

Ozone Research and Monitoring
GAW Report No. 303

Report of Part I of the Twelfth Meeting of the Ozone Research Managers of the Parties to the Vienna Convention for the Protection of the Ozone Layer

(Geneva, 24–26 April 2024)

WEATHER CLIMATE WATER



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INTRODUCTION

The Ozone Research Managers (ORM) of the parties to the Vienna Convention for the Protection of the Ozone Layer held their 12th Meeting (ORM12) at WMO headquarters in Geneva, from 24 to 26 April 2024.

The meeting was organized by the Secretariat for the Vienna Convention and its Montreal Protocol (the Ozone Secretariat), United Nations Environment Programme (UNEP), in cooperation with WMO, in accordance with decision I/6 of the 1st meeting of the Conference of the Parties to the Vienna Convention for the Protection of the Ozone Layer (COP1), Helsinki, 26–28 April 1989. A list of participants is provided in Annex 1 to the present report.

OPENING OF THE MEETING

The meeting started on Wednesday, 24 April 2024.

Opening statement (Meg Seki, Executive Secretary, Ozone Secretariat)

The Executive Secretary of the Ozone Secretariat, Ms Megumi Seki, opened the meeting, addressing the Co-Chairs of the 11th Meeting of the Ozone Research Managers of the parties to the Vienna Convention for the Protection of the Ozone Layer (ORM11),¹ online, 8–10 July 2020 and 19–23 July 2021; the ORM; the Co-Chairs of the three Assessment Panels² under the Montreal Protocol on Substances that Deplete the Ozone Layer; and colleagues from WMO, the National Aeronautics and Space Administration (NASA) and the Ozone Secretariat. She welcomed the meeting participants and thanked WMO for hosting the meeting and working closely with the Ozone Secretariat to arrange it. She also extended a warm welcome to Paolo Laj, incoming Head of the WMO Global Atmosphere Watch (GAW) Programme, noting that she looked forward to working closely with him and his team with a view to strengthening the long-standing partnership between the Ozone Secretariat and WMO on ORM-related activities and on the activities of the General Trust Fund for Financing Activities on Research and Systematic Observations Relevant to the Vienna Convention (hereinafter referred to as “the Trust Fund”).

The Vienna Convention for the Protection of the Ozone Layer and its Montreal Protocol are the two multilateral environmental agreements that constitute the international ozone layer protection regime, which is one of the undoubted success stories of international cooperation. From the very start, the negotiators of the two treaties established a framework that enabled science to be the basis for policy and decision-making. Embracing the precautionary principle, the Vienna Convention was adopted even before the hard, observational evidence of the actual depletion of the ozone layer became available.

Established as a subsidiary body of the Vienna Convention, the ORM review ongoing national and international research and monitoring programmes to ensure proper

¹ Mr Héctor Estévez (Mexico) and Mr Kenneth Jucks (United States of America)

² Co-Chairs of the Scientific Assessment Panel (SAP): Ms Lucy Carpenter (United Kingdom of Great Britain and Northern Ireland), Mr David Fahey (United States), Mr Kenneth Jucks (United States) and Mr Bonfils Safari (Rwanda)

Co-Chairs of the Environmental Effects Assessment Panel (EEAP): Ms Janet Bornman (United States) and Mr Paul Barnes (United States)

Co-Chairs of the Technology and Economic Assessment Panel (TEAP): Ms Bella Maranion (United States), Ms Marta Pizano (Colombia) and Mr Ashley Woodcock (United Kingdom)

coordination, identify gaps that need to be addressed and recommend actions to fill those gaps. Having met for the first time in 1991, the ORM held their previous (eleventh) meeting online in two parts in 2020 and 2021, owing to the coronavirus disease (COVID-19) pandemic.

In addition to recommendations made on the customary four areas of research, systematic observations, data archiving and capacity-building, ORM11 addressed a fifth topic, gaps in atmospheric monitoring of controlled substances, in response to a request by the parties to the Montreal Protocol after the 2018 scientific findings of an unexpected increase in global emissions of trichlorofluoromethane (CFC-11). Since then, a number of assessments of the issue have been carried out by the Assessment Panels, and a pilot project, funded by the European Union, on addressing gaps in monitoring of controlled substances started and continues to be implemented.

Noting that the issue of monitoring of controlled substances was included in the agenda of the meeting, Ms Seki stressed that one of the key questions of the parties to the Montreal Protocol concerned the costs of establishing monitoring stations for controlled substances. Parties had requested the Secretariat, in consultation with the ORM, SAP, TEAP and the Multilateral Fund Secretariat for the Implementation of the Montreal Protocol, to look into refining the cost estimates for enhancing monitoring, identifying potential monitoring station locations and reporting on the options for sustainable funding for establishing new regional monitoring capacities. The inputs of the ORM on those issues would therefore be important.

She also noted that the recommendations of the meeting would be presented to the combined 13th meeting of the Conference of the Parties to the Vienna Convention and the 36th Meeting of the Parties to the Montreal Protocol (COP13–MOP36), scheduled to be held from 28 October to 1 November 2024 in Bangkok.

She further informed the meeting that members of the Bureau of the 12th meeting of the Conference of the Parties to the Vienna Convention for the Protection of the Ozone Layer (COP12), online, 23–27 November 2020 and 25–29 October 2021, had been invited to and were attending the meeting with a view to following the deliberations and considering ways to support the recommendations of the ORM at COP13–MOP36.

In closing, Ms Seki thanked the three Assessment Panels and the Advisory Committee of the Trust Fund for their continuous support under the ozone treaties, as well as the ORM, and the international scientists and experts who had been invited as resource persons, for their work and efforts to enhance stratospheric ozone research and monitoring.

Welcome statement
(Paolo Laj, WMO)

On behalf of WMO, Mr Paolo Laj extended a warm welcome to the attendees of ORM12. He noted the acknowledgement by WMO of the community's achievements in monitoring stratospheric ozone and ozone-depleting substances (ODSs) amidst a changing climate and underscored that ozone research remained a priority within the GAW Programme, with emphasis on ongoing research and monitoring programmes globally.

The objectives of the ORM include reviewing national and international research and monitoring programmes, identifying gaps in network implementation, technological challenges and financing needs. Recent discussions highlighted upcoming issues with monitoring technologies and data access, crucial for WMO and the GAW Programme.

Despite advancements, the poor coverage in certain regions remains a limitation, emphasizing the need for collaboration and clear communication with stakeholders and funders. The GAW Programme's five-year implementation plan focuses on research infrastructure, scientific strategy, support to services and policies, and capacity-building.

ORM would address these pillars, fostering discussions and recommendations for the Programme's strategy.

In closing, Mr Laj noted the excitement of WMO for the upcoming discussions and assured full support for ORM activities and research endeavours.

