the natural effects from large volcanic eruptions.

If SAI were deployed, it would impact stratospheric ozone by altering stratospheric chemical reactions that control ozone and by absorbing solar and terrestrial radiation, leading to stratospheric warming that affects ozone via changes in stratospheric transport and dynamics. The detailed effects of SAI on stratospheric ozone depend on the scenario, which includes the evolution of background atmospheric conditions, the target surface climate state, and the timeframe of the injection. The effects on stratospheric ozone would also depend on the SAI strategy, which includes the location and frequency of injection and the type of material.

Climate models are key tools for evaluating SAI. This report assesses model representation of the processes that determine the radiative, chemical, and dynamical impacts of SAI and their effects on stratospheric ozone. Potential factors that are currently unexplored and/or not included in models are also discussed. This report does not consider other important topics related to SAI including, but not limited to, effects on surface climate, oceans, and ecosystems, alongside issues around SAI governance, feasibility, and ethics.

- **Multi-model simulations have provided new estimates of future stratospheric ozone changes under an SAI scenario that follows assumptions that are closer to current climate targets than the simulations in the 2022 Assessment.** The simulations use a middle-of-the-road climate scenario (SSP2-4.5) and the WMO (2014) ODS scenario. Sulfate-based SAI is carried out from 2035 onwards with progressively increasing SO_2 injection rates in the subtropics of both hemispheres to hold global mean surface temperature at 1.5 °C above the pre-industrial era.
    - Models simulate decreases in global average total column ozone (TCO) due to SAI ranging from 3 to 5 DU around the middle of the century (2045–2055) compared to the no-SAI scenario (Figure ES-7). This response corresponds to a global TCO decrease of around 4–5 DU per °C of surface cooling at mid-century and delays the recovery of global TCO by about 15–20 years.
    - Models simulate decreases in Antarctic October TCO due to SAI ranging from 17 to 37 DU, corresponding to a delay in recovery of about 10–15 years. Arctic March TCO is reduced by 3–12 DU around mid-century in this SAI scenario. SAI-induced springtime polar ozone depletion does not reach the level of maximum historical losses in either hemisphere.
    - Models simulate changes in the tropical (20°S–20°N) annual mean TCO that are small and inconsistent in the sign of the response.

Projected Ozone and Temperature Anomalies from a Subtropical SAI Scenario

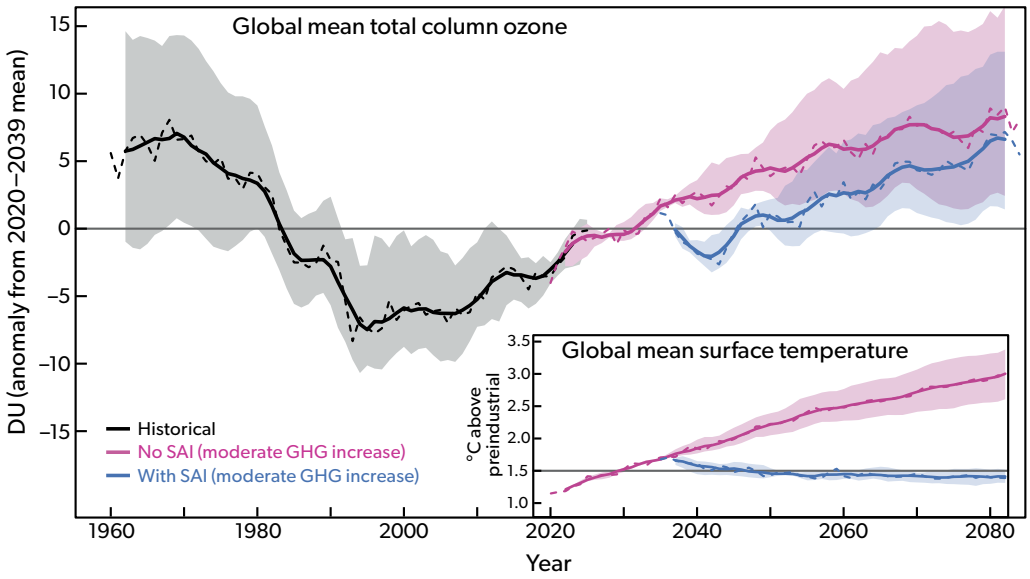


Figure ES-7. Simulated global (90°N–90°S) annual-mean total column ozone (TCO) anomalies from 1960 to 2085 relative to 2020–2039 mean values. The black line shows simulated historical ozone. The pink line shows simulated future ozone under a middle-of-the-road emissions scenario (SSP2-4.5) that includes declining halogen loading. The blue line shows how simulated ozone in the SSP2-4.5 scenario changes in response to sulfate-based SAI with injections in the subtropics starting in 2035. The annual injected amounts are chosen to decrease global surface warming and hold temperatures near 1.5 °C above the pre-industrial era (inset panel). The models used require different annual SO_2 injection amounts to maintain the 1.5 °C temperature target. Dashed lines show the raw multi-model mean values, thick lines show the 5-year running average for the multi-model mean, and shading denotes the range across nine chemistry-climate models for the historical period and three models for the future period. Adapted from Figures 6-5 and 6-14.

- **Since the 2022 Assessment, there have been advances in understanding the dependence of stratospheric ozone responses on SAI injection strategy.** Climate model simulations show that the magnitude, and in some regions the sign, of the stratospheric ozone response to SAI depends strongly on the strategy, including the latitude of injection and the injected material.
  - The decrease in global mean TCO due to sulfate-based SAI applied in the subtropics shown in Figure ES-7 contrasts with the increase in global TCO found in multi-model simulations with equatorial SAI injection evaluated in the 2022 Assessment. Additional simulations with a single model suggest that this difference is due to the altered SAI injection latitude.
  - Model simulations show that TCO in the southern mid-latitudes and the Arctic in spring increases for an equatorial SO_2 injection and decreases for a subtropical injection. The increase in Northern Hemisphere mid-latitude TCO reported in the 2022 Assessment has been shown to be specific to equatorial and tropical SAI injection strategies; recent simulations with subtropical or polar injections show minimal changes in Northern Hemisphere mid-latitude TCO.
  - Model simulations that apply sulfate-based SAI simultaneously at the same latitude in both hemispheres consistently show decreases in Antarctic springtime TCO, irrespective of the latitudes where the injection is applied.
  - Some studies have suggested that non-sulfate SAI materials such as alumina and calcite might cause smaller impacts on stratospheric ozone due to reduced stratospheric warming and heterogeneous chemical effects. Overall confidence in the effects of non-sulfate SAI materials on stratospheric ozone remains low due to limited data on their physicochemical properties under stratospheric conditions.
- **Since the 2022 Assessment, there have been advances in understanding the response of stratospheric ozone to various SAI scenarios, including the dependence on surface climate target, background atmospheric conditions, and the start and end dates of SAI.**
  - An SAI scenario that offsets a larger amount of surface warming requires a larger injection mass and consequently has larger impacts on stratospheric ozone.

- ODSs are projected to decline during the 21st century, reducing the potential for a given mass of injected aerosol to deplete stratospheric ozone through heterogeneous chemical reactions. Model simulations show that the global TCO loss per unit mass of SO_2 emission is around a factor of two larger in 2045–2064 compared to 2065–2084. Any SAI-induced changes in global TCO would occur on top of a rising background due to ozone recovery. The combination of these effects means the lowest TCO levels under SAI would occur if it were deployed earlier rather than later in the century.

- **Gaps in the understanding of aerosol microphysics and optical and chemical properties, as well as limitations in the ability to model stratospheric chemistry, transport, dynamics, and plume-scale effects, contribute to significant uncertainties in quantifying the effects of SAI on stratospheric ozone.**

6 SCENARIOS AND INFORMATION FOR POLICYMAKERS



The Zeppelin Observatory in Svalbard measures more than 30 chlorinated and fluorinated greenhouse gases that are controlled by the Montreal Protocol. (Photo credit: NILU)

This section assesses activities where there may be the potential to build on the successes of the Montreal Protocol by further limiting ozone depletion and/or climate change. The metrics used are globally averaged total column ozone depletion and global average surface air temperature (GSAT) changes. GSAT, rather than the integrated radiative forcing of previous policy chapters, provides a more tangible way of assessing these policy options. The baseline scenario used here assumes full compliance with the Montreal Protocol. Various hypothetical control measures are examined, including the reduction and/or elimination of banks, production, and emissions of gases that are both controlled and uncontrolled by the Montreal Protocol. The feasibility or cost-effectiveness of the scenarios is not considered or assessed.

In the current baseline scenario, the return of EESC from long-lived ODSs to 1980 levels occurs two years and five years later for the mid-latitude and polar regions, respectively, as compared with the baseline scenario in Chapter 7 of WMO (2022). This difference is primarily due to the inclusion, for the first time, of projected growth in feedstock emissions. Consistent with previous assessments, these EESC calculations only consider ODSs.

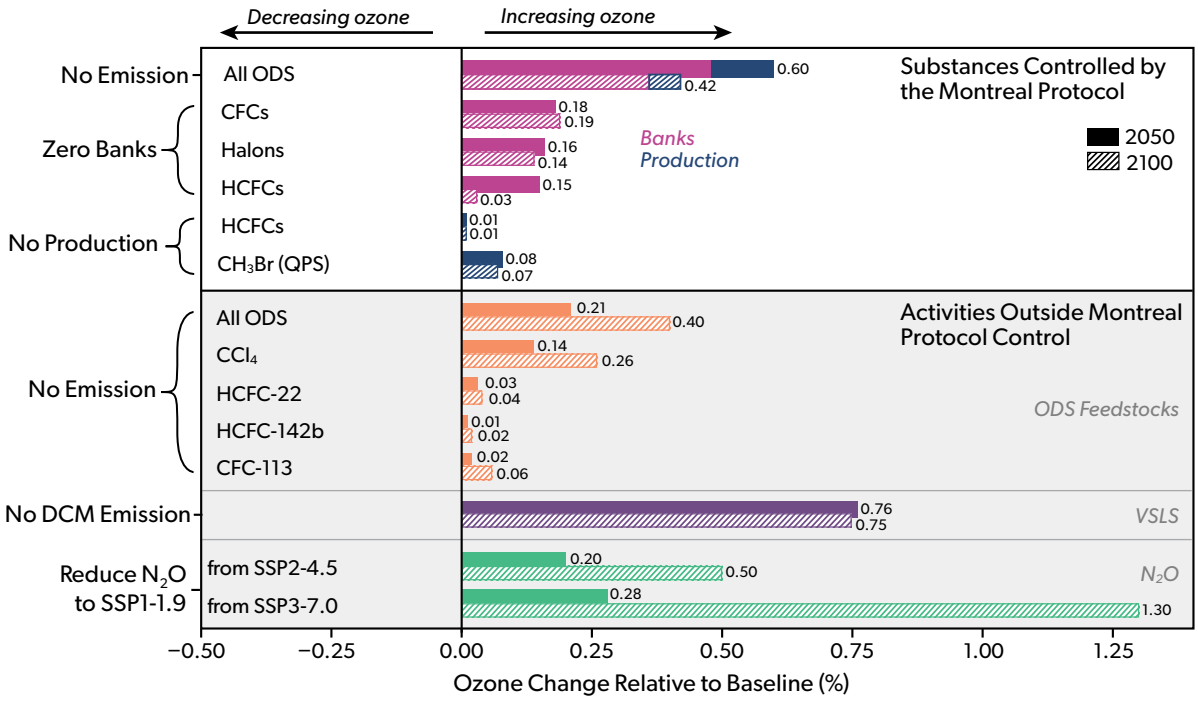
To put the results of this chapter in context, for ozone, the peak globally averaged depletion was roughly 5% in the early 1990s, relative to the 1964–1980 average. For climate, the observed average warming for the period 2016–2025 relative to 1850–1900 was 1.26 (1.13–1.36) °C, of which 1.24 (1.0–1.5) °C is attributable to human activity.