The 2022 WMO/UNEP Scientific Assessment of Ozone Depletion (David Fahey and Bonfils Safari, Co-Chairs of the Scientific Assessment Panel)

The WMO/UNEP Scientific Assessment of Ozone Depletion is a quadrennial report produced for the parties to the Montreal Protocol on Substances that Deplete the Ozone Layer. The SAP Co-Chairs led a large group of international scientists in developing the 2022 report. The presentation conveyed the highlights of the 2022 report, which included (a) decreases in ODSs; (b) continuation of recovery of the ozone layer; (c) the decline in unreported global emissions of CFC-11; (d) an increase in global trifluoromethane (HFC-23) and dichloromethane (CH₂CL₂) emissions; and (e) the projected changes in stratospheric ozone in scenarios of stratospheric aerosol injection (SAI) to reduce global warming. Special topics included the Hunga Tonga–Hunga Ha'apai volcanic eruption and an early look at the possible influence of the eruption on the size of subsequent Antarctic ozone holes. The newly revised edition of the *Twenty Questions and Answers About the Ozone Layer* booklet³ was highlighted as an excellent outreach document that captures the science of the assessment reports for non-scientists and policymakers. All the SAP reports and documents are available on the Ozone Secretariat website.⁴

Overview of the interface between the Scientific Assessment Panel, the Ozone Research Managers' recommendations and the resultant decisions of the 12th meeting of the Conference of the Parties to the Vienna Convention (Héctor Estévez and Kenneth Jucks, Co-Chairs of the 11th Meeting of the Ozone Research Managers)

The Co-Chairs of ORM11, Héctor Estévez (Mexico) and Kenneth Jucks (United States), presented on the past findings of the ORM. The presentation concentrated on the defined, related yet separate roles of the ORM relative to the SAP process. The presentation then went on and highlighted the findings of ORM11 in the areas of scientific research, systematic observations, gaps in coverage of ODS compounds, data archive and stewardship, and capacity-building. That set the framework for how the rest of ORM12 proceeded.

Election of the Co-Chairs of the 12th Meeting of the Ozone Research Managers (Meg Seki, Executive Secretary, Ozone Secretariat)

The Executive Secretary introduced this agenda item. She expressed her sincere appreciation to the ORM11 Co-Chairs, Mr Héctor Estévez (Mexico) and Mr Kenneth Jucks (United States), for their valuable contributions during their tenure, especially during the challenging COVID-19 pandemic period when ORM11 took place online and in two parts. Ms Seki invited the ORM in the plenary to nominate candidates, one from a developed country and another from a developing country, to be elected as Co-Chairs for ORM12.

³ <https://ozone.unep.org/science/assessment/sap>

⁴ <https://ozone.unep.org/>

Based on the nominations received, Mr Wolfgang Steinbrecht (Germany) and Ms María Del Carmen Cazorla Andrade (Ecuador) were elected unanimously to be Co-Chairs of ORM12.

Adoption of the agenda of the 12th Meeting of the Ozone Research Managers (Co-Chairs of the 12th Meeting of the Ozone Research Managers)

The agenda, as contained in Annex 2 to the present report, was unanimously adopted. The summaries of the presentations given under sessions 1–8 are provided below. Full copies of the presentations are available at: <https://ozone.unep.org/meetings/12th-meeting-ozone-research-managers/plenary-presentations>.

SESSION 1: ISSUES RELATED TO THE GENERAL TRUST FUND FOR RESEARCH AND SYSTEMATIC OBSERVATIONS

Work under the Trust Fund

The status of the Trust Fund (Sophia Mylona, Ozone Secretariat)

The General Trust Fund was established in accordance with decision VI/2 of the 6th meeting of the Conference of the Parties to the Vienna Convention (COP6), Rome, 25–29 November 2002. In that decision, the COP requested that UNEP, in consultation with WMO, establish an extrabudgetary fund for receiving voluntary contributions from the parties and international organizations, for the purpose of financing activities on research and systematic observations relevant to the Vienna Convention in developing countries and countries with economies in transition (CEITs).

The aim of the Trust Fund, according to the decision, is to provide complementary support for the continued maintenance and calibration of the existing WMO/GAW ground-based stations monitoring column ozone, ozone profile and ultraviolet (UV) radiation in developing countries and CEITs. The decision also provides that consideration should be given to supporting other activities identified by the ORM for the improvement of the observation network and relevant research.

The activities of the Trust Fund are overseen by an Advisory Committee, established pursuant to decision X/3 of the 10th meeting of the Conference of the Parties to the Vienna Convention for the Protection of the Ozone Layer (COP10), Paris, 17–21 November 2014. The Committee's mandate is to develop and implement a long-term strategy for the Trust Fund and a short-term action plan to meet urgent needs and the best possible use of resources; and to ensure quality control of individual proposals, striving for regional balance and identifying possibilities for complementary funding to maximize resources.

The total contributions to the Trust Fund from its inception in 2003 until 15 April 2024 amounted to 912 674 US dollars (USD), received from 16 countries. During the same period, a total amount of USD 635 426 was disbursed or allocated to 22 approved activities, resulting in a balance of USD 277 248 available for supporting activities in future project proposals.

In November 2023, the Secretariat invited all developing countries and CEITs to submit project proposals for possible support under the Trust Fund. In response, 14 proposals had been received by 15 April 2024 from 11 parties⁵ and were under consideration by the

⁵ Burundi, Chile, Comoros, Ecuador, Indonesia, Morocco, Mozambique, Rwanda, Somalia, Uganda and Venezuela (Bolivarian Republic of)

Advisory Committee. Additional proposals were expected to be submitted during and after ORM12.

Information about the activities under the Trust Fund can be found on the Ozone Secretariat's website at the following link: <https://ozone.unep.org/activities>.

Report on activities under the Trust Fund (John Rimmer, WMO)

The Trust Fund supports national and international research and monitoring activities in developing countries and CEITs. Recently completed or ongoing projects are the following:

- Establishment of an ozone observatory in Comoros, with installation of a mini Zenith Observation Analysis System (SAOZ)⁶, was completed in October 2023.
- South American Brewer Spectrophotometer network repair and intercomparison held in Santa Maria, Brazil, February 2024. Collaboration with five countries plus in-kind contribution from the State Meteorological Agency, Spain (AEMET)⁷ providing an operator's course, expertise and reference instrument.
- Ultraviolet B radiation (UVB) solar radiation monitoring in Central America and the Caribbean. A collaboration of five countries to establish a UV radiation network in this area through the installation of instrumentation and training of operators in the use of the instruments and data submission. The project is expected to be completed in early 2026.

Several new proposals from South America and Africa are currently under consideration and include Burundi (Pandora spectrometer), Chile (UV), Ecuador (UV), Indonesia (ozone (O₃), ODSs and UV), Morocco (Pandora spectrometer), Mozambique (O₃, UV), Nigeria (Brewer Spectrophotometer Network), Rwanda (O₃), Somalia (O₃), Uganda (ODSs) and Venezuela (Bolivarian Republic of) (ODSs).

Report of the Advisory Committee of the Trust Fund (Sophie Godin-Beekmann, Advisory Committee Chair)

The Advisory Committee was established in 2014 through decision X/3 of COP10. Its mandate is (a) to implement the long-term objectives of the Trust Fund and priorities from the overarching goals of the ORM; (b) establish a short-term action plan linked to urgent needs and best possible use of resources; (c) evaluate individual proposals from developing countries and CEITs; and (d) identify possibilities for complementary funding. Considering the limited resources of the Trust Fund, its main goals are focused on maintaining observations dedicated to ozone layer science and surface UV radiation by providing support for capacity-building.