Substances controlled by the Montreal Protocol

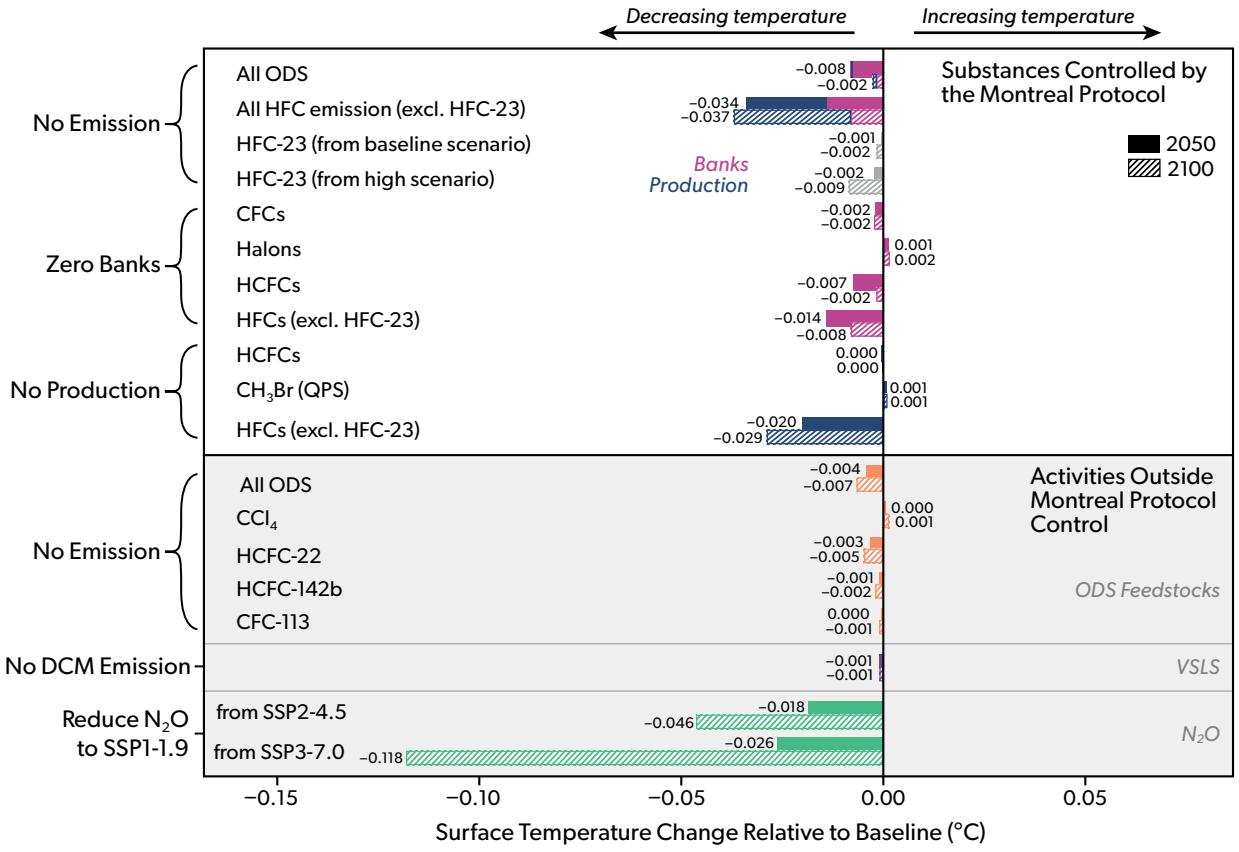
Due to the existing controls of the Montreal Protocol, substantial benefits have been achieved by reducing ODS and HFC production and consumption. The impacts below are in addition to these benefits. Ensuring full adherence with the Protocol is a key objective for the controlled substances.

- **Eliminating all future ODS emissions from dispersive applications in the baseline scenario is projected to lead to an increase in globally averaged total column ozone of about 0.6% in 2050 and 0.4% in 2100.** This corresponds to about 2 DU and 1 DU in 2050 and 2100, respectively.
- **Eliminating all emissions of CFCs, halons, and HCFCs from their projected 2028 banks is projected to lead to increases in ozone of 0.18%, 0.16%, and 0.15% in 2050 and of 0.19%, 0.14%, and 0.03%, respectively, in 2100.**

Ozone Depletion Avoided in 2050 and 2100 from Future Control Scenarios



Surface Temperature Change in 2050 and 2100 from Future Control Scenarios



(see caption on following page)

Figure ES-8. Scenarios of various hypothetical controls or other changes and their impacts on global total column ozone and surface temperature relative to the baseline scenario. The baseline scenario assumes full compliance with the Montreal Protocol and its Amendments and Adjustments. In the scenarios, the elimination of emissions, production, or banks is prescribed to begin in 2028. Ozone and temperature metrics are shown here for 2050 and 2100. These scenario results and others are tabulated in Table 7-7. Details of all scenarios are provided in Sections 7.8.2 and 7.8.3. All halocarbon-induced temperature changes include the direct effect of the halocarbon as well as the indirect effect of any associated total column ozone change. Dichloromethane (DCM) is expected to remain the largest VSLS source of chlorine to the stratosphere for the foreseeable future.

- **Eliminating emissions of CH_3Br associated with QPS uses at the reported production level in 2024 is projected to lead to an increase in ozone of 0.08% in 2050 and 0.07% in 2100.**
- **Full compliance with the Kigali Amendment provisions is projected to prevent warming of up to 0.4 °C in 2100 compared to projected temperatures without HFC control measures.** Elimination of future HFC emissions, which goes beyond compliance, prevents a further warming of 0.03 °C in 2050 and 0.04 °C in 2100, of which HFC banks in 2028 contribute 0.01 °C.
- **Eliminating future emissions of HFC-23 (100-yr GWP of 14,500) has the potential to prevent warming that is substantial relative to that from future emissions of the other HFCs.** As an example, eliminating HFC-23 emissions from a scenario in which those emissions increase by approximately 3% per year over the next decade and are subsequently held roughly constant prevents 0.01 °C of warming by 2100, which is about a quarter of the warming from future emissions of all other HFCs. Quantifying this benefit is challenging due to uncertainties in the magnitudes of HFC-23 emission sources, particularly those associated with current and future production of HCFC-22 and other fluorocarbons.

Substances and activities outside Montreal Protocol control

Despite their potential impacts on ozone, chlorinated very short-lived substances, N_2O, and production of halocarbons intended for feedstock use are not controlled by the Montreal Protocol.

Feedstock use

- **Driven by a rapidly expanding polymers industry, the production and use of ODSs as feedstock continue to rise.** In addition, ODS feedstock use for HFO and HCFO production is increasing while feedstock use for HFCs is declining. The combination of this rapid growth (average annual growth rate of 7% by mass for 2020–2023) and a higher emission ratio (3.6% as compared to the 2% in the previous Assessment) increases the projected impact of feedstock-related emissions on both ozone recovery and climate forcing.
- **Eliminating ODS emissions from feedstock use in the baseline scenario from 2028 onward is projected to increase ozone by 0.21% in 2050 and 0.40% in 2100.** From a scenario in which feedstock emissions were to continue to increase through 2050, rather than being constant from 2035, eliminating these emissions would lead to an increase in global ozone of 0.25% in 2050 and 0.69% in 2100. It would also prevent warming of about 0.01 °C in 2100.

Very short-lived substances

- **The combined impact of CH_2Cl_2, CH_2ClCH_2Cl, $CHCl_3$, and C_2Cl_4 is to reduce present-day global ozone by an estimated 0.3% to 0.7%, based on the current emissions level and published ODP estimate.** Collectively these four Cl-VSLSs add about 140 ppt Cl to stratospheric chlorine in 2024 (Chapter 1, Section 1.3.2.1, WMO 2026). Large amounts of Cl-VSLSs are produced every year. Among all Cl-VSLSs, CH_2Cl_2 is unique in its predominant use (about 75%) for emissive applications and rapid growth in production and emissions. (Table 7-3, WMO 2026)
- **In a scenario in which CH_2Cl_2 emissions continue to grow at the current rate until 2035 and are then held constant, ozone is approximately 0.6% to 1.0% less in 2050 and 2100 than compared with a scenario in which there are no future emissions, with some variation in this amount that depends on location and season of emission.**

Nitrous oxide

- **Future anthropogenic N_2O emissions have the potential to lead to substantially more ozone depletion and warming than future expected ODS emissions.** The importance of N_2O is more apparent now because ODSs have declined due to the controls of the Montreal Protocol (Chapter 7, Section 7.4, WMO 2026). Because of its growing emissions, there is also increased recognition of the future impacts of anthropogenic N_2O. The N_2O emissions from agricultural activities are the major source of anthropogenic emissions. Industrial activity currently accounts for approximately 5% of total anthropogenic emissions.
    - **Reducing future anthropogenic emissions of N_2O from the baseline scenario (SSP2-4.5; N_2O mole fraction of 377 ppb in 2100, compared to 270 ppb in the year 1750) to a highly mitigated one (SSP1-1.9; N_2O mole fraction of 354 ppb in 2100) would lead to 0.5% more ozone and would prevent 0.05 °C of warming in 2100.**
    - **Reducing future emissions of N_2O from a higher-emission scenario (SSP3-7.0; N_2O mole fraction of 422 ppb in 2100) to the highly mitigated scenario would lead to 1.3% more ozone and would prevent 0.12 °C of warming in 2100.**

SCIENTIFIC SUMMARIES OF THE CHAPTERS

Chapter 1:
Ozone-Depleting Substances (ODSs) and Other Gases of Interest to the Montreal Protocol

This chapter presents an update on atmospheric abundances of ozone-depleting gases and other gases of interest to the Montreal Protocol. Here we discuss the long-term trends as well as the emissions of these gases, based on observations. Chapter 1 discusses all gases controlled under the Montreal Protocol except for the hydrofluorocarbons (HFCs), which are controlled under the Kigali Amendment to the Montreal Protocol. These are discussed in Chapter 2. Chapter 1 also discusses ozone-depleting gases not controlled under Montreal Protocol because of their short lifetimes, so-called very short-lived substances. Global emissions presented here are derived from atmospheric observations assimilated into the AGAGE 12-box model (Western et al., 2025b). This approach combines atmospheric observations with atmospheric transport and loss calculations to derive a best estimate of emissions of the gases covered here. Absolute emissions and uncertainties quoted here include random and systematic (i.e., primarily due to lifetime and calibration scale uncertainty) sources of uncertainty. When discussing changes in emissions, uncertainties in the differences between years are given excluding systematic uncertainties, which do not strongly influence the overall trend. Unless otherwise stated, all uncertainties given are 1-sigma values. We also compare the observed long-term trends in atmospheric mole fractions with scenarios from previous Assessments, which projected the evolution of atmospheric mole fractions into the future. Unless otherwise stated, mole fractions in the summary are derived from combined global network data. The scenarios that are updated in Chapter 7 of this report are based on observations available at the time of writing, with assumptions about future emissions and atmospheric loss processes. Note that the scenarios are developed to be consistent with compliance under the Montreal Protocol, but are not meant to be predictions, as some deviations from the projections are expected.

Changes in tropospheric chlorine and bromine between 2020 and 2024

- **The atmospheric abundances of tropospheric chlorine (Cl) from long-lived, ozone-depleting substances (ODSs) controlled under the Montreal Protocol have continued to decline since the 2022 Assessment.** The observed rate of decline in tropospheric chlorine due to substances controlled under the Montreal Protocol accelerated from 16.0 ± 3.3 parts per trillion (ppt) Cl yr^{-1} between 2016 and 2020 to 21.5 ± 1.5 ppt Cl yr^{-1} between 2020 and 2024. This is due to a faster decrease in Cl from chlorofluorocarbons (CFCs) and a change from increasing to decreasing Cl from the major HCFCs during this most recent four-year period. This observed decrease in hydrochlorofluorocarbon (HCFC) mole fractions was not projected for this assessment period in the 2022 A1 baseline scenario of future atmospheric composition under the assumption of full global compliance with the Montreal Protocol and its Amendments.
- **For several ODSs, current emissions are likely dominated by losses associated with feedstock use, leakage of intermediates, or formation and release as by-products during the manufacture of other chemicals. As other sources have declined, emissions from feedstock-related processes have become better quantified. Typical emission factors for these processes are larger than assessed historically: 3–5% of production, rather than about 0.5%.** Atmospheric observations show that emissions have increased since 2010 for several controlled substances with few or no known dispersive uses, including CFC-115, CFC-113a, CFC-13, CFC-114a, and CFC-112a.
- **Tropospheric chlorine from very short-lived substances (VSLSs) has continued to increase.** Unlike brominated and iodinated VSLSs, the sources of chlorinated VSLSs are mainly anthropogenic. The emissions of chlorinated VSLSs are not controlled under the Montreal Protocol, and the observed average rate of increase was 4.1 ppt Cl yr^{-1} (2.7% yr^{-1}) in the period between 2020 and 2024, which is similar to increases over the past decade within the observed year-to-year variability of about 4.5 ppt yr^{-1}. VSLS chlorine now contributes about 4.5% to total global tropospheric chlorine. No information on tropospheric trends of brominated or iodinated VSLSs is available.
- **Tropospheric bromine (Br) from substances controlled under the Montreal Protocol has continued to decline. The observed rate of decline in tropospheric bromine**

from controlled substances was 0.13 ± 0.04 (1-sigma inter-annual variability) ppt Br yr^{-1}, which is in line with the 0.1 ppt yr^{-1} projected in the 2022 A1 scenario. Overall bromine from both halons and CH_3Br continued to decrease since the previous Assessment.