Since the previous ORM meeting in 2021, the activities of the Advisory Committee have focused on the evaluation of proposals received in response to a call issued in December 2020. Another call was issued in December 2023. For each proposal, the funding is limited to USD 50 000, and an emphasis is placed on the need for cost-sharing in order to guarantee the sustainability of the projects. Regarding the implementation of long-term and short-term plans of action, the following recommendations were provided:

⁶ SAOZ: Système d'Analyse par Observation Zénithale

⁷ AEMET: Agencia Estatal de Meteorología

- There is still a need to strengthen high-quality ozone observations in the tropics and the southern hemisphere. Considering the reduced reliance on Dobson and Brewer spectrometers, it is now important to develop new cost-effective instrumentation for total ozone measurements, such as Pandora, SAOZ and BiTec Sensor (BTS) spectrometers. The ozone sonde network needs also to be extended in these undersampled regions.
- A strategy needs to be devised in order to further facilitate relocation of unused Dobson and Brewer instruments, based on a stronger link with ozone monitoring networks.
- Given additional resources, support can be provided to parties operating under paragraph 1 of article 5 of the Montreal Protocol, for the monitoring of ODSs.
- In order to further build capacity, it is necessary to increase the visibility of the Trust Fund within the global climate observing network, as well as to maintain close connections with bodies involved in the science of the ozone layer (such as the International Ozone Commission (IO₃C) and Atmospheric Processes And their Role in Climate (APARC)), and with networks monitoring controlled substances, for example, the National Oceanic and Atmospheric Administration (NOAA) and Advanced Global Atmospheric Gases Experiment (AGAGE) networks.

Clarification of the tasks and roles of discussion leaders, rapporteurs and experts in the breakout groups to frame recommendations on: research needs; systematic observations; gaps in the global coverage of atmospheric monitoring of controlled substances and options to enhance such monitoring; data archiving and stewardship; capacity-building

(Co-Chairs of the 12th Meeting of the Ozone Research Managers)

Discussion leaders and rapporteurs for the recommendation areas were selected as follows:

- Research needs – Discussion Leaders: Lucy Carpenter (United Kingdom) and David Fahey (United States) (SAP Co-Chairs); Rapporteur: Kenneth Jucks (United States) (SAP Co-Chair).
- Systematic observations – Discussion Leaders: Sophie Godin-Beekmann (France) and Damaris Kirsch Pinheiro (Brazil); Rapporteur: Stefan Reimann (Switzerland).
- Gaps in the global coverage of atmospheric monitoring of controlled substances and options to enhance such monitoring – Discussion Leaders: A.R. Ravishankara (United States) and Ray Weiss (United States); Rapporteur: Stephen Montzka (United States).
- Data archiving and stewardship – Discussion Leaders: Martine De Mazière (Belgium) and Tove Svendby (Norway); Rapporteurs: Alberto Redondas (Spain) and Viktoria Sofieva (Finland).
- Capacity-building – Discussion Leaders: Samuel Paré (Burkina Faso) and Sergio Moreno (Switzerland); Rapporteur: Irina Petropavlovskikh (United States).

SESSION 2: THE STATE OF THE OZONE LAYER AND FACTORS IMPACTING THE SPEED OF ITS RECOVERY

Updates on the state of the ozone layer (Wolfgang Steinbrecht, German Weather Service)

The Montreal Protocol has successfully stopped the decline of stratospheric ozone observed from the 1960s to the mid-1990s. Since around 2000, the ozone layer has been on the path to recovery. The clearest signs of recovery are seen in the upper stratosphere, where declining ODSs and stratospheric cooling result in observed ozone increases of about 2% per decade – consistent with expectations from model simulations. The size and depth of the Antarctic ozone hole also show clear signs of a beginning recovery. Full recovery of the ozone layer, however, is not expected before the second half of the twenty-first century. Ozone in the lower stratosphere and total column ozone do not yet show clear signs of recovery; they have been more or less stable for the past 20 years. In some regions, small declines are observed. Variations in the transport of ozone and other gases throughout the stratosphere have a considerable influence on ozone on all timescales. Climate change, warming of the troposphere and cooling of the stratosphere are affecting these transports – for example, the meridional Brewer–Dobson circulation (BDC) – and will affect them even more in the future. As ODSs are slowly disappearing from the atmosphere, climate change and future emissions of greenhouse gases (GHGs) (including carbon dioxide (CO₂), methane (CH₄) and nitrous oxide (N₂O)) will become more and more important for the recovery path of the ozone layer.

Benefits of the Montreal Protocol: effects on climate, ultraviolet radiation, and stratospheric ozone (Janet Bornman, Environmental Effects Assessment Panel Co-Chair)

The benefits of the Montreal Protocol were presented in the context of its positive, far-reaching effects due to the protection of stratospheric ozone, and the many interactive processes that occur from environmental change, climate, and human activities that are shaping the future of the planet.

The EEAP considered seven interlinking topics in its 2022 Quadrennial Assessment, and also produced a set of questions and answers across the topics. These topics align with many of the United Nations Sustainable Development Goals (SDGs).

While UV radiation is both beneficial and a risk factor to be considered, the Montreal Protocol has made it possible for life on Earth to benefit from the positive effects of a more moderate level of UV radiation. This was exemplified by model calculations of clear-sky UV indices of up to 40 by the end of the twenty-first century, had the Montreal Protocol not been successfully implemented.

Examples from an extreme environmental scenario of the consequences of changes in climate, UV radiation and stratospheric ozone estimated that, without the Montreal Protocol, the capacity of the Earth's vegetation to take up CO₂ would have been severely compromised. This would likely have led to increased atmospheric levels and associated additional global warming.

Challenges still remain for balancing the benefits and harms of exposure to UV radiation. Some of the damaging effects include skin cancers, several eye diseases and UV-photosensitive drugs in common use. At the same time, it was emphasized that the Montreal Protocol has prevented millions more cases of skin cancers and eye diseases.

A number of factors were listed that require our attention in the twenty-first century if we are to maintain a sustainable environment. Among these is pollution. An example is the role of UV radiation and climate change (for example, rising temperature) as main drivers in the breakdown of plastic waste in the environment. Some of the consequences of this photodegradation include plastics entering the food chain and posing a potential hazard to the environment and many life forms.

One of the important by-products of the Montreal Protocol has been the stimulation of innovation across many sectors. One of these has been research and development for improving plastic materials – for instance, incorporation of additives to increase the useful lifetime of certain plastic products. Plastic composites containing metals such as zinc oxide and titanium dioxide have also been used for significantly reducing UV transmission through fabrics as a protective measure against UV exposure of the skin.

Emerging issues of interest to the parties
(Lucy Carpenter, Scientific Assessment Panel Co-Chair, and Bella Maranion, Technology and Economic Assessment Panel Co-Chair)

The SAP Co-Chair began the presentation with a discussion of very short-lived substances (VSLs), which are still a minor contributor to stratospheric chlorine but are growing in abundance and have the potential to offset gains under the Montreal Protocol, noting that there are some new emerging VSLs. A number of minor chlorofluorocarbons (CFCs) used as feedstocks are increasing – this is at least partially linked to the massive increase in hydrofluorocarbon (HFC) production since 2000 in parties operating under paragraph 1 of article 5 of the Montreal Protocol. The atmospheric community is developing approaches to identify and quantify feedstock emissions, including measurement of minor compounds and isomers to discern production processes. Sufficient granularity (for example, by country) of reported annual production and consumption data from the Secretariat is crucial to inform feedstock estimates.

There is an ongoing need to identify and quantify emissions gaps by comparing “top-down” emissions with TEAP modelling of emission expectations. The carbon tetrachloride (CCl₄) emissions gap has still not been resolved. There is a need to enhance monitoring of ongoing emissions at global and regional scales.

The TEAP Co-Chair started the presentation by providing the list of the current 21 members of the TEAP, composed of members of government, military, academic and industry organizations with expertise in ozone layer protection policy, regulations and the various industry sectors where ODSs and high global warming potential (GWP) HFCs are used: refrigeration, air conditioning, fire suppression, solvents, aerosols, adhesives, coatings, and inks, motor vehicle air conditioning, and foams. The TEAP provides, at the request of parties to the Montreal Protocol, technical information related to the alternative technologies that have been investigated and employed to make it possible to phase out ODSs and begin the phase-down of HFCs to protect the ozone layer and climate. The TEAP also provides reports and documents produced by itself and its five Technical Options Committees (TOCs): Flexible and Rigid Foams Technical Options Committee (FTOC); Fire Suppression Technical Options Committee (FSTOC); Medical and Chemicals Technical Options Committee (MCTOC); Methyl Bromide Technical Options Committee (MBTOC); and Refrigeration, Air Conditioning and Heat Pumps Technical Options Committee (RTOC).