Total stratospheric chlorine and bromine

- **Total chlorine entering the stratosphere from both controlled and non-controlled ODSs including source gas and product gas injections from VSLSs, declined by 510 ppt (14%) between the 1993 peak (3670 ppt) and 2024 (3160 ppt) (Figure ES-2).** This long-term decrease of about 0.5% yr^{-1} was largely driven by decreasing abundances of CH_3CCl_3 and CFCs, with some contribution from decreasing CCl_4.
- **HCl is the major chlorine reservoir in the upper stratosphere. Its average abundance in the region from 60°S to 60°N decreased by 0.61 ± 0.06 % yr^{-1} between 1997 and 2024.** This decrease is in line with decreases in tropospheric chlorine of 0.48% yr^{-1} from the ground-based networks over the same period with a variability of 0.28% yr^{-1}.
- **Total bromine entering the stratosphere from controlled and non-controlled ODSs, including source gas and product gas injections from VSLSs, declined by 3.6 ppt (16%) between the 1999 peak (22.0 ppt) and 2024 (18.4 ppt) (Figure ES-2).**

Equivalent Effective Stratospheric Chlorine (EESC)

EESC is the chlorine-equivalent sum of chlorine and bromine derived from long-lived ODS tropospheric abundances, weighted to reflect their expected depletion of stratospheric ozone. The growth and decline in EESC depend on a given tropospheric abundance propagating to the stratosphere with varying time lags (on the order of years) associated with transport to different regions of the stratosphere. Therefore, the EESC magnitude, its peak timing, and its rate of decline are different in different regions of the stratosphere.

- **EESC has continued to decline and was, in 2024, 18% lower than the 1998 peak values in mid-latitudes and 13% lower under polar winter conditions (peak in 2001). These changes are, respectively, 44% and 28%, of the decrease required to reach the 1980 reference values.** As other factors contribute to trends in stratospheric ozone, the evolution of stratospheric ozone is not expected to fully follow the evolution of EESC.

Chlorofluorocarbons (CFCs)

- **Total chlorine from CFCs continued to decline in the atmosphere at an average rate of 16.5 ppt yr^{-1} between 2020 and 2024.** This decrease is faster than the 15.5 ppt yr^{-1} decline projected for this period in the 2022 A1 scenario and the observed 13.5 ppt yr^{-1} decline for the period from 2016 to 2020.
- **The global mean mole fraction of CFC-11 declined in the atmosphere at an average rate of 2.4 ppt yr^{-1} (1.1% yr^{-1}) since 2020, similar to the downward trend reported for 2019–2020 in the 2022 Assessment. The 2018 Assessment reported a smaller rate of decline, following a period of unreported production since 2013.** In 2024, CFC-11 contributed about 20% to the chlorine entering the stratosphere. Global emissions of CFC-11 have continued to decline steadily over the period 2020–2024, decreasing from 47 ± 10 Gg yr^{-1} in 2020 to 27 ± 10 Gg yr^{-1} in 2024. The reduction in global CFC-11 emissions was 20 ± 5 Gg yr^{-1} during this period. While there has been no update on CFC-11 emissions in eastern China, a region previously shown to have contributed to elevated global CFC-11 emissions between 2013 and 2019, CFC-11 emissions in the southeastern region of China have shown a decreasing trend since 2020 and are in line with bottom-up estimates.
- **The global mean mole fraction of CFC-12 has continued to decline at a rate of 3.9 ppt yr^{-1} (0.8% yr^{-1}) between 2020 and 2024, similar to the rate of 3.9 ppt yr^{-1} between 2019 and 2020 reported in the 2022 Assessment.** In 2024 CFC-12 contributed about 31% to the chlorine entering the stratosphere. Global CFC-12 emissions have also dropped from 26 ± 21 Gg yr^{-1} in 2020 to 14 ± 21 Gg yr^{-1} in 2024, which is a reduction of 13 ± 9 Gg yr^{-1}.
- **The global mean mole fraction of CFC-113 continued to decrease at around 0.6 ppt yr^{-1} between 2020 and 2024.** In 2024, CFC-113 contributed about 6% to the chlorine entering the stratosphere. Global emissions of CFC-113 remained at around 4 ± 2 Gg yr^{-1} since the previous Assessment, with no clear overall increasing or decreasing trend.
- **The global mean mole fraction of CFC-114 decreased from 15.4 to 15.1 ppt between 2020 and 2024, and emissions decreased from 1.5 ± 0.9 Gg yr^{-1} in 2020 to less than 0.1 Gg yr^{-1} in 2024.**
- **Global CFC-13 mole fractions showed a slight increase from 3.4 to 3.5 ppt while overall emissions declined between 2020–2024, reaching 0.43 ± 0.23 Gg yr^{-1} in 2024. Global CFC-115 mole fractions increased from 8.7 to 9.0 ppt. Emissions were 1.4 ± 0.8 Gg yr^{-1} in 2024 and exhibited a peak of about 2.1–2.4 Gg yr^{-1} between 2021 and 2023.** The elevated CFC-115 emissions relative to early years, together with similar increases around 2016–2019, could be due to leakages during the HFC-125 production process. Atmospheric mole fractions of other minor CFCs, such as CFC-113a and CFC-114a, have continued to increase but are at low overall levels.
- Summed together, minor CFCs contributed less than 0.7% to total chlorine. Summed emissions of minor CFCs increased from 5.4 to 7.1 Gg yr^{-1} between 2020 and 2024, likely associated with feedstock usage. These emissions were dominated by CFC-113a.

Hydrochlorofluorocarbons (HCFCs)

- **As a result of Montreal Protocol controls, chlorine from HCFCs has begun decreasing in the atmosphere. This decline was earlier than projected in the previous assessment scenarios.** While total chlorine from HCFCs had increased by 2.5 ± 0.8 ppt yr^{-1} between 2016 and 2020, it decreased by 2.6 ppt yr^{-1} between 2023 and 2024, and this change was dominated by the decline in HCFC-22. In 2024, HCFCs contributed about 10% to chlorine entering the stratosphere.
- **Global abundances of HCFC-22 peaked in 2021 at 249 ppt. The global mean mole fraction of HCFC-22 was 245 ppt in 2024, and its growth rate has changed from an increase of 1.2 ppt yr^{-1} between 2019 and 2020 to a decrease of 2.2 ppt yr^{-1} between 2023 and 2024.** Global emissions of HCFC-22 decreased from 346 ± 54 Gg yr^{-1} in

2020 to 297 ± 54 Gg yr^{-1} in 2024, equivalent to a reduction of 49 ± 9 Gg yr^{-1}.

- **Global abundances of HCFC-141b peaked between 2020 and 2021, and those of HCFC-142b continued to decline between 2020 and 2024.** Global mole fractions of HCFC-141b and HCFC-142b decreased by about 0.1 ppt and 1.0 ppt between 2020 and 2024, respectively. Emissions of HCFC-141b and HCFC-142b decreased by 7% and 13%, respectively, between 2020 and 2024, consistent with a sharp drop in reported HCFC consumption after 2012, particularly from Article 5 countries.
- Emissions of several low-abundance HCFCs (e.g., HCFC-124, HCFC-133a, and HCFC-132b) remained stable or increased between 2020 and 2024, likely related to their by-production during fluorochemical manufacture.

Halons

- Bromine from halons continued to decline at an average rate of 0.1 ppt yr^{-1} between 2020 and 2024. Halon-1211 and halon-2402 abundances declined over this period, while halon-1301 showed no significant trend. In 2024, halons contributed about 38% to stratospheric bromine, with halon-1301 comprising the largest fraction. Emissions of halon-1301 and halon-2402 remained relatively constant, while emissions of halon-1211 declined by about 25% between 2020 and 2024.

Carbon tetrachloride (CCl_4) and methyl chloroform (CH_3CCl_3)

- **The global mean mole fraction of CCl_4 continued to decrease at a rate of 0.9 ppt yr^{-1} between 2020 and 2024, similar to the rate of 1 ppt yr^{-1} observed during the 2016 to 2020 period.** In 2024, CCl_4 contributed about 9% to the chlorine entering the stratosphere.
- **Global CCl_4 emissions have remained largely constant during the last 15 years at about 44 Gg yr^{-1}, with annual variability of about 3 Gg yr^{-1}.** The estimated emissions were 39 ± 14 Gg yr^{-1} in 2020 and 44 ± 14 Gg yr^{-1} in 2024. The overall discrepancy between bottom-up and top-down emission estimates has been reduced since the previous Assessment, mainly due to an increase in feedstock-related bottom-up estimates. The two approaches agree within their uncertainty ranges, although the central top-down estimate is about 50% higher than the central bottom-up estimate.
- **Globally, emissions associated with feedstock production and use are estimated to be a major and increasingly important contributor to CCl_4 emissions.** Emission rates of CCl_4 from processes related to feedstock uses have been assessed to be about 4.3%, much higher than the 0.5% assessed historically. Regional studies in China also indicate an increasing contribution from feedstock uses, as well as possible contributions from other anthropogenic sources including the iron and steel industry, manufacturing of general-purpose machinery, and production of raw chemical materials and chemical products.
- **Global CH_3CCl_3 mole fractions have continued to decline, from 1.4 ± 0.2 ppt in 2020 to 0.9 ± 0.2 ppt in 2024.** Emissions of CH_3CCl_3 decreased from 2.3 ± 1.0 Gg yr^{-1} in 2020 to 1.6 ± 0.7 Gg yr^{-1} in 2024.

Methyl bromide (CH_3Br)

- **The atmospheric abundance of methyl bromide (CH_3Br) averaged 6.5 ± 0.1 ppt between 2020 and 2024, which is about 30% lower than its peak between 1996 and 1998.** CH_3Br now contributes about 35% to stratospheric bromine. Reported controlled production for critical use exemptions of CH_3Br between 2020 and 2024 was close to zero, and quarantine and pre-shipment (QPS) consumption has been relatively stable for more than two decades at 10 ± 1 Gg yr^{-1}. Gaps remain in the understanding of the global budget of CH_3Br, with sinks outweighing known sources.

Effect of ODSs on climate

- **The direct radiative forcing (RF) from ODSs has declined by about 10 mW m^{-2} since 2020, reaching 342 mW m^{-2} in 2024.** This radiative forcing is due to CFCs (268 mW m^{-2}), HCFCs (61 mW m^{-2}), CCl_4 (12 mW m^{-2}), and halons (2 mW m^{-2}) and does not include indirect effects due to the depletion of ozone caused by these gases. RF from all groups has decreased since the last Assessment.

Halogenated very short-lived substances (VSLSs)

- **The VSLS chlorine input to the stratosphere from the four most important chlorinated VSLS source gases (C_2Cl_4, $CHCl_3$, CH_2Cl_2, and CH_2ClCH_2Cl) and from product gases is estimated as 140 ± 30 ppt in 2024, compared to 130 ± 30 ppt in 2020, as reported in the previous Assessment.** In 2024, chlorine from VSLSs contributes about 4.4% to the chlorine entering the stratosphere.
- **CH_2Cl_2 is the largest source of VSLS chlorine, and its atmospheric mole fraction has increased from 41 to 50 ppt during the period from 2020 to 2024 at an average rate of 2.4 ppt yr^{-1}.** The global mean mole fraction of $CHCl_3$ continues to decline from 8.4 ppt in 2020 to 7.8 ppt in 2024, consistent with the downward trend reported in the 2022 Assessment. Mole fractions of both CH_2ClCH_2Cl and C_2Cl_4 have remained unchanged within the observed atmospheric variability.
- **In the absence of new information, the overall estimates of the bromine and iodine inputs to the stratosphere from VSLSs remain unchanged since the last Assessment.** While some new information on possible anthropogenic sources of $CHBr_3$ has been reported, no information on possible long-term changes in the atmospheric levels of brominated VSLS source gases is available. Our best estimate of the total VSLS input from both source and product gases is unchanged from the previous Assessment at 5 ± 2 ppt for bromine, which accounts for 27% of the bromine entering the stratosphere. The iodine input to the stratosphere is assessed at 0.3–0.9 ppt for iodine with no long-term change.

Other gases that influence stratospheric ozone and climate

- **The global mean mole fraction of nitrous oxide (N_2O) continued to increase since the previous Assessment, reaching 338.0 ± 0.9 parts per billion (ppb) in 2024 from 333.2 ± 0.8 ppb in 2020.** The average annual growth rate between 2020 and 2024 was 1.2 ± 0.1 ppb yr^{-1}, higher than the 2016–2020 average annual increase of 1.0 ± 0.1 ppb yr^{-1} reported in the previous Assessment and about 50% higher

than rates of increase during the beginning of the century. The 2020–2024 increase exceeds all of the IPCC projected pathways.

- **Anthropogenic N_2O emissions (ODP-weighted) in 2024 are estimated to range from 168–337 Gg yr^{-1}, which corresponds to approximately 4–8 times the total ODP-weighted emissions from all CFCs combined in 2024, and 18–36% of CFC peak emissions in 1988.**
- **The global mean mole fraction of methane (CH_4) continues to increase, reaching 1929 ± 5 ppb in 2024 from 1878 ± 5 ppb in 2020.** These increases correspond to the average annual growth rate of 13 ± 5 ppb yr^{-1} for CH_4 during the period 2020–2024, higher than the 2016–2020 mean growth rate of 9 ± 2 ppb yr^{-1}.
- **Long-lived non-ODS, non-HFC, fluorinated substances (e.g., SF_6, PFCs, SO_2F_2, NF_3) have continued to increase.** Total direct radiative forcing from these species increased from 0.013 W m^{-2} in 2020 to 0.015 W m^{-2} in 2024. This contribution corresponds to approximately 30% of the radiative forcing attributable to HFCs in 2024.
- **The global mean mole fraction of hydrogen (H_2) has increased from approximately 549 ppb in 2020 to 559 ppb in 2024.** H_2 is a stratospheric source gas for hydrogen oxide radicals which may influence ozone chemistry and also increases stratospheric water vapor (H_2O) when oxidized. Even under cases of large increases in atmospheric H_2 due to its use as an energy carrier in a future reduced-fossil fuel economy, it is likely to have a negligible impact on ozone layer recovery.

Chapter 2: Hydrofluorocarbons (HFCs)

Hydrofluorocarbons (HFCs) are substitutes for ozone-depleting substances (ODSs) controlled under the Montreal Protocol. Unless otherwise stated, the term HFC is used in this Chapter for saturated HFCs controlled under the Kigali Amendment. These HFCs are used in refrigeration, air conditioning, heat pumps, foam blowing, as propellants and as solvents, in fire extinguishers, and as chemical feedstocks. Some HFCs, including HFC-23, may be generated as unwanted by-products during the production of other chemicals and are subsequently released to the atmosphere. HFC-23 may also be produced in the atmosphere from the decay of HFCs, hydrofluoroolefins (HFOs), and hydrochlorofluoroolefins (HCFOs).

HFCs were introduced as suitable long-term replacements for ozone-depleting substances (ODSs) because of their negligible impact on stratospheric ozone. However, many HFCs have large global warming potentials (GWPs), which are comparable to or even larger than those of many HCFCs, but smaller than those of most CFCs. As a result of their high GWPs, the production and consumption of 18 saturated HFCs are now being phased down under the Kigali Amendment to the Montreal Protocol, which came into force in 2019. Additional controls are placed on emissions of HFC-23 as a by-product from the controlled production of HCFCs and HFCs, which must be destroyed to the extent practicable and emissions reported under the Kigali Amendment.

In addition, countries classified as Annex I under the United Nations Framework Convention on Climate Change (UNFCCC) are required to submit annual national inventories of emissions of HFCs. Reporting obligations under the UNFCCC rely on inventory methods, which utilize knowledge of quantities of production, usage, and storage of HFCs and the emission rates associated with these activities. Emissions can also be derived from measurements of the HFC atmospheric abundance together with a model of atmospheric chemistry and transport, using a statistical method. The temporal evolution of global total emissions can be used to assess the effectiveness of the Kigali Amendment. These emissions are derived on a global scale and, where measurement coverage is sufficient, can be derived for certain countries or regions around the world. However, the current paucity of global measurement coverage means that regional estimates of emissions are limited.

HFOs and HCFOs have increasingly been adopted as lower-GWP alternatives to HFCs, particularly in sectors affected by the HFC phase-down under the Kigali Amendment. Although they are very short-lived substances, their atmospheric abundances are increasing due to their growing use. Some of these HFOs and HCFOs (and several HFCs and HCFCs) degrade at least partly to trifluoroacetic acid (TFA) and other persistent compounds.

The above is discussed in detail within this chapter, and the key findings are that:

- **Global HFC emissions are aligned with the phase-down schedules of HFC production and consumption under the Kigali Amendment and follow projections from earlier Assessments.** For most HFCs, global emissions and atmospheric abundances are still increasing, as expected, and fall below what would be expected without the controls of the Kigali Amendment. Emissions of several less-widely used HFCs with relatively low abundances in the atmosphere are now declining. The effects of a range of restrictions on HFC production and consumption, including

under the Kigali Amendment, are reflected in measured abundances and emissions.

- **As expected, annual CO_2-equivalent emissions from all HFCs have surpassed annual emissions of all ODSs since the last Assessment, following the transition from ODSs to HFCs.** The total carbon dioxide-equivalent emissions (CO_2-eq, calculated using 100-year global warming potentials or GWPs) due to HFCs contributing to climate change were 1.4 ± 0.1 Pg CO_2-eq yr^{-1} in 2024, 17% higher than in 2020 (1.2 ± 0.1 Pg CO_2-eq yr^{-1}). The increase in HFC emissions is consistent with expectations as a result of the controls on production and consumption. The relative growth between 2020 and 2024 (17%) was smaller than between 2016 and 2020 (20%). HFC-125 (32%) was the largest contributor to CO_2-eq emissions from all HFCs in 2024, followed by HFC-134a (28%), HFC-23 and HFC-143a (each 15%), and HFC-32 (6%).
- **HFC emissions reported by countries classified as Annex I under the UNFCCC account for less than one third of the global CO_2-eq emissions derived from measurements in 2022, the last year for which all reports are available.** In 2022, the last year for which there was complete reporting to UNFCCC, the HFC emissions reported by Annex I countries can explain 28% of the global CO_2-eq emissions derived from measurements. This has declined from 30% in 2020 and 35% in 2016. Reported HFC production and consumption data has recently become available through UNEP reporting by countries dominating production and consumption of controlled HFCs.
- **The radiative forcing from HFCs has increased, as expected, by 27% between 2020 and 2024, which is consistent with the projection from the last Assessment.** Radiative forcing due to HFCs reached 54 ± 4 mW m^{-2} in 2024, an increase from 42 ± 3 mW m^{-2} since 2020.
    - HFC-134a remained the largest contributor (42%), followed by:
        - HFC-125 (21%)
        - HFC-23 (13%)
        - HFC-143a (10%)
        - HFC-32 (8%)

  Radiative forcing from HFCs was less than 2% of the total radiative forcing from all well-mixed anthropogenic greenhouse gases in 2024 (~3.5 W m^{-2}).
- **Compliance with HFC production and consumption levels, as prescribed by the Kigali Amendment, is projected to prevent up to 0.4 °C of global temperature rise by 2100.** HFCs were estimated to have contributed 0.02 °C to global temperature increases through 2024 and, following the controls under the Kigali Amendment, their contribution is projected to remain below 0.06 °C through the 21st century.
- **HFC-23 emissions have decreased from 16 ± 1 Gg yr^{-1} in 2020 to 14 ± 1 Gg yr^{-1} in 2024. Emissions decreased despite an increase in HCFC-22 production, the primary known process responsible for HFC-23 generation.** The decrease may reflect increased mitigation of HFC-23 and/or a decrease in emissions of other less well-understood sources. HCFC-22 feedstock production is driving an ongoing increase in total HCFC-22 production.
- **In 2024, less than 25% of HFC-23 emissions derived from atmospheric measurements can be explained by reported emissions and other known sources.** The unexplained emissions emerged around 2015 and coincide with an increase in reported abatement of HFC-23.
- **Production of several HFCs for feedstock use is increasing, primarily driven by use in the polymer industry.** For example, over 100 Gg yr^{-1} of HFC-152a is used as a feedstock, mainly to produce polymers, and HFC-245fa is used as a feedstock in the production of HFOs.
- **Emerging applications of lower GWP alternatives (e.g., HFOs), for example in air conditioning and refrigeration, include mixtures of HFCs with low-GWP alternatives to lower the direct climate impact of refrigerants.**
- **Available measurements of abundances of short-lived HFOs and HCFOs show that their emissions are increasing rapidly around the world. This increase is consistent with the adoption of technology using these next-generation HFC alternatives.** Atmospheric measurements in Europe, East Asia, and the USA show that HFO-1234yf, HFO-1234ze(E), and HCFO-1233zd(E) emissions are increasing. Despite their short atmospheric lifetimes, these chemicals have become detectable far from their major emissions regions, for example, in the Arctic.
- **The breakdown of some HFCs, HFOs, and HCFOs in the atmosphere can result in the formation of very persistent compounds.** For example, HFC-23, CFC-13, CF_4, trifluoroacetic acid (TFA), and others are formed during the atmospheric degradation of Montreal Protocol-controlled substances and some alternatives. Yields for these persistent compounds are summarized in Table A-4 of the Annex.
- **The atmospheric formation of HFC-23 from the breakdown of some HFCs, HFOs, and HCFOs contributes less than 2% to the current global HFC-23 emissions of 14 ± 1 Gg yr^{-1}. The projected contribution of atmospheric decomposition as a source of HFC-23 will stay under 20% of current emissions throughout the 21st century.** The atmospheric oxidation of some HFCs, HFOs, and HCFOs with a CF_3 moiety can lead to the formation of HFC-23. Based on current atmospheric concentrations of these precursor gases, the secondary formation of HFC-23 is currently less than 0.22 Gg yr^{-1}, which is a minor contribution compared to total global sources of HFC-23.
- **Levels of persistent trifluoroacetic acid (TFA) in precipitation and inland water bodies are measurably increasing, in part because of the atmospheric breakdown of various HCFCs and HFCs controlled under the Montreal Protocol, as well as HFOs and HCFOs.** In the coming decades, the atmospheric formation of TFA is expected to increase due to the increased use of HFOs and HCFOs. HFO-1234yf, which is increasingly used to replace HFC–134a in mobile air conditioners, has become an important precursor of TFA in the atmosphere. Measured TFA concentrations in precipitation are too high to be explained by formerly published yields from the degradation of HCFCs, HFCs, HFOs, and HCFOs. Newly estimated higher yields discussed in this Chapter and in the Annex of this Assessment could at least partly explain the gap. Potential other TFA sources are direct emissions into the atmosphere, conversion of precursors emitted from industrial processes or waste incinerators, and conversion

of precursors from medication and herbicides. Certain pesticides and industrial or wastewater dis-charges could also contribute to the increase of TFA concentrations in surface waters.

- **Various HCFCs and HFCs controlled under the Montreal Protocol, and their replacements (i.e., HFOs, HCFOs) as well as some degradation products (e.g., TFA), may be categorized as being PFAS (per- and polyfluoroalkyl substances) under some definitions.** Example definitions of PFAS and substance categorization are included in Table A-4 of the Annex (WMO 2026). Depending on the definition of PFAS, specific substances may fall under regional or global regulations in addition to those in the Montreal Protocol.
- **Emissions from appliances could be reduced by nearly half through lifecycle refrigerant management (LRM) of HFCs and HCFCs between 2025 and 2050, relative to no management.** Lifecycle refrigerant management can reduce emissions of refrigerants and lower demand for new refrigerant production through measures including leakage prevention, refrigerant recovery, recycling, reclamation and reuse, and proper destruction at end of life.
- **Additional climate benefits could be achieved by improving energy efficiency of equipment containing HFCs and their alternatives.** Reducing emissions during operation by raising appliance and equipment energy efficiency standards, by implementing passive cooling, and by accelerating the phase-down under the Kigali Amendment could reduce total CO_2-equivalent emissions from cooling, refrigeration, and heat pumps by about 60% by 2050.

Chapter 3:
Global Ozone: Past, Present, and Future

This chapter presents our current understanding of global ozone outside of the polar regions, covering 60°S–60°N. The decline of stratospheric ozone observed from the 1960s to the mid–1990s has been unambiguously attributed to rising concentrations of ozone-depleting substances (ODSs). Since the late 1990s, stratospheric ODS levels have steadily decreased due to the successful implementation of the Montreal Protocol and its subsequent Amendments and Adjustments. As a result, near-global stratospheric ozone is expected to recover to 1980 levels within the next 20 years. In addition to ODS concentrations, the future evolution of ozone at different latitudes and vertical levels depends on future concentrations of greenhouse gases (GHGs) and precursors of tropospheric ozone.

Compared to the previous Assessment, extended observational records show a slightly larger and, for the first time, statistically significant increase in near-global total column ozone (TCO). Averaging over the entire 60°S–60°N latitude range reduces variability relative to that seen in individual regions, where the increase is only significant in the SH mid-latitudes. Different processes operating at different altitudes complicate interpretation of the drivers of the overall TCO trend. However, a significant increase in upper-stratospheric ozone noted in the previous Assessment continues, driven by declines in ODSs and increases in GHGs. Model simulations support our overall understanding of these trends.

Changes to date in total column ozone

- **Aggregated ground- and space-based observations indicate an increase of 0.5% decade^{-1} (with a 2-sigma uncertainty of at least ±0.3% decade^{-1}) in near-global (60°S–60°N) average TCO for the 1996–2024 period.** This trend is statistically significant and is consistent with model simulations and our scientific understanding of the processes controlling ozone. Whether this significance will remain robust through the next Assessment cycle is uncertain because TCO exhibits large variability on interannual-to-decadal timescales. (Section 3.3.1.2)
- **Over the same 1996–2024 period, the TCO trends averaged over broad latitude bands are as follows:**
  - SH mid-latitude (60°S–35°S) TCO has changed by +1.1% decade^{-1}, with 2-sigma uncertainty of ± 0.9% decade^{-1}.
  - NH mid-latitude (35°N–60°N) TCO has changed by +0.1% decade^{-1}, with 2-sigma uncertainty of ± 0.8% decade^{-1}.
  - Tropical (20°S–20°N) TCO has changed by +0.2% decade^{-1}, with 2-sigma uncertainty of ±0.4% decade^{-1}. In this region, lower stratospheric ozone is decreasing primarily due to transport changes, while tropospheric ozone is increasing due to changes in precursor emissions.