The presentation included the highlights of the TEAP 2022 Assessment, which the panel presented to parties to the Montreal Protocol in 2023. For its quadrennial assessment, parties had requested the TEAP to report on technical progress in the production and consumption sectors in the transition to alternatives; on the status of banks and stocks of

controlled substances; on challenges facing developed and developing parties, including on feedstock uses and by production; on the impact on sustainable development; and on technical advances on alternatives for use in countries under high ambient temperature conditions. The key message of the TEAP on the ODS phase-out is that actions under the Montreal Protocol support continued progress in consumer, commercial, industrial, agricultural, medical and military sectors, with ODSs no longer consumed in many applications worldwide. The key messages of the TEAP on HFCs included that the HFC phase-down is driving industry to lower GWP alternatives, especially in key sectors such as refrigeration and foams; that challenges in finding the best solutions for each application remain; that restricting the growth of products containing high GWP HFCs and energy-inefficient equipment reduces long-term need for HFCs as well as energy demand; and that supply shortages of low-GWP alternatives have been less severe since the COVID-19 pandemic, but insufficient supply could delay transitions away from HFCs.

The presentation also included an overview of the latest decisions of parties at the 35th Meeting of the Parties to the Montreal Protocol on Substances that Deplete the Ozone Layer, Nairobi, 23–27 October 2023 (MOP35), requesting updated information from the TEAP, including: decision XXXV/6 on VSLs; decision XXXV/7 on emissions of HFC-23; decision XXXV/8 on feedstock uses; and decision XXXV/9 on abating emissions of CCl₄. The TEAP is coordinating with the SAP to respond to these decisions in reports prepared for parties when they meet in 2024. In conclusion, the recommendations from ORM11 remain relevant as related to the work of the TEAP. In particular, the recommendations related to expanded coverage by global monitoring stations to derive regional emissions support the work of the TEAP to report on the status of sector transitions to alternatives for the ODS phase-out and HFC phase-down.

SESSION 3: INTERACTIONS BETWEEN OZONE LAYER DEPLETION, CLIMATE CHANGE AND RELATED EMERGING ISSUES

Links between stratospheric ozone and climate (Amanda Maycock, University of Leeds, United Kingdom)

Stratospheric ozone plays a key role in the climate system, influencing conditions in the stratosphere, the troposphere and at the Earth's surface. Stratospheric ozone was the dominant driver of global lower stratospheric cooling trends between the late 1970s and mid-1990s, and contributed to middle and upper stratospheric cooling trends over the same period.

Ozone depletion led to pronounced changes in southern hemisphere atmospheric circulation over the late twentieth century, including a poleward migration of the tropospheric jet stream and storm track. New evidence shows a weakening of the southern hemisphere circulation trend since the early 2000s compared with earlier decades, associated with the smaller influence of ozone forcing – this is consistent with evidence of the onset of Antarctic ozone hole recovery. Observed trends in some aspects of southern hemisphere climate, including Southern Ocean freshening and warming since the 1950s and fluctuations in Southern Ocean carbon uptake, have been mainly influenced by GHG increases and internal climate variability, and are not thought to be directly linked to stratospheric ozone depletion.

The latest Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (AR6) shows that, in the future, the effects of ozone recovery will compete with the effects of GHG increases on southern hemisphere atmospheric circulation, particularly in the austral summer. Models show a poleward shift of the southern hemisphere atmospheric circulation

in all seasons, but in summer the trends in the next 20 years are generally expected to be smaller than those observed during the late twentieth century owing to these opposing effects.

New research from Earth system models shows that, in the absence of the Montreal Protocol and its Amendments, unmitigated increases in ODS emissions would have reduced land carbon sinks through devastating surface UV impacts on the biosphere. The simulations show the weakened carbon sinks would have caused elevated atmospheric CO₂ levels, potentially leading to further global surface warming of between 0.5 and 1.0 K. Thus, there is evidence of further avoided global climate change through the Montreal Protocol in addition to the avoided direct greenhouse effect of ODSs themselves.

In addition to the effects on long-term climate changes, there is evidence for an influence of ozone depletion on surface climate at shorter timescales in both hemispheres, via the radiative feedback by ozone on the strength of the stratospheric winter polar vortices. This has the potential to contribute to improved sub-seasonal to seasonal climate prediction.

Trends of hydrochlorofluorocarbons and hydrofluorocarbons controlled under the Montreal Protocol and other substances that affect the ozone layer and climate (Guus Velders, Dutch National Institute for Public Health and the Environment)

Emissions of HFCs have increased significantly in the past two decades, primarily as a result of the phase-out of ODSs under the Montreal Protocol and the use of HFCs as their replacements. In the absence of regulations, large increases in HFC emissions are projected in the twenty-first century. As HFCs are potent GHGs they are projected to have contributed significantly to global average surface warming by 2100.⁸ In the Kigali Amendment to the Montreal Protocol, it was agreed to phase down the consumption and production of HFCs globally. The Kigali Amendment is currently in effect, reducing HFC consumption in developed countries by 40% and freezing consumption in one group of developing countries.

An analysis of trends in reported HFC production and consumption data from the United Nations Framework Convention on Climate Change (UNFCCC) and the UNEP/Ozone Secretariat, and trends in observed atmospheric mixing ratios from the AGAGE network, showed that, although the mixing ratios of most HFCs are still increasing, the global emissions derived from these mixings are below projected emissions (without any regulations) up to 2022. In particular, emissions of 1,1,1-trifluoroethane (HFC-143a), used mainly for industrial and commercial refrigeration, are less than half the projected emissions, indicating significantly lower use of this chemical in the past five years. Emissions of difluoromethane (HFC-32) and pentafluoroethane (HFC-125), used mainly in stationary air conditioning, are also below projected emissions. The emissions of the other main HFC, 1,1,1,2-tetrafluoroethane (HFC-134a), are still close to projected emissions, although the data reported to UNFCCC by developed countries show that the use of this chemical for mobile air conditioning is decreasing significantly.

The presentation also discussed the projected limited effect of the formation of tropospheric ozone from the increased use of hydrofluoroolefins (HFOs) as alternatives for HFCs, and the limited effect of trifluoroacetic acid (TFA) from the degradation products of HFCs and HFOs.

⁸ Velders, G.J.M.; Fahey, D.W.; Daniel, J.S. et al. The Large Contribution of Projected HFC Emissions to Future Climate Forcing. *Proceedings of the National Academy of Sciences of the United States of America* **2009**, *106*, 10949–10954. <https://doi.org/10.1073/pnas.0902817106>.