  The latitudinal pattern of these TCO trends is largely consistent with our scientific understanding and is reproduced by the latest set of chemistry-climate models (CCMs). (Section 3.3.1.2)
- **Annual mean TCO as measured from space- and ground-based platforms and averaged over the present day**

(2021–2024) remains lower than the 1964–1980 average by:

- about 2% for the near-global average (60°S–60°N),
- about 2% in the NH mid-latitudes (35°N–60°N), and
- about 6% in the SH mid-latitudes (60°S–35°S).

In the tropics (20°S–20°N), present-day (2021–2024) TCO matches the 1964–1980 average. These values are similar to those given in the previous Assessment for the 2017–2020 averages. (Section 3.3.1.1)

- **Notable reductions in SH mid-latitude TCO occurred during the 2020–2024 period due to the Australian New Year's (ANY) wildfires (~3–5% decrease) and the Hunga volcanic eruption (~5–7% decrease).** The ozone response to these events was driven by both circulation changes and halogen-driven chemical ozone loss. While the Hunga eruption was unusual due to the submarine nature of the volcano, eruptions without excess water vapor have occurred frequently over the past two decades, and several previous eruptions have had a larger impact on ozone. The meteorological conditions conducive to large wildfires capable of perturbing stratospheric composition are expected to become more common in the future. (Section 3.3.1.1)

Changes to date in vertically resolved ozone

Vertically resolved trends remain positive in the upper stratosphere, while trends in the lower stratosphere are less negative than those reported in the previous Assessment.

- **Measurements show unambiguous increases in upper stratospheric ozone from 2000 to 2024.** Positive trends have a range of ~1–3% decade^{-1} at mid-latitudes in both the Northern and Southern Hemispheres and ~0.5–2.5% decade^{-1} in the Tropics. (Section 3.3.2.2)
- **There are multiple lines of evidence from both observations and models for a small and uncertain decrease (0.5–2.5% decade^{-1}) in tropical lower stratospheric ozone from 2000 to 2024.** This decrease is consistent with climate change–driven acceleration of the large-scale stratospheric circulation and has a small impact on TCO. Chemical ozone loss from chlorine and bromine is comparatively minor in the tropical lower stratosphere. (Section 3.3.2.2)
- **The observed decline in mid-latitude lower stratospheric ozone (~0.5% decade^{-1}) is smaller than reported in the previous Assessment. The 2000–2024 trends are less negative and are in better agreement with chemistry-climate model simulations that suggest small increases in mid-latitude lower stratospheric ozone.** Ozone in the mid-latitude lower stratosphere has large year-to-year variability, and measurements of this region are more uncertain than those of the middle and upper stratosphere. Thus, the trends have large uncertainties, and they are not robust across all datasets and models. The disagreement between models and measurements appears to be primarily associated with dynamical processes. (Section 3.3.2.2)
- **Zonally averaged TCO trends are broadly consistent with those in the integrated stratospheric column and thus primarily reflect ozone changes in the stratosphere.** However, in some locations recent tropospheric ozone trends are of the same order of magnitude as stratospheric column trends. As a result, attribution of TCO trends in those locations requires detailed understanding of changes in both the stratosphere and troposphere. (Section 3.3.2.4)
- **By the time of the next Assessment, daily global vertically-resolved spaceborne measurements of ozone-related trace gases that underpin much of our understanding of the chemical and dynamical processes controlling ozone variability will no longer be available.** A multi-year gap in these trace-gas observations is expected between the end of current capabilities (i.e., no later than 2028) and the earliest planned replacement mission (i.e., no earlier than 2030). Moreover, there are no plans to replace current spaceborne measurements of the largest chlorine reservoir, HCl. Daily global measurements of ozone and aerosol will continue outside of polar night through the gap period. (Box 3-2)

Future ozone changes

Projections of future stratospheric ozone are based on model simulations following the Shared Socioeconomic Pathways (SSPs). These scenarios assume continued compliance with the Montreal Protocol and its Amendments and Adjustments for ODSs, while spanning a wide range of future greenhouse gas and pollutant emissions pathways. While the previous Assessment relied on simulations performed as part of CMIP6, this Assessment also includes results from the CCMI-2022 simulations. As in the previous Assessment, the key drivers of future stratospheric ozone abundances continue to be declining ODS concentrations, coupled with the effects of increasing GHGs (e.g. CO_2-driven cooling in the upper stratosphere and a strengthening of the Brewer-Dobson circulation). TCO will also be affected by changes in the tropospheric ozone burden.

Return dates are defined as the return of decadally smoothed TCO time series to a historical benchmark. The purpose of this smoothing is to reduce the influence of interannual variability. In so doing, projected return dates can only be evaluated against those from observations several years after the nominal return date has passed.

- **Latest estimates of the year in which TCO returns to 1980 levels are consistent with those in previous Assessments.** Multi-model mean projections from the CCMI-2022 baseline (refD2) simulations following the middle-of-the-road SSP2-4.5 scenario indicate a return around:
  - **2040** for the near-global mean (60°S–60°N);
  - **2045** for the Southern Hemisphere mid-latitudes (60°S–35°S); and
  - **2030** for the Northern Hemisphere mid-latitudes (35°N–60°N).

  While multi-model mean return dates are broadly consistent with previous Assessments, the associated uncertainties are large and span several decades in some regions due to substantial spread among models. For the near-global mean and mid-latitudes, models projecting later return dates are more consistent with observations, suggesting that the CCMI-2022 multi-model mean return dates may be earlier than the expected recovery (Section 3.4.1). In addition, the CCMI-2022 simulations use the WMO 2018 A1 ODS scenario, which has an EESC return date that is a decade earlier than the most recent ODS scenarios produced for this Assessment (Chapter 7).

- **Near-global (60°S–60°N) TCO is projected to return to 1980 values more than two decades before stratospheric Cl_y is projected to reach its 1980 values.** This difference reflects the influence of changes in stratospheric composition, temperature, and circulation associated with changing GHG concentrations, as well as TCO changes driven by tropospheric ozone precursor emissions. (Section 3.4.1)
- **Projections of TCO are dependent on which future scenario of GHG and tropospheric ozone precursor concentrations is used.** While near-global (60°S–60°N) stratospheric column ozone is projected to increase over the coming decades under all scenarios, the magnitude of this increase varies between scenarios. In contrast, both the magnitude and the sign of tropospheric column ozone projections differ substantially between future emissions scenarios. (Section 3.4.2)
- **Emerging technologies such as a hydrogen economy, rocket launches/space debris, and supersonic aviation have so far had only minor effects on stratospheric ozone depletion compared to the impacts of ODSs.** Even under very large leakage scenarios, current studies suggest that a potential future hydrogen economy will have little impact on ozone recovery. New studies also confirm previous findings that the impact on ozone from both supersonic and hypersonic aircraft fleets is expected to be small, with some dependence on fuel mixtures and flight corridors. In contrast, the impacts of a growing space industry, which is expected to continue to rapidly expand, are highly uncertain due to dependencies on fuel type, the number of launches and their location, and the possible alteration of chemistry by particles emitted during launch and reentry. (Sections 3.4.3 and 3.4.4)

Chapter 4:
Polar Stratospheric Ozone: Past, Present, and Future

The response of polar ozone to chemical and dynamical processes is well understood. Polar ozone depletion is fundamentally driven by anthropogenic chlorine and bromine, with the severity of the chemical loss each year in both hemispheres strongly modulated by meteorological conditions (i.e., temperatures and winds) and, to a smaller extent, additional factors such as episodic stratospheric compositional changes and the solar cycle.

As noted in previous Assessments, the stratospheric halogen concentration resulting from the emissions of ozone-depleting substances (ODSs) reached its peak in the polar regions around the turn of the century and has been gradually declining since, in response to actions taken under the Montreal Protocol and its Amendments and Adjustments. The 2018 Assessment reported for the first time that signs of the onset of ozone recovery from the effects of ODSs had been detected over the Antarctic. More varied and robust signs of the onset of recovery have since emerged; as the observational record lengthens, ozone hole recovery trends are expected to continue to slowly become clearer against the background of natural variability. Nevertheless, the Antarctic ozone hole is expected to continue to be a recurring phenomenon until at least the middle of the century, albeit with a progressively decreasing average size.

The Arctic is considerably more dynamically variable, making the identification of a significant increase in Arctic ozone more challenging. Cold conditions conducive to substantial stratospheric ozone loss occur in some Arctic winter/spring seasons and are expected to continue to do so, interspersed with warmer years with little or no ozone depletion. These considerations imply the concept of an ozone return date is considerably less meaningful in the Arctic than in the Antarctic. New chemistry-climate model (CCM) projections generally confirm previous studies that, when averaged over multiple years, springtime polar total column ozone (TCO) will return to 1980 historical levels in the first half of the 21st century in the Arctic and second half of the 21st century in the Antarctic.

Observed changes in polar ozone

- **Antarctic ozone holes continued to develop each spring between 2022 and 2025, as has been the case since the early 1980s.** This ongoing, seasonal ozone loss in the southern polar region is consistent with our long-established understanding of polar chemistry during the period of slowly declining, but still substantial, concentrations of human-induced ODSs.
- **The 2022 and 2023 ozone holes were large and deep compared to most in the second decade of the 21st century, although not as large or deep as most ozone holes observed around the turn of the century when concentrations of ODSs peaked. In contrast, the 2024 and 2025 Antarctic ozone holes were smaller and more comparable to many of those in the years between 2010 and 2018 by most metrics.** The four recent springtime Antarctic ozone minima also varied in longevity, with the 2022–2024 ozone holes lasting into December and the 2025 one closing in November. Interannual variability in the magnitude of springtime Antarctic ozone reduction is mainly driven by year-to-year variations in planetary wave activity.

- **Recovery of Antarctic ozone continues despite occasional large ozone holes in recent years.** New lines of evidence and analyses since the last Assessment have strengthened this conclusion. Deviations from long-term recovery trends during recent years were primarily driven by dynamical forcings and radiative feedbacks.
- **Arctic polar cap ozone reached record high values in March 2024 primarily due to high levels of poleward transport of ozone and extreme dynamical activity in the stratosphere in that year, with a small contribution from the long-term decline of ozone-depleting substances due to the Montreal Protocol.** High-latitude TCO remained unusually high through the summer and fall of 2024.
- **Because of considerable interannual variability of Arctic stratospheric ozone, no clear statistically significant signature of its recovery has yet been detected. A multiple linear regression analysis with sufficient dynamical and aerosol proxies yields a 2001–2024 polar cap March TCO trend of 2.1 ± 2.6% per decade, based on several long-term observational data sets (with a 95% uncertainty range).** However, there is emerging evidence of statistically significant positive ozone trends of similar magnitude obtained from measurements taken at selected locations and within specific altitude ranges over the Arctic.

Understanding of polar ozone processes

- **The 2022 Hunga eruption affected the chemical composition of the polar regions but, compared to interannual variability, had only a small impact on Antarctic ozone chemistry in the years immediately following the event.** While the 10% increase in stratospheric water vapor content from the eruption resulted in very large volumes of polar stratospheric clouds in the Antarctic in 2023, saturation of chemical processing, typical for the Southern Hemisphere, prevented significant additional Hunga-induced chemical ozone loss. Future effects of Hunga on polar ozone are expected to be even smaller and are already negligible in the Arctic.
- **Dynamical forcing is the major driver of polar springtime TCO year-to-year variability in both hemispheres.** Chemical perturbations from recent extreme events, such as the Australian New Year's wildfires and the Hunga eruption, have had a smaller influence on polar ozone.
- **Chemistry on smoke particles from the January 2020 Australian New Year's wildfires caused additional chemical ozone loss over Antarctica in 2020.** Model simulations indicate that this smoke-induced ozone loss occurred near the edge of the polar vortex, increasing the area of the ozone hole by about 2.5 million km^2 (i.e., about 10%).
- **Future increases in space activity could contribute to polar ozone loss, although considerable uncertainties remain in the future number of launches and large unknowns remain in the effects of reentry emissions.** Large growth in the rate of rocket launches to about 20 times 2019 levels could lead to a reduction of springtime Antarctic TCO by a few percent, with contributions from the dynamical impacts due to emission of black carbon and from the chemical impacts due to emissions of ClO_x, NO_x, water vapor, and alumina. Similar impacts due to black carbon are expected in the Arctic, particularly if launches continue to occur predominantly in the Northern Hemisphere.

Future changes in polar ozone

- **A new set of chemistry-climate model simulations, CCMI-2022, projects a return of Antarctic spring TCO to 1980 levels during the 2060s.** This projection is similar to that from the last two Assessments, although it is later than the return date derived from the earlier CCMVal2 model simulations reported in the 2010 Assessment. The trend towards later dates partly reflects a tendency towards later recovery of stratospheric halogens in scenarios of ODSs specified for the chemistry-climate models.
- **The large variability in Arctic ozone compared to the magnitude of the forced response to changing concentrations of ODSs and GHGs implies that the concept of return date is less appropriate in the Arctic than the Antarctic.** The return date in both models and observations can only be obtained after substantial smoothing. An observed ozone return date could only be identified as such several years after it has occurred. The following estimate is reported here for consistency with previous Assessments. The central date for the projected return to 1980 levels for Arctic spring TCO from the new model simulations is the mid-2030s.
- **Projections of future evolution of Arctic ozone are dependent on modeled changes in stratospheric circulation in response to increasing GHGs.** The large range of the dynamical response seen in model simulations results in significant spread in Arctic ozone projections in the second half of the century.
- **Low Arctic ozone remains possible during winters with cold conditions in the stratosphere, as long as halogen levels remain substantially above natural levels.** New studies based on chemistry-climate model simulations underscore the role of declining halogen levels in limiting the amount of Arctic ozone depletion in the second half of the century, even under future climate change scenarios with high levels of warming.
- **CCMI-2022 is an internationally coordinated set of chemistry-climate model simulations carried out using participating state-of-the-art chemistry-climate models.** Previous Assessments over many years have relied on such initiatives to project return dates for polar ozone in both hemispheres. Nonetheless, the results should be interpreted with the appropriate degree of caution. The considerable spread in the projected return dates in part reflects the degree to which different models can accurately represent the wide variety of relevant, interconnected physical and chemical processes. Furthermore, over time, projected forcings change as our understanding of ODS emissions, banks, and lifetimes continues to advance.

Chapter 5:
Stratospheric Ozone Changes and Climate

Since the 2022 Assessment, new research has continued to advance knowledge on the two-way coupling between stratospheric ozone and climate. In particular, new studies have improved understanding of both ozone's indirect (i.e., through ozone-circulation coupling) and direct (i.e., through radiative forcing) influences on surface climate. Continued monitoring and quantification of interannual variability and changes in stratospheric climate have emphasized the impact of the 2022 Hunga volcanic eruption, amidst continued changes due to increasing greenhouse gases and ozone recovery. Southern Hemisphere circulation trends attributed to ozone depletion have continued to slow as the ozone layer recovers, despite large internal variability and recent Antarctic ozone extremes. New studies show that while ozone-depleting substances almost certainly have provided a positive direct radiative forcing since the mid-20th century, the magnitude of the indirect radiative effects is larger—and thus the net effective radiative forcing is smaller—than previously assessed. On the other hand, new research provides further evidence of the influence of stratospheric ozone and ozone depleting substances on the climate system. This remains in line with the previously assessed climate benefits of the Montreal Protocol, enhanced by the Kigali Amendment controls on HFC emissions.

Observed and simulated changes in stratospheric climate

Relevant natural and anthropogenic external forcing agents

- The concentrations of the most important greenhouse gases (GHGs) from anthropogenic emissions (i.e., carbon dioxide, methane, and nitrous oxide) have continued to increase since the last Assessment, driving long-term changes in stratospheric ozone and climate.
- The Hunga volcanic eruption in January 2022 injected into the stratosphere aerosols and extraordinary amounts of water vapor that strongly impacted the stratospheric temperature, circulation, and composition between 2022 and 2024. The net radiative forcing of the eruption was likely negative (between –0.47 and +0.07 W m^{-2} over the 2022–2023 period).

Stratospheric temperatures

- The mid-to-upper stratosphere has cooled globally by about 0.5 °C $decade^{-1}$ from 1979 to 2024, primarily in response to increased carbon dioxide, with ozone depletion contributing over the last decades of the 20th century.
- The Hunga eruption cooled the global mid-to-upper stratosphere by an additional 0.5–1 °C during the 2022–2024 period and the mesosphere by >1 °C during the 2023–2024 period as a consequence of the large increase in water vapor injected into the stratosphere. This cooling from Hunga is in contrast to stratospheric warming due to large stratospheric aerosol loading following the El Chichón (1982) and Pinatubo (1991) volcanic eruptions.

Water vapor

- From 2000 to 2021, stratospheric water vapor had a small positive trend (~2–3% per decade) amidst pronounced decadal variability.
- According to model simulations, enhanced stratospheric water vapor projected under increasing greenhouse gas concentrations exerts a small positive climate feedback and contributes to global warming. However, the exact magnitude is uncertain due to differences in the representation of key processes regulating stratospheric water vapor and sensitivity to the methods adopted in diagnosing the global climate feedback in models.
- The 2022 Hunga eruption increased the global mass of stratospheric water vapor by 10% compared to pre-eruption background amounts, and approximately 50% of the perturbation remained in the stratosphere in early 2025. Anomalously high water vapor is expected to remain in the stratosphere until 2027–2031.

Brewer-Dobson circulation (BDC)

- An acceleration of the Brewer-Dobson circulation (BDC) over the entire depth of the stratosphere in response to increasing GHGs continues to be projected by additional model simulations since the previous Assessment. Ozone depletion substantially contributed to the acceleration of the global overturning circulation, which is 1–2% per decade from 1980 to 1999 in the new model simulations, and ozone recovery is projected to reduce it by about half.
- In the lower stratosphere, observational evidence for a long-term acceleration of the BDC reported in the last Assessment is supported by new studies.
- In the middle-upper stratosphere, there remain larger observational uncertainties. While the last Assessment reported that observational estimates do not show a long-term (1979–2017) acceleration of the BDC in the NH middle-upper stratosphere, a new study calls into question these trends and obtains a statistically significant acceleration in the NH middle stratosphere from in situ data between the 1990s and 2020s.
- Large variability on interannual-to-decadal timescales has been observed over the last two decades in the BDC. This large natural variability is identified in new studies as a key driver of the ozone decline observed between 1998 and 2018 in the northern lower stratosphere middle latitudes.

Stratosphere-troposphere exchange

- Stratosphere-to-troposphere transport of ozone is expected to increase in the future by about 4% per decade, based on additional modeling studies. This is largely due to higher ozone concentrations in the extratropical lowermost stratosphere, associated with enhanced BDC driven by GHG increase and ozone recovery from ODS decline.

- Recent studies have found a substantial enhancement of stratospheric ozone transport into the troposphere following Sudden Stratospheric Warming events.

Polar vortices

- There continues to be large uncertainty in the response of the NH polar vortex to increasing GHGs, with some models projecting a strengthening and others a weakening. This uncertainty increases with larger GHG forcing and is likely related to model uncertainty in tropospheric planetary wave responses, lower stratospheric subtropical wind biases, or possibly to the representation of ozone-circulation coupling.
- The SH polar vortex is robustly projected to strengthen in the winter, while in the spring the sign of future changes is uncertain, primarily due to the offsetting effect of Antarctic ozone recovery, which is dependent on emission scenarios.

Quasi-Biennial Oscillation (QBO)

- The amplitude of the Quasi-Biennial Oscillation (QBO), the main mode of variability in the tropical stratosphere, is expected to decline because of increasing GHGs. This decline suggests an increased likelihood of disruptions to the regularity of the QBO with global impacts on ozone variability, as indicated by new studies.
- In climate models with prescribed ozone and internally generated QBO variability, the tropical stratospheric circulation does not evolve freely and synchronizes with the QBO signal imprinted in the ozone forcing. This points to the importance of accurately representing ozone to improve future projections of the QBO.

Effects of changes in stratospheric ozone and ODSs on climate

Impacts on tropospheric circulation and surface climate

- The observed delay of the springtime SH polar vortex breakdown and the poleward shift of the summertime SH mid-latitude tropospheric jet and southern Hadley cell edge during the last two decades of the 20th century are attributed primarily to ozone depletion by additional modeling studies.
- Summertime SH tropospheric circulation trends have slowed since around 2000, consistent with the influence of ozone recovery. Future ozone changes, largely due to expected recovery, weaken the springtime stratospheric polar vortices in both hemispheres, which in turn leads to an equatorward shift of the tropospheric eddy-driven jets. In the SH, this effect opposes the year-round GHG-driven strengthening of the polar stratospheric winds and associated surface impacts. Uncertainty in the relative magnitude of these opposing influences under different emission scenarios adds to uncertainty in future projections of spring and summer SH circulation trends.
- Under present-day high ODS concentrations, ozone-circulation coupling increases the interannual variability of stratospheric circulation during spring, according to new modeling studies. This enhanced variability can amplify polar vortex extremes and lead to more pronounced surface impacts.
- Stratospheric ozone observations are important not only for understanding long-term ozone changes and how they couple with circulation, but also for improving prediction of weather impacts on subseasonal-to-seasonal timescales. Recent studies that prescribe realistic stratospheric ozone in numerical forecast models show improved subseasonal-to-seasonal prediction of springtime SH polar vortex strength, leading to improved predictive skill of the Southern Annular Mode (SAM) and SH rainfall anomalies in some regions.

Impacts on the ocean and cryosphere

- New modeling studies have provided further evidence that ozone depletion has played a large role in past meridional overturning circulation strengthening in the Southern Ocean through its influence on near-surface wind stress and Ekman transport via the SAM, but only a limited role in past sub-surface (0–500m) temperature changes in the Southern Ocean. Conversely, a new single model study suggests ODSs may have made a more substantial contribution to past sub-surface warming of the Southern Ocean, due to their direct radiative forcing effect.
- Between 1979 and 2015, the SH high-latitude sea surface cooled and Antarctic sea ice increased. While previous Assessments found these changes unlikely to be driven by stratospheric ozone depletion, new research suggests that ozone depletion has contributed to the Southern Ocean SST cooling in austral summer, with a peak contribution in the Pacific region. In addition, more work has been done to understand why models struggle to reproduce the observed SST cooling, which includes the inability to resolve small-scale processes such as ocean eddies.
- The extent to which ozone trends have contributed to the net weakening of the Southern Ocean carbon sink since the 1980s remains unclear. The main cause of this long-term weakening is the increase in atmospheric CO_2 concentrations. In addition, a new study has provided further modeling evidence that stratospheric ozone depletion has contributed to the temporary Southern Ocean carbon sink weakening observed between the 1980s and early 2000s.

Modulation of the climate response to CO_2 forcing by stratospheric ozone

- Stratospheric ozone changes in response to increased CO_2 modulate the atmospheric circulation response to CO_2. Specifically, additional studies since the last Assessment show that the CO_2-driven ozone changes alter the local radiative heating in a way that dampens the BDC acceleration and the SH polar vortex strengthening and opposes the poleward shift of the tropospheric eddy-driven jets.

Net radiative forcing of ODS on climate

- ODSs have exerted a positive net effective radiative forcing (ERF) on climate, contributing to observed global warming. New model evidence indicates that the net ERF of ODSs as of the early 21st century is between 0.09 and 0.22 W m^{-2}, which is a smaller contribution of ODSs to global warming than previously assessed. Studies since the last Assessment better quantify the wide range of indirect effects arising from rapid adjustments including ozone depletion and associated chemical changes, which oppose

the direct effect of ODSs as greenhouse gases (+0.35 W m^{-2}). A net ODS ERF of ~0.2 W m^{-2} corresponds to a global-mean surface temperature increase of ~0.1 °C over the second half of the 20th century.

- New evidence from two climate models suggests that ODSs were an important contributor to global and Arctic warming over the second half of the 20th century and contributed substantially to decreases in Arctic sea ice extent and volume, as well as to changes in Southern Hemisphere circulation and temperature. Given that these particular models are on the high end of the net ODS ERF estimates, these effects might be less pronounced in other models.

Climate impacts of the Montreal Protocol

- The control of ODS emissions due to the implementation of the Montreal Protocol and its Amendments has prevented additional global warming, and these benefits will grow over the 21st century. The expected reduction in HFC emissions due to the Kigali Amendment will prevent additional warming in the future. The prevented global warming from ODSs due to the Montreal Protocol is estimated to be 0.09–0.41 °C by 2025 and 0.25–0.89 °C by 2050. The prevented global warming from HFCs due to the Kigali Amendment is projected to be 0.05–0.06 °C by 2050 and 0.2–0.4 °C by 2100.
- The Montreal Protocol could delay the occurrence of the first ice-free September in the Arctic by one to two decades, associated with the direct radiative effect of decreasing ODSs. This result is based on two climate models.
- Multiple lines of evidence support that ozone depletion has driven significant large-scale Southern Hemisphere circulation and temperature changes, in both the atmosphere and in the ocean, that will be mitigated due to the Montreal Protocol.

Chapter 6:
Stratospheric Aerosol Injection and Its Potential Effects on the Stratospheric Ozone Layer

Current nationally determined contributions (NDCs), which are non-binding, self-defined climate action plans submitted by countries under the United Nations Framework Convention on Climate Change (UNFCCC) are insufficient to achieve the UNFCCC 2015 Paris Agreement target to hold long-term global surface temperature to well below 2 °C above the pre-industrial era. Consequently, there has been a growth in research on potential technological interventions that could temporarily offset some of the anthropogenic surface warming and reduce the risk of climate tipping points that may be irreversible. One such intervention explored by scientists and engineers is the artificial injection of sulfate aerosols (or their gaseous precursors) or fine solid particles into the stratosphere to mimic the effect of large explosive volcanic eruptions on the planetary albedo and energy balance, termed stratospheric aerosol injection (SAI).