Stratospheric aerosol injection and the ozone layer (David Fahey, National Oceanic and Atmospheric Administration)

Climate intervention refers to cooling the Earth by human means to offset the warming and other impacts due to GHG accumulation. Should it ever become important for society to cool Earth rapidly, climate intervention by solar radiation modification (SRM) methods is the only way that has been suggested by which humans could potentially cool Earth within years after deployment. Projections of continuing emissions of GHGs and growing impacts of climate change are increasing global interest in climate intervention. The leading SRM method is SAI, which would inject aerosol or aerosol precursors into the stratosphere. Observations following explosive volcanic eruptions, along with model simulations, confirm that increasing stratospheric sulfate aerosols can substantially cool the planet. SAI is expected to change stratospheric ozone chemistry and stratospheric heating, potentially altering the global ozone distribution. In response to the potential importance of SAI to the future ozone layer, the parties to the Montreal Protocol have made an initial assessment of the potential effects on the stratospheric ozone layer in its 2022 assessment cycle. The presentation introduced the concept of climate intervention, described SAI scenarios and response mechanisms, discussed the expected changes in stratospheric ozone from SAI based on global model results, and discussed the value of an international SRM assessment.

SESSION 4: INTERNATIONAL MONITORING PROGRAMMES FOR OZONE AND ULTRAVIOLET

The International Ozone Commission (Irina Petropavlovskikh, International Ozone Commission)

The International Ozone Commission (IO₃C) was established in 1948 as one of the special commissions of the International Union of Geodesy and Geophysics (IUGG). It represents the world's community of ozone research scientists. The purpose of the IO₃C is to help organize ozone studies around the world, including ground-based and satellite measurement programmes and analyses of the atmospheric chemistry and dynamical processes affecting ozone. The early history of the IO₃C involved developing and using the first ozone observing systems to understand atmospheric composition. The discovery and reporting of the first signs of the ozone hole in observations were noted in presentations at the Quadrennial Ozone Symposium held in Halkidiki, Greece, 3–7 September 1984, albeit there was no wide recognition of a major trend. Since then, the science of polar and global ozone depletion has been a continued focus of the IO₃C and its Quadrennial Ozone Symposium.

The IO₃C supports the Vienna Convention and Montreal Protocol by organizing and hosting scientific research that includes analyses of ozone observations and contributions of ODS emissions to the chemical destruction of the stratospheric ozone layer. Over the Commission's history, IO₃C members have organized and supported new instrument developments (that is, satellite, ground-based and suborbital platforms), advanced global chemistry models for interpretation of atmospheric composition changes and contributed to studies of ozone impacts on the UV changes resulting in biological and health-related impacts. Among the leadership and members of the IO₃C, there are Nobel Prize laureates who have steered the focus of the international community towards an understanding of atmospheric processes that contribute to ozone depletion and recovery.

16 September is the International Day for the Preservation of the Ozone Layer, celebrating the anniversary of the signing of the Montreal Protocol on Substances that Deplete the Ozone Layer in 1987. On this day, IO₃C publishes its annual press releases, including [*The International Ozone Commission, on the 36th Anniversary of the Montreal Protocol, Reports Successes and New Milestones for Progressing Toward Ozone Layer Recovery*](#), published in

2023. Through its communications, the IO₃C assures dissemination of accurate and scientifically correct information about ozone recovery. The IO₃C also hosts a Facebook page that shares publications of interest to the community. It has many followers and benefits from active community discussions on its pages.

During the International Quadrennial Ozone Symposium held in Tromsø, Norway, 29 June–5 July 2008, the IO₃C Assembly issued a resolution urging an update of ozone absorption cross sections to homogenize ozone records derived from different instrumental platforms. This task has been recently accomplished with a detailed publication of data analyses.⁹ Some Dobson and Brewer ozone data have been reprocessed and archived at the stations for testing and verification purposes. The progress continues with centralized reprocessing of historical ozone records archived at the WMO GAW Ozone and Ultraviolet Radiation Data Center (WOUDC), under the guidance of the WMO Scientific Advisory Group on Ozone and Solar UV Radiation (SAG-O3&UV). These efforts are essential to stratospheric ozone recovery detection and to assure coherent results of trend estimates from different observing platforms. The IO₃C regularly contributes to APARC activities aimed at development of methodology in detection of stratospheric ozone trends (that is, Long-term Ozone Trends and Uncertainties in the Stratosphere (LOTUS) and Observed Composition Trends and Variability in the Upper Troposphere and Lower Stratosphere (OCTAV-UTLS)). Its members are co-authors of numerous WMO/UNEP ozone assessments.

The IO₃C also sponsored the WMO-led *Ozonesonde Measurement Principles and Best Operational Practices – ASOPOS 2.0 (Assessment of Standard Operating Procedures for Ozonesondes)* (GAW Report No. 268) activity, which was essential for homogenization of ozonesonde records. The IO₃C provides continuous support to the tropospheric ozone assessment initiative (the Tropospheric Ozone Assessment Report, Phase II (TOAR-II)) under the International Global Atmospheric Chemistry (IGAC) project.

The next Quadrennial Ozone Symposium will be held from 15 to 19 July 2024 in Boulder, Colorado, United States. The local organizing committee, together with the IO₃C leadership, has organized six science sessions that cover all aspects of ozone science and its environmental impacts. Special activities are planned for early career scientists (ECSs) and students from a wide range of countries. With the support of the IUGG/International Association of Meteorology and Atmospheric Sciences (IAMAS), WMO/GAW, the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT), the Ozone Secretariat and several commercial organizations, the Symposium will be held in a hybrid format and will provide a venue for the active discussions of science topics that will help form the next ozone assessment.

IO₃C recommends the following actions:

- Continued support for ground-based stations, aircraft, mobile and satellite observations to assure long-term records for tracking ozone recovery and the phase-out of ODSs.
- Allocation of resources to calibrate and analyse ozone observations to provide clear and accurate information on the state of the ozone layer, ozone pollution and global change.

⁹ Voglmeier, K.; Velazco, V.A.; Egli, L. et al. The Transition to New Ozone Absorption Cross Sections for Dobson and Brewer Total Ozone Measurements. *Atmospheric Measurement Techniques* **2024**, *17*, 2277–2294. <https://doi.org/10.5194/amt-17-2277-2024>.

- Develop and test global and regional chemistry–climate models suitable to account for interpretation of ozone and UV changes under climate change, large volcanic events and potential geoengineering scenarios.
- Allocate resources for development of new technologies that provide cheap, fast and robust records with adequate accuracy and precision to track atmospheric composition change.
- Assure stability of climate records during/after transition from ageing to new instruments.
- Increase engagement with scientists from developing countries and ECSs dedicated to ozone research.
- Pursue the accurate and consistent reporting of ozone science.
- Develop strategy for continuation of satellite observations that support ozone science and Montreal Protocol compliance.

**The WMO Global Atmosphere Watch Ozone Observing System
(*Matt Tully, Chair of the WMO Scientific Advisory Group on Ozone and Solar UV Radiation*)**

The WMO GAW Programme has, since 1987, incorporated the Global Ozone Observing System (GO3OS), which itself dates back to the mid-1950s and which, through the Vienna Convention, parties undertake to make “fully operational”.

A number of other overlapping ozone measuring networks exist in addition to GAW, such as the Network for the Detection of Atmospheric Composition Change (NDACC), Southern Hemisphere Additional Ozonesondes (SHADOZ) and the European Brewer Network (EUBREWNET). While, in general, relations between the networks are very cooperative and some steps towards greater interoperability have been taken, the existence of multiple networks and data centres still presents obstacles for both data providers and data users.

Since ORM11, submission of Dobson data to WOUDC has been quite well maintained, with only a very small number of stations no longer providing data during this period.

Total ozone observations from Brewer, Filter and SAOZ instruments also continue to be submitted to WOUDC with no significant reduction in the number of stations since ORM11. There remain about 60 active ozonesonde stations around the world, with data submitted to a number of different data centres, including WOUDC, NDACC, SHADOZ and NOAA.