This chapter assesses the current understanding of the potential effects of SAI on the future evolution of stratospheric ozone. SAI can impact stratospheric ozone by providing surfaces for heterogeneous chemical reactions that release reactive halogens from their reservoir species and modulate nitrogen partitioning, as well as by absorbing solar and terrestrial radiation leading to stratospheric temperature changes that affect ozone transport via dynamical changes and affect the rates of chemical reactions that produce and destroy ozone.

Since SAI has not been deployed on a climatically relevant scale at the time of writing, the chapter assesses hypothetical scenarios simulated in global climate models, applying SAI to achieve a range of climate targets and using different injection strategies (i.e., what material, where, and when). Since models are a key source of evidence for the Assessment, the chapter assesses their ability to represent the key processes that determine the radiative, chemical, and dynamical impacts of SAI in the stratosphere. We also consider potential factors that are currently unexplored and/or not included in models. The chapter does not consider the details of surface climate or ecosystem responses to SAI or ethical aspects of SAI; we refer the reader to other literature for coverage of these topics.

Since the previous Assessment, there have been several coordinated multi-model simulations that enable assessment of future stratospheric ozone changes under a single sulfate-based SAI scenario and strategy. There have also been new studies with single models assessing the dependence of ozone responses on the assumed SAI scenario (e.g., target warming level, start date of SAI) and SAI strategy (e.g., altitude, latitude, and season of injection). New combined laboratory and model studies have improved understanding of the potential impacts on stratospheric ozone of performing SAI with non-sulfate materials.

Coordinated multi-model simulations performed since the 2022 Assessment have shifted the focus to scenarios that

are more closely aligned with current international climate mitigation policies and global temperature targets, and utilize SAI strategies injecting sulfate gaseous precursors away from the equator to minimize undesirable side effects. The simulations (G6-1.5K-SAI) use a middle-of-the-road climate scenario (SSP2-4.5) and the WMO (2014) ODS scenario. Sulfate-based SAI is carried out in the subtropics of both hemispheres (30°N/°S) from 2035 onwards to target global mean temperature stabilization at 1.5 °C above the pre-industrial era.

- The models consistently estimate around 0.1 °C surface cooling per 1 Tg SO_2 injected per year. The simulations show decreases in global annual mean total column ozone (TCO) of around 4 Dobson units (DU) per °C of surface cooling over 2045–2064, and around 0.4 DU per Tg SO_2 injected per year, relative to the no-SAI scenario.
- Antarctic October TCO is modeled to decrease by 17–37 DU around mid-century compared to the baseline scenario without SAI (range denotes spread across three models). The recovery of October Antarctic TCO is consequently delayed by around 10–15 years. Arctic March TCO decreases by 3–12 DU around mid-century. The changes in tropical (20°S–20°N) annual mean TCO are small and inconsistent in sign across the models.
- For the period 2035–2055, the simulations including SAI show around a 1-in-12 chance of Antarctic October TCO in any given year being below the 2020–2024 mean; this magnitude of TCO anomaly is not found in the simulations without SAI. Owing to the simulated recovery of stratospheric ozone during the 21st century, the SAI-induced depletion does not reach the level of the maximum historical ozone losses in either simulation.
- Northern Hemisphere (NH) midlatitude TCO in the latter part of the century (2065–2084) increases by a smaller amount than reported in the 2022 Assessment due to the different SAI strategy, specifically injection in the subtropics rather than at the equator. The subtropical injection strategy also decreases Southern Hemisphere (SH) annual mid-latitude TCO by 7–12 DU per °C global surface cooling over 2045–2064.

The timing of SAI deployment relative to present day would influence the impact on ozone through the dependence on the evolving background atmospheric conditions, particularly stratospheric halogen loading.

- As stratospheric halogens are projected to decrease over the 21st century, the potential of a fixed mass of aerosol to deplete stratospheric ozone through heterogeneous chemical reactions also decreases: global models project a factor of two larger global ozone loss per Tg of SO_2 emission in an earlier period of the 21st century (2045–2064) than in a later period (2065–2084). However, if global greenhouse gas emissions continue to rise and the SAI scenario targets stabilization at a fixed surface temperature target, then larger injection amounts would be required, meaning some of the decrease in the rate of chemical loss of ozone would be counteracted by higher aerosol amounts.
- A scenario in one climate model in which deployment of SAI is delayed from 2035 to 2045 while achieving the same surface temperature target of 1.5 °C above the pre-industrial shows no significant difference in the long-term (2050–2070) impacts on Antarctic springtime ozone, with both scenarios delaying ozone recovery by around 15 years. The earlier deployment, however, impacts simulated Antarctic ozone earlier in the century when its climatological level is lower. In the NH mid-latitudes, the delayed deployment shows a larger increase in TCO in the second part of the century (2050–2070) due to the larger aerosol burden causing changes in ozone transport.

Earth system model simulations show that the response of stratospheric ozone to SAI depends strongly on the injection strategy (e.g., material, altitude, latitude, season of injection). Different injection locations lead to contrasting chemical and dynamical effects in models, the net effect of which can play a first-order role in determining the TCO response, including its sign, in various regions.

- Models show that tropical SAI injection increases aerosol lifetime and produces greater global average surface cooling, as well as significant tropical lower stratospheric warming. In contrast, high latitude injections (60°N/°S) reduce tropical lower stratospheric warming, but require larger injection amounts to achieve comparable global-mean surface cooling.
- The modeled strength of SAI-induced stratospheric heating broadly scales with the modeled strength of the dynamical response in the stratosphere, including the strengthening of the stratospheric vortex in both hemispheres and changes in the Brewer-Dobson circulation, and tends to increase as injections occur closer to the equator.
- Model simulations show that subtropical and polar injection SAI strategies would deplete Antarctic ozone by releasing reactive halogens through heterogeneous chemical reactions on SAI aerosol. Enhanced chemical polar ozone loss could occur under SAI even without significant polar aerosol enhancement if the stratospheric polar vortex strengthens and cools.
- There is confidence that stratospheric injections of strongly absorbing particles such as black carbon (and co-injection with sulfate aerosols) result in increased stratospheric heating and changes in dynamics associated with stronger ozone depletion compared to sulfate aerosols.
- Some non-sulfate SAI materials may have less impact on ozone compared with sulfate aerosols, but confidence remains low. Low-absorbing particles such as alumina and calcite could reduce stratospheric heating and associated ozone changes, while their heterogeneous chemistry may also cause less ozone depletion than sulfate aerosols. However, very limited experimental and observational data of their physicochemical properties and evolution in the stratosphere results in high uncertainty in the sign and magnitude of the potential resulting ozone responses relative to a no-SAI scenario.
- New simulations since the 2022 Assessment show that for an equivalent global surface temperature target, the spread in Antarctic spring TCO response to sulfate-based SAI is several times larger across different Earth system models (ESMs) for the same SAI strategy (e.g., equatorial, tropical, or subtropical injection) compared with the spread across different SAI strategies within a single ESM. This highlights the importance of further reducing model structural uncertainties to allow better constraints on the predicted Antarctic ozone response to SAI.
- Conversely, for Arctic spring TCO, the spread across different SAI strategies in one ESM is several times larger than the inter-model spread for a single SAI strategy,

including potential differences in the sign of ozone change; therefore, the resultant ozone response has a stronger dependence on the assumed location of SAI injection than the particular ESM used for modeling.

Numerical atmospheric models with interactive chemistry and aerosol microphysics remain the primary tools for investigating potential impacts of SAI on stratospheric ozone. Gaps in the understanding of aerosol microphysics and optical and chemical properties, as well as limitations in the ability to model stratospheric chemistry, transport, dynamics and plume scale effects, contribute to significant uncertainties in quantifying the effects of SAI on stratospheric ozone.

- One limitation of current global models is they do not include plume-scale processes at scales smaller than model grid boxes. This is likely to lead to different representations of particle formation and growth in models compared to what would occur in reality, but the importance of this missing process for the relationship between injected mass and the spatial distribution of aerosol optical depth over longer timescales is unclear.
- Uncertainties arise from limited process understanding of some aspects of aerosol behavior. 1) New SAI simulations and comparisons with volcanic observations have revealed uncertainties in the representation of stratospheric aerosol microphysical processes and transport in current climate models, affecting confidence in predicted spatial aerosol distributions and their effects on climate and ozone. 2) Compared to sulfate aerosols, there is generally significantly lower process understanding for non-sulfate particles with respect to particle dispersion, coagulation, heterogeneous chemistry, optical properties, and particle interaction with clouds, sulfate aerosols, and water, as well as the subsequent impacts on ozone.
- Processes related to the presence of organic aerosols in the stratosphere, space rocket and reentry emissions and their interaction with SAI are poorly constrained and not accounted for in global models used for assessing SAI, which adds uncertainty to projected ozone impacts.

Chapter 7:
Scenarios and Information for Policymakers

A key focus of this chapter is to explore processes and activities that have the potential to significantly affect future stratospheric ozone and may be of particular interest to policymakers. This includes assessing the potential impacts of controlled ODSs, the use of ODSs as feedstocks, very short-lived substances (VSLSs), the major greenhouse gases CO_2, CH_4, and N_2O, a potential move towards a hydrogen economy, and space activities. The impact of many of these above-mentioned emissions and activities on climate is also considered. For the first time, this SAP Assessment uses temperature change as the primary metric to evaluate these climate impacts across the various scenarios considered. Impacts of HFC emissions and trifluoroacetic acid (TFA) are primarily discussed in Chapter 2. The climate intervention approach of Stratospheric Aerosol Injection (SAI) is discussed in Chapter 6; in addition to many other side effects, SAI could have important stratospheric ozone impacts.

A suite of scenarios is presented to perform these analyses. The focus of the scenarios is on the impact of future emissions and/or production, because these are things that can be changed; the influence of past emissions on ozone or climate is not significantly explored. The scenarios are not intended to imply any assessment of feasibility or cost-effectiveness of particular actions. Rather, they are meant to demonstrate the significance of various future emission sources for ozone and climate. Unless otherwise stated, the quantification of ozone impacts in this chapter represents globally averaged total column ozone changes relative to the baseline scenario as calculated by a 2-D model. Temperature changes represent globally averaged surface air temperature (GSAT) differences from the baseline scenario. Both metrics are provided for the years 2050 and 2100. Temperature impacts of the halocarbon and N_2O scenarios are calculated by a reduced-complexity Earth system model, which includes an estimate of the stratospheric ozone response to the presence of these compounds. Quantifying the impact of these ozone responses to halocarbons on climate is quite uncertain, potentially large relative to the ODS direct forcing in some cases, and continues to be an area of active research (see Chapter 5). Appendix B shows estimates of the uncertainty due to this ozone response for the halocarbon scenarios. The year when equivalent effective stratospheric chlorine (EESC) returns to its 1980 level is also provided for the ODS scenarios. These return dates are strictly reflective of this metric and do not consider other atmospheric composition changes that might occur, including, for example, those involving CO_2, CH_4, and N_2O. Because of this, dates when ozone returns to 1980 levels provided in other chapters are often substantially different from those presented here.

To put the results of this chapter in context, for ozone,

the peak globally averaged depletion was roughly 5% in the early 1990s relative to the 1964–1980 average. For climate, the observed warming for the 2016–2025 decade average relative to the period 1850 to 1900 was 1.26 (1.13–1.36) °C, of which 1.24 (1.0–1.5) °C was attributed to human activity.

The 2026 baseline scenario

The baseline scenario presented in this chapter assumes full compliance with the Montreal Protocol for future ODS production and consumption for dispersive uses. It also includes unrestricted applications and compounds, such as allowing projected growth in feedstock use of ODSs through 2035 at up to 6% yr^{-1} depending on compound and projected growth in CH_2Cl_2 emissions of 70 Gg yr^{-1} through 2035. For feedstock-related use and CH_2Cl_2, it is assumed that emissions are constant after 2035. HFC-23 emissions follow the "Kigali Amendment" scenario of Chapter 2 and demonstrate a decline of approximately 70% over this same time period. Scenarios for the other HFCs are only changed from WMO (2022) in updated times for elimination of banks, production, and all emissions. The SSP2-4.5 scenario, which reflects a middle-of-the-road assumption for growth in global development and energy use, is assumed for N_2O, CH_4, and CO_2.

All mitigation options discussed in this chapter represent a deviation from the baseline scenario. If future actions were to occur that are contrary to the assumptions underlying this scenario, such as illegal production, different feedstock emission fractions, different growth rates, etc., the quantification regarding the benefits of certain actions would change.

In the current baseline scenario, the return to 1980 EESC levels from long-lived ODSs occurs 1.7 years (year 2067.7) and 5.4 years later (year 2092.0) for the mid-latitude and polar regions, respectively, as compared with the baseline scenario in Chapter 7 of WMO (2022). This difference is primarily due to the inclusion of projected growth in feedstock emissions. Consistent with previous assessments, these EESC calculations only consider ODSs and do not include N_2O or very short-lived substances. (Section 7.8.4)

Substances controlled by the Montreal Protocol

One measure of the Montreal Protocol's success is demonstrated by the limited ozone and climate impacts achievable from further controls on production and consumption associated with dispersive applications. The projections of emissions from these applications are among the most well-constrained of the scenarios discussed in this chapter. Compliance with existing controls is the key consideration for compounds and activities in this category.