Measurement quality from the Dobson and Brewer networks is underpinned by regular calibrations, which have usually required support from the General Trust Fund to enable developing countries to participate. A further round of regional Dobson intercomparison campaigns is now due for Africa, South America and Asia.

Recent highlights from GAW include progress on implementing new ozone cross sections in the global network, with a path forward for introducing corrections due to stratospheric temperature now agreed by the WMO SAG on Ozone and Solar UV Radiation. GAW Report No. 268 has now been published, representing a sustained body of work from many expert contributors and reviewers from the ozonesonde community. A new annual *WMO Ozone and*

*UV Bulletin*¹⁰ was published for the first time in 2023, giving an overview of many different activities currently being undertaken by WMO, UNEP and the international ozone community, spanning observations, assessments and services.

The Network for the Detection of Atmospheric Composition Change (Martine De Mazière, Royal Belgian Institute for Space Aeronomy)

NDACC is still growing and expanding its observational capabilities, covering vertical profiles and total column observations of ozone and related key species and variables, including ODSs and some substitutes, short- and long-lived climate pollutants, volcano and fire emission products, spectral UV, temperature and winds. A specific strategy for water vapour observations has been worked out.

Monitoring stratospheric ozone in support of the Montreal Protocol is one of the original objectives of NDACC. In order to highlight the vast range of NDACC activities, the presentation does not cover ozone-specific activities, for which it refers to contributions by other authors affiliated to NDACC.

Progress has been made in the move towards more compact, more mobile and cheaper instruments, automation of data acquisition and centralized data processing, for enhancing the sustainability of the network, its internal consistency and traceability to agreed standards.

Continued monitoring, data curation and reprocessing for establishing long-term, high-quality and homogenized data records, and detecting and quantifying changes, remain high on the agenda. Examples of the contributions of NDACC to the detection and understanding of sudden events and unexpected phenomena (for example, the COVID-19 pandemic, the Hunga Tonga–Hunga Ha'apai eruption and Australian wildfires) are also shown. NDACC has provided information about trends in atmospheric transport (BDC) through long-term records of atmospheric tracers (for example, inorganic fluorine, hydrogen chloride (HCl) and nitric acid (HNO₃)). Some results suggest deficiencies in our ability to forecast the evolution of stratospheric ozone in a changing climate, for example, because transport is not correctly represented in climate–chemistry models or because we lack insight into heterogeneous chemistry processes on smoke aerosols.

Recovery of historical CFC-11 data has been attempted successfully but highlights once more the challenge of instrument change management for long-term trend detection.

NDACC is a key contributor to satellite data validation activities and international research programmes like Stratospheric Processes and their Role in Climate (SPARC), international assessments like TOAR-II, the European Space Agency (ESA) Climate Change Initiative (CCI), European Copernicus services and the Aerosol, Clouds and Trace Gases Research Infrastructure (ACTRIS). Climate-relevant data records are submitted to the Copernicus Climate Data Store. In addition to the above research-oriented applications, NDACC data serve operational applications, like operational monitoring of satellite data quality (mission performance centres), and downstream applications, like Copernicus data quality assessments; hereto a rapid delivery data stream is provided.

The NDACC data host facility has been moved from NOAA to the NASA Langley Research Center (LaRC) to guarantee a sustainable long-term archival of the data. The data archiving and dissemination is targeting compliance with the findable, accessible, interoperable and reusable (FAIR) data principles, and user friendliness (for example, different formats and

¹⁰ <https://library.wmo.int/records/item/66208-no-1-june-2023>

visualization) – interoperability of the data ensures that data can be exchanged with other data portals.

NDACC is considered a provider of reference data; it is targeting compliance with the requirements for delivering Fiducial Reference Measurements (FRMs).

NDACC is in the process of updating its strategy, including ways to face the challenges to maintain the network and keep it relevant in view of actual research questions and societal needs. The updated strategy will be presented in the introductory paper to the special issue that will be published on the occasion of the thirty-fifth anniversary of NDACC in 2025.

The Brewer networks and their future

(Alberto Redondas, State Meteorological Agency, Spain, and John Rimmer)

The presentation discusses the role of EUBREWNET in maintaining high-quality observations of total ozone, spectral UV radiation, and aerosol optical depth in the UV range. It highlights a decline in submitted Brewer observations and suggests shifting the focus from development and implementation to network management, including quality assurance/quality control tools and series evaluation. Brewer calibration traceability is identified as an ongoing concern. Collaboration between EUBREWNET and the reference Central Calibration Laboratory (CCL) is noted as positive, and efforts are under way to define the traceability of the network, including observations and metadata storage to enable traceability, reprocessing and error budget determination. It also addresses the issues arising from the cessation of production of Brewer spectrophotometers.

International ozonesonde activities

(Roeland Van Malderen, Royal Meteorological Institute of Belgium)

The ozonesonde network is characterized by large variety owing to different operating procedures, different data processing strategies and data archiving in different formats in different international databases. We report on the past (past 5 years), current and future harmonization activities that are undertaken in those three “pillars”.

The main driver behind these harmonization efforts is GAW Report No. 268, published in 2021 by ASOPOS. This panel reviewed the current understanding of the instrument and made recommendations for standard operating procedures (SOPs) (preparation, hardware, processing, (meta)data archiving and so forth). This report has also been “translated” into practical webinars, made available online, to ensure implementation of those recommendations in the global ozonesonde network.

The report also sets the standard for data processing and includes guidelines for homogenizing historical ozonesonde data records – the so-called Ozonesonde Data Quality Assessment (O3S-DQA) homogenization. This activity has been quite successful (about 45 out of 60 “active” stations have been homogenized) and has recently been sped up under the umbrella of the TOAR-II Harmonization and Evaluation of Ground-based Instruments for Free-Tropospheric Ozone Measurements (HEGIFTOM) focus working group. Comparisons of the homogenized ozonesonde time series with measurements from other ground-based instruments or with satellite ozone retrievals (for example, microwave limb sounders (MLSs)) have confirmed the improvement and the overall long-term stability of the ozonesonde network. Continuous data quality monitoring is envisaged.

However, new processing algorithms have been developed recently that correct for the two time constants present in the ozonesonde signal and that make use of real, measured, pump flow efficiency measurements, instead of empirical correction tables. Important to mention also is that this new technique makes the ozonesonde data traceable to the

network reference instrument, that is, to the ozone photometer in the simulation chamber of the World Calibration Centre for Ozonesondes (WCCOS) hosted by Forzungszentrum Jülich (FZJ). Implementation of this new processing strategy in the global network is still too premature and requires some additional testing first.

Following the guidelines on metadata content of GAW Report No. 268, the different leading international archives for ozonesonde data (WOUDC, NDACC and SHADOZ) have agreed on a common (meta)data format and protocol, Generic Earth Observation Metadata Standard (GEOMS) Hierarchical Data Format (HDF) (GEOMS HDF). Efforts are being taken at the moment to practically implement this decision, both for historical and future data records.

Overall, the ozonesonde network is in good shape. WCCOS is now guaranteed by FZJ and the Royal Meteorological Institute of Belgium (KMI–RMI)¹¹ and will ensure future quality assurance, although long-term, structural funding commitment from international bodies is lacking. Maintaining the current ozonesonde station network remains a challenge, with stations lowering down their launch frequency (for example, Irene, South Africa, and Lauder, New Zealand), or completely shutting down (Indonesia and two Japanese sites). The needed extension of the network, especially over the tropics and the southern hemisphere, is even more difficult. Another threat is the (near-future) retirement of many ozonesonde principal investigators, who are rarely replaced with scientists.

Atmospheric Processes And their Role in Climate (*Michaela Hegglin, Institute of Energy and Climate Research, Germany*)

The presentation provides an overview and update on the World Climate Research Programme (WCRP)'s core project, APARC (previously SPARC). Since 1992, SPARC/APARC has been coordinating research activities that are aimed at understanding the chemical and dynamical processes leading to stratospheric ozone depletion and the formation of the Antarctic ozone hole. Reflecting the progress made in our understanding of the stratosphere and its complex interactions with other components of the climate (or Earth) system, APARC has since expanded to include more and more climate-related research topics. APARC now leads 18 activities covering topics related to atmospheric composition, variability and trends across timescales, and atmospheric dynamics, all aimed at our understanding of the evolving climate and its impacts.

Of particular interest to the ORM are the Hunga Tonga–Hunga Ha'apai Impacts Activity, which will generate a report on the January 2022 Hunga Tonga eruption owing to it being the hitherto largest observed disturbance in stratospheric water vapour concentrations with potential implications for the stratospheric ozone layer; the LOTUS activity, which will produce an update on the state of the stratospheric ozone layer as derived from observations and the attribution of observed changes to its drivers (decreasing ODSs and climate change); and the activity of VSLs, which are key components of ODSs. The results will feed into the next WMO/UNEP Scientific Assessment of Stratospheric Ozone Depletion in 2026. Since January 2024, the APARC International Project Office (IPO) has a new host, FZJ in Germany, which is part of the Helmholtz Association and whose scientists have been involved in SPARC/APARC since its origin.

The new goals of the IPO are to support the above APARC activities in day-to-day tasks, writing newsletters, and support the generation of APARC scientific assessments and reports. The IPO will also aim to greatly expand the capacity-building and outreach activities of APARC, with the first training school having taken place in Kigali in October 2023.

¹¹ KMI–RMI: Koninklijk Meteorologisch Instituut van België/Royal Météorologique de Belgique

The World Ozone and Ultraviolet Radiation Data Centre – data reporting and archiving

(Sum Chi Lee, Environment and Climate Change Canada)

Managed by the meteorological service of Canada, Environment and Climate Change Canada (ECCC), WOUDC continues to provide support for submission, archiving and dissemination of ozone and UV data and products. Reporting to the WMO SAG on Ozone and Solar UV Radiation and participating in the WMO Expert Team on Atmospheric Composition Data Management, the data centre provides access to over 900 000 data files and reports from 547 stations.

Since ORM11, data from 14 new stations and 6 new contributors have been added. 2023 data processing metrics show over 50 000 data files submitted with a 90% passing rate (of which under 4% of files required manual metadata updates/fixes), and an overall fail rate of under 10%. Data metrics show over 150 million downloads for published data for 2023.

In December 2023, departmental operational system upgrades affected processing as well as contributor notifications. Capability was fully restored in March 2024.

The data centre continues towards version 2.0 of the website with a modernized user interface experience as well as application programming interfaces (APIs). WMO Information System 2.0 (WIS 2.0) integration will also be available in support of GAW data centre integration as part of the WMO data exchange infrastructure. Version 2.0 is currently available in a beta capacity at <https://beta.woudc.org>.

New website capabilities include the new Jülich Ozone Sonde Intercomparison Experiment (JOSIE)/Balloon Experiment on Standards for Ozone Sondes (BESOS) products as well as a dedicated ozone maps search interface (both available on the beta website).

Future work includes support for the GEOMS format as well as Total Ozone Dobson new cross sections (also targeted for WOUDC 2.0).

SESSION 5: INTERNATIONAL MONITORING PROGRAMMES ON SUBSTANCES CONTROLLED BY THE MONTREAL PROTOCOL

Ground-based networks for measuring ozone- and climate-related trace gases and current state of the atmosphere

(Stephen Montzka, National Oceanic and Atmospheric Administration)

The presentation provided an overview of the capabilities of ground-based networks for measuring substances controlled by the Montreal Protocol and how those capabilities have changed in recent years. A main point was that the sampling/measurement network remains sparse spatially. This sparseness, however, does not prevent accurate measurements of global mean atmospheric abundance and its change over time for substances with long lifetimes (> six months). When combined with an understanding of loss rates (lifetimes), results from these remote sites provide accurate estimates of global total emissions. The low spatial density of the network in 2020 limited its ability to provide estimates of emission by region from all regions of the world that are likely to be significant contributors. Also, a sparse network is not well-suited for providing atmosphere-based estimates of global mean concentrations, emissions and impacts of short-lived gases (that is, HFOs).

Since 2020, substantial additional measurement capacity has been added at new locations. High-frequency measurements were added at various sites between 2021 and 2023,

including at six locations on the southern and eastern coasts of China, and in central Germany. Additional high-frequency locations are planned for southern Italy, the Netherlands (Kingdom of the), Norway, Rwanda and the United Kingdom. Flask sampling was begun in Bangladesh, Barbados, Hungary, Malaysia, the Maldives, the Netherlands (Kingdom of the), Norway, Taiwan Province of China, and Viet Nam. Surveys to identify good locations for additional flask sampling in the United States are being explored. Despite these important and substantial additions to the global measurement network, it remains unable to accurately quantify emissions from many large regions such as southern Asia, Central Asia, Africa, the Middle East, and Central and South America.

The presentation also highlighted recent global-scale atmospheric changes. Updated measurements of CFC-11 show that its global emission continues to be substantially lower than it was during 2014–2018, suggesting that the elevated emissions noted during 2014–2018 have not re-emerged. In contrast, global emissions and concentrations of a number of other long-lived but low-abundance CFCs are increasing; however, the cause of these increases is not well understood. Declines in total chlorine continue and were notably faster after 2018, owing in large part to the accelerated declines observed for CFCs following that year. Chlorine from HCFCs was no longer increasing, and bromine from controlled gases continues to decrease at a rate that has changed little, on average, since 2000.

Gaps in the global coverage of atmospheric monitoring of controlled substances and options on ways to enhance such monitoring

(Paul Newman, National Aeronautics and Space Administration; A.R. Ravishankara, Colorado State University; and Ray Weiss, Scripps Institution of Oceanography)

An observation of the map of current monitoring stations across the globe shows the gaps in needed observations to ensure that we have a robust monitoring network to quantify emissions of Montreal Protocol-related gases. The European Union funded a pilot project for measurements of Montreal Protocol-related gases on Bhola Island, Bangladesh. The parties to the Montreal Protocol requested an assessment of the costs of establishing such stations. The Ozone Secretariat tasked the Steering Committee for the European Union pilot project to hold an online workshop to estimate the costs.

The presentation describes the science behind quantifying emissions from atmospheric observations, the so-called “top-down method”. It is emphasized that calibration to a reference standard is essential for quantifying emissions and deducing trends of the emissions. Two currently established approaches – (a) high-frequency measurements and (b) flask sampling – were considered for estimating the costs.

About 45 people, consisting of 35 experts and 10 observers with interest, took part in the video workshop. Information provided by these experts was collected, and the costs were estimated. The report summarized these findings regarding the costs:

- There are highly variable facility costs, personnel costs, shipping costs and so forth (very location dependent);
- Start-up costs ranged from ~USD 195 000 to USD 1 300 000;
- Many costs may be unnecessary if there is existing infrastructure;
- Co-opting facilities would significantly reduce costs;
- The operational costs are dependent on location.

The reported costs did not include the following:

1. Personnel costs (variable from place to place and in the future);
2. Maintenance and operating costs;
3. Observing System Simulation Experiments (OSSE) studies;
4. Data analyses.