- **Eliminating all future ODS emissions from dispersive applications in the baseline scenario is projected to lead to an increase in globally averaged total column ozone of about 0.6% in 2050 and 0.4% in 2100. This corresponds to about 2 DU and 1 DU in 2050 and 2100, respectively. These same emissions are projected to lead to a warming of approximately 0.01 °C in 2050 and much less than 0.01 °C by 2100.** (Section 7.8.4)
- **Eliminating all future ODS production for dispersive applications from the baseline scenario is estimated to lead to an increase in ozone of 0.11% in 2050 and 0.08% in 2100 and very little temperature change in both years.** This ozone increase arises almost entirely from the elimination of CH_3Br emissions associated with quarantine and pre-shipment (QPS) activities, which are assumed to continue at the present level indefinitely in the baseline scenario. (Section 7.8.4)
- **Eliminating emissions of CH_3Br associated with QPS uses at the 2024 level would lead to an increase in ozone of about 0.08% in 2050 and 0.07% in 2100.** Eliminating these emissions has a negligible direct effect on temperature and is expected to lead to a small level (<<0.01 °C) of atmospheric warming, which arises from the associated ozone increase. (Section 7.8.4)
- **Banked ODS halocarbons will continue to be emitted in the coming decades. Global halocarbon banks have been estimated to be more than 8,340 Gg in 2021, equivalent to ~3,680 Gg CFC-11-eq and ~24 Pg CO_2-eq.** In contrast to CFCs, which were previously predominantly used in non-Article 5 countries and where the majority of the bank resides, for HCFCs, about two-thirds of the global HCFC bank resides in Article 5 countries. China holds the largest share of the various HCFC banks among A5 countries, about one third of the global total, with all other A5 countries combined also holding one third. The remaining third resides in non-A5 countries, concentrated mainly in North America, Europe, and Japan. There is a large uncertainty associated with bank estimates, and the accessibility of the banked ODSs (i.e., how easily they could be captured) varies greatly by application and life-cycle stage. (Sections 7.2.1 and 7.8.4)
- **Eliminating all emissions of CFCs, halons, and HCFCs from their projected 2028 banks is estimated to lead to increases in ozone of 0.18%, 0.16%, and 0.15%, respectively, in 2050 and of 0.19%, 0.14%, and 0.03%, respectively, in 2100. Together, this is about one tenth of the magnitude of ozone depletion experienced at its peak in the early 1990s.** Eliminating these emissions is estimated to lead to a cooling of less than 0.01 °C in 2050 and 2100. These values represent elimination of the total banks; the subset of the banks, particularly those consisting of CFCs and HCFCs, that is cost-effective or even technically feasible to capture is certainly smaller, and possibly much smaller, than the total bank. (Section 7.8.4)
- **Eliminating future emissions of CCl_4 not associated with feedstock use is projected to have a very small impact on ozone depletion and climate.** This follows from the assumption in the baseline scenario that these emissions of CCl_4 will linearly decline to zero by 2035. As discussed in Chapter 1, however, CCl_4 emissions may have risen slightly from 2020 to 2024. If these increases are not associated with feedstock use, this would imply a shortcoming in the baseline scenario. (Section 7.8.4)
- **Full compliance with the Kigali Amendment provisions to the Montreal Protocol is projected to prevent warming of up to 0.4 °C in 2100 (not considering any potential benefits from energy-efficiency improvements) compared to projected temperatures without HFC control measures.** Eliminating future emissions, which goes beyond compliance, prevents a further warming of 0.03 °C in 2050 and 0.04 °C in 2100, to which the 2028 HFC banks contribute 0.01 °C. HFCs have little influence on stratospheric ozone. (Section 7.8.4)
- **Eliminating future emissions of HFC-23 (100-yr GWP of 14,500) has the potential to prevent warming that is substantial relative to that from the elimination of**

emissions of the other HFCs. As an example, relative to a scenario in which HFC-23 emissions increase by about 3% per year through 2035 and then remain constant, eliminating future HFC-23 emission would prevent 0.01 °C of warming by 2100, which is about one quarter of the warming from eliminating the future emissions of all other HFCs. Quantifying this benefit is challenging due to uncertainties in the magnitudes of HFC-23 emission sources, particularly those associated with current and future production of HCFC-22 and other fluorocarbons .(Section 7.8.4, Chapter 2)

Substances and activities outside Montreal Protocol control

The Montreal Protocol does not control the production of ODSs used in feedstock applications, nor does it control chlorine- and bromine-containing VSLSs. Emissions projections of these substances are thus largely unconstrained, and their impacts on ozone and climate are highly dependent on the assumptions underlying the projections.

Feedstock use

- **Primarily driven by a rapidly expanding polymers industry, the production and use of ODSs as feedstock continue to rise. In addition, ODS feedstock use for HFO and HCFO production is increasing, while feedstock use for HFCs is declining.** The combination of this rapid growth (i.e., an average growth rate of 7% yr^{-1} by mass from 2020 to 2023) and a higher emission ratio (for all compounds except CCl_4) increases the projected impact of feedstock-related emissions on both ozone recovery and climate forcing. (Section 7.2.2.1)
- **The current best-estimated emission ratio for most ODSs used as feedstocks has been revised upward from 2% in the previous Assessment to 3.6% (with a range of 1.5% to 6.1%) of production (TEAP 2024).** By reporting the amount of production used in feedstock applications, the Parties enable the calculation of annual emission estimates from this emission ratio. (Section 7.2.2.1)
- **Eliminating ODS emissions from feedstock use from the baseline scenario from 2028 onward is projected to increase ozone by 0.21% in 2050 and 0.40% in 2100; it is estimated that this would prevent a warming of about 0.01 °C in 2050 and 2100.** From a scenario in which these feedstock emissions were to continue to increase through 2050, rather than being held constant after 2035, the elimination of these future emissions would lead to an increase in ozone of 0.25% in 2050 and 0.69% in 2100; this elimination would also prevent a warming of slightly more than 0.01 °C by 2100. (Section 7.8.4)
- **Future CCl_4 emissions are the most significant feedstock-related emissions for ozone depletion in the baseline scenario.** Eliminating these emissions would lead to an increase in ozone of 0.14% in 2050 and 0.26% in 2100. Eliminating these emissions is projected to have very little impact on temperature. (Section 7.8.4)
- **Future HCFC-22 emissions are the most significant of the feedstock-related emissions for global temperature change in the baseline scenario.** These emissions are projected to partially offset the gains achieved from the phase-down of regulated uses. Eliminating these emissions would lead to a temperature reduction somewhat below 0.01 °C. (Section 7.2.2.1, Section 7.8.4)

Very short-lived substances (VSLSs)

- **The combined impact of CH_2Cl_2, CH_2ClCH_2Cl, $CHCl_3$, and C_2Cl_4 is to reduce present-day global ozone by an estimated 0.3% to 0.7% (or 0.8 DU to 2.1 DU), based on current emissions level and published ODP estimates.** Collectively, these four Cl-VSLSs added 140 ± 30 ppt Cl to stratospheric chlorine in the year 2024 (Chapter 1, Section 1.3.2.1). C_2HCl_3 is estimated to contribute less than 1 ppt Cl to stratospheric chlorine, and the present-day ozone impact is negligible. Large volumes of chlorinated-VSLSs are produced every year. Among all Cl-VSLSs, CH_2Cl_2 is unique in its predominant use (about 75%) for emissive applications and rapid growth in production and emissions; more than 70% of its total production is released into the atmosphere. Presently, CH_2Cl_2-related ozone depletion accounts for 70–86% of the total Cl-VSLS ozone impact. (Sections 7.3.1, 7.8.4, Table 7-3)
- **In a scenario in which CH_2Cl_2 emissions continue to grow at the current rate until 2035 and then remain constant, ozone is approximately 0.8% (0.6%–1.0%) less in 2050 and 2100 compared with a scenario in which there are no future emissions. There is some variation in this quantity that depends on location and season of emission.** The direct warming from these emissions is estimated to be much less than 0.01 °C. (Section 7.8.4)

Major well-mixed greenhouse gases

CO_2, CH_4, and N_2O strongly affect ozone levels through various processes. Uncertainties in the combined future trajectories of CO_2 and CH_4 lead to more uncertainty in ozone projections than do ranges of future ODS emissions that are consistent with full compliance with the Montreal Protocol.

- **Future N_2O emissions have the potential to lead to substantially more ozone depletion and warming than future ODS emissions.** The benefits of future controls on N_2O emissions depend on the projected levels in a scenario in which such controls do not exist. Constructing such a scenario is challenging due to current limited policy constraints. (Section 7.4)
- **Reducing future anthropogenic emissions of N_2O from the baseline scenario (SSP2-4.5) to a highly mitigated one (SSP1-1.9) would lead to increases in ozone of about 0.2% in 2050 and 0.5% in 2100; this would also lead to a cooling of 0.02 °C in 2050 and 0.05 °C in 2100. If a higher-emission scenario (SSP3-7.0) were chosen for the baseline, the benefits of reducing N_2O to the highly mitigated scenario would be 0.3% (1.3%) more ozone and 0.03 °C (0.12 °C) cooling in 2050 (2100).** Recent N_2O emissions have been increasing faster than in any of the Shared Socioeconomic Pathways, although the implications of this trend for the more distant future are unclear. (Section 7.8.4)
- **If CO_2 and CH_4 concentrations continue to increase in the future, they will lead to increased globally averaged ozone levels that could be higher than levels experienced before significant emissions of ODSs commenced.** Conversely, a combined reduction in CO_2 and CH_4 concentrations from the baseline scenario to the highly mitigated SSP1-1.9 scenario is calculated to lead to a 2–3% reduction in stratospheric ozone by 2100. (Section 7.4)

Other activities that affect stratospheric ozone

Various emerging sectors and technologies have the potential to perturb the stratosphere, though estimates of their impacts vary greatly in certainty. The likelihood of high levels of growth in some of these sectors suggests the need for high levels of vigilance. Stratospheric aerosol injection (SAI), a type of climate intervention, will have impacts across the Earth system. For example, in addition to its impact on temperature, SAI will alter stratospheric composition and will almost certainly affect stratospheric ozone. This is discussed in detail in Chapter 6.

- **Growth in space-industry emissions will continue to perturb the stratosphere in the future through the launch phase and satellite sublimation during end-of-life reentry, leading to some amount of ozone depletion.** Estimates of the magnitude of the impact suggest relatively small effects when assuming moderate growth in the rate of launches and reentries. However, key limitations exist in projecting future growth rates, and large gaps remain in the understanding of spaceflight emissions and the chemical and aerosol processes that could be important to determine ozone impacts. Evolving rocket propellant and spacecraft material properties further limit accurate projections of future emissions and relevant ozone chemistry. Metals from satellite and rocket body ablation during atmospheric reentry have already been measured in stratospheric aerosol particles and mesospheric plumes. (Section 7.5)
- **Since the previous Assessment, the likelihood of having commercial supersonic air travel in the next decade or so has increased. If implemented at a substantial fraction of current air travel, this has the potential to alter the distribution of stratospheric ozone.** However, the impact is highly uncertain, as both the magnitude and sign of the change are dependent on the height and location of flight tracks, engine operating conditions, and the sulfur content of the fuel, with higher flight tracks and more sulfur generally leading to more ozone depletion. (Section 7.5)
- **The general consensus in the literature continues to be that stratospheric ozone would be largely unaffected by a transition to a hydrogen economy and by the associated increase in molecular hydrogen (H_2) emissions.** This remains true despite the fact that H_2 levels in the atmosphere have risen by more than 50% relative to 1900. (Section 7.6, Chapter 3)

Annex A:
Summary of Abundances, Lifetimes, ODPs, REs, GWPs, and GTPs

- The present analysis has updated climate metrics that reflect 2024 CO_2 forcing, leading to ~3% higher GWP and GTP values for all non-CO_2 compounds compared to the previous Assessment.
- A misapplication of a formula in the IPCC AR6 report was corrected, leading to ~4% lower GWP and GTP values for all compounds except CH_4 and N_2O, where the correction led to a GWP/GTP reduction of ~6% and ~2%, respectively, compared to the previous Assessment.
- Additional compounds have been added to Table A-5, totaling 65 since the last Assessment. All Montreal Protocol-controlled CFCs are now included.
- Tropospheric OH reactive loss lifetimes in Table A-5 have been updated using a reference CH_3CCl_3 OH reactive loss lifetime of 5.9 years. A lifetime of 6.1 years was used in WMO (2022).
- A table (Table A-4) has been added that summarizes persistent compound yields for HFC-23 (CHF_3), CFC-13 ($CClF_3$), PFC-14 (CF_4), trifluoroacetic acid (TFA), perfluoropropanoic acid (PFPrA), and perfluorobutanoic acid (PFBA) formed in the atmospheric degradation of Montreal Protocol-controlled substances and some alternative compounds.
- Per- and polyfluoroalkyl substances (PFAS) included in Table A-5 are now identified according to the Buck et al. (2011), OECD (2021), and US EPA (2024) PFAS definitions.

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