The key messages from the workshop and the ongoing European Union-funded pilot programme are:

- Utilizing in-kind contributions (the Bhola Island pilot project, Bangladesh, is an example) of expertise and personnel significantly reduces costs;
- Cost-sharing and in-kind contributions from using existing facilities and, especially, towers can significantly reduce costs;
- Collaboration with other observational programmes (WMO Global Greenhouse Gas Watch (GGGW), WMO, the Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO), the Integrated Carbon Observation System (ICOS), air quality monitoring and so forth) can help identify potential sites and infrastructures;
- Staff training and capacity-building, including exchanges of graduate students and postdoctoral scholars, is essential for obtaining data and capacity-building;
- Calibration scale propagation and national metrology institutions to establish reference scales are more important than absolute accuracy to take full advantage of measurement precision;
- Data sharing (not just sharing processed data, but data at the instrumental level) is essential for diagnosing instrument performance and maintenance;
- Peer review of the methodology, obtained data and data analysis ensure the needed high quality of data.

SESSION 6: SATELLITE RESEARCH AND MONITORING

Ozone layer and climate observations from space: status of activities and challenges ahead

***North American satellite programmes: National Aeronautics and Space Administration, National Oceanic and Atmospheric Administration, Canadian Space Agency and other agencies
(Kenneth Jucks, National Aeronautics and Space Administration, and Marcus Dejmek, Canadian Space Agency)***

The North American space programmes operated by the Canadian Space Agency (CSA), NOAA and NASA have been quite active for a very long time with their combined set of observations related to ozone, ODSs and the stratosphere in general. NOAA continues its systematic set of UV backscatter observations begun over 40 years ago with the nadir Ozone Mapping and Profiler Suite (OMPS) observations on board the operational Joint Polar Satellite System (JPSS) satellites. NASA operates the OMPS-limb set of observations for

altitude-resolved limb observations of stratospheric ozone and aerosols. CSA operates two well-trusted limb observing assets – Scientific Satellite 1 (SCISAT-1) and Optical Spectrograph and Infrared Imaging System (OSIRIS) – that have produced altitude profiles of multiple ozone-related gases for over 20 years now. OMPS-limb is complemented by the well-trusted Stratospheric Aerosol and Gas Experiment III (SAGE-III) observations on the International Space Station (ISS) until the end of the decade.

The most scientifically used set of observations from NASA come from the Aura satellite, which currently has the nadir observing Ozone Monitoring Instrument (OMI) for both column ozone and numerous parameters used for air quality studies, and the MLS instrument, which provides dense observations in thermal emission of ozone and numerous molecules used to understand the changes in ozone. This satellite will continue to operate until ~2026, when it will run out of fuel and power on the solar panels. The most recent scientific advancements coming from CSA assets include determining the chemical composition of aerosols in the stratosphere; merging datasets with those from NASA ozone monitoring assets; use of CFC, HFCs and HFC measurements; and contributing to our understanding of the impact of wildfires on ozone depletion and water vapour in the atmosphere. SCISAT-1 and the Atmospheric Chemistry Experiment Fourier Transform Spectrometer (ACE-FTS) instrument now measure over 70 molecules and isotopologues to advance ozone chemistry and atmospheric composition studies. There is no known technical reason for SCISAT-1 to stop monitoring anytime soon, while the OSIRIS mission could be extended for many more years. CSA is working to develop a new limb observing set of instruments to operate on the NASA Atmosphere Observing System (AOS) mission, and NASA may select a new limb observing mission. Neither would be launched until the early 2030s.

***European Space Agency activities
(Michael Eisinger, European Space Agency)***

ESA activities related to ozone cover past, present and future satellite instruments – Global Ozone Monitoring Experiment (GOME); Scanning Imaging Absorption Spectrometer for Atmospheric Cartography (SCIAMACHY); GOME-2; Sentinel-5p, -4 and -5; and the Atmospheric Limb Tracker for the Investigation of the Upcoming Stratosphere (ALTIUS) – as well as science studies within CCI, specifically the Ozone CCI project. The Ozone CCI project produces time series of total ozone and ozone profiles from a large portfolio of satellite instruments flown by ESA and other space agencies, some of them used in synergy, together with their validation and error characterization. The latest results of the Ozone CCI project were presented. ESA activities ensure long-term continuity of ozone monitoring, both on the hardware side, via the Sentinel missions implemented in cooperation with EUMETSAT and the European Commission, and on the climate science side, via the ESA CLIMATE-SPACE programme, which feeds into operational Copernicus services.

***The development and application of satellite remote sensing for total ozone column in China
(Pengfei Ma, Center for Satellite Application, Ministry of Environment and Ecology of China)***

The development and application of satellite remote sensing for total ozone column in China have shown remarkable progress, driven by advancements in active and passive detection technologies, as well as the deployment of dedicated satellite missions such as the FengYun-3 (FY-3), Gaofen-5 (GF-5) and Atmospheric Environment Monitoring Satellite (DQ) series.

These efforts have significantly enhanced the understanding of ozone dynamics, particularly in the context of secondary air pollution and the persistent challenges posed by polar ozone holes.

***Committee on Earth Observation Satellites Atmospheric Composition Virtual Constellation ozone harmonization projects
(Diego Loyola, German Aerospace Centre)***

The presentation outlined the work of the Committee on Earth Observation Satellites (CEOS) Atmospheric Composition Virtual Constellation (AC-VC) activities since ORM11 on ozone harmonization projects.

Total ozone satellite data records are continuously compared and used in scientific publications, including the Bulletin of the American Meteorological Society (BAMS)'s *State of the Climate*. Furthermore, the total ozone trends at regional scale from the European GOME-type Total Ozone Essential Climate Variable (GTO-ECV) data record were used in the 2024 WMO/UNEP ozone assessment.

CEOS AC-VC activities related to tropospheric ozone dataset validation and harmonization were initiated in 2019. A major topic of the annual AC-VC meetings from 2021 to 2023 was the geophysical validation and harmonization of tropospheric satellite products – significant progress was achieved, including the development of new harmonizing methods.

The current work focuses on applying the harmonization techniques to a number of satellite products and the subsequent calculation of tropospheric ozone trends.

CEOS AC-VC and TOAR-II are cooperating with reciprocated participation in meetings organized by the two entities.

***Summary of the key issues in space-based measurements: identification of future needs and opportunities
(Jean-Christopher Lambert, Royal Belgian Institute for Space Aeronomy)***

The presentation starts with a reminder of the ORM11 recommendations relevant to systematic observations from space. The satellite research and monitoring programme implemented by the space agencies is reviewed with respect to requirements for the measurement of columns and profiles of ozone, related trace gases, water vapour, sources and reservoirs, aerosols and dynamical tracers.

Low-earth orbit (LEO) nadir satellite programmes implemented by China (FY-3, GF-5 and DQ), Europe (Sentinel-5P and -5, and Infrared Atmospheric Sounding Interferometer-Next Generation (IASI-NG)) and the United States (Suomi National Polar-orbiting Partnership (SNPP) and JPSS) ensure the needed continuity of column monitoring and low-resolution profiling of global ozone and a few other trace gases at least for the next decade. The constellation of geostationary air quality and ozone satellites being implemented by the European, Korean and United States space agencies (Sentinel-4, Geostationary Environment Monitoring Spectrometer (GEMS) and Tropospheric Emissions: Monitoring of Pollution (TEMPO)) offer new research opportunities. Recent and upcoming aerosol/cloud profiling missions are expected to give new insights into aerosol concentration, size and composition in the troposphere. The increasing interest of the limb satellite community in water vapour, aerosols, the upper troposphere and lower stratosphere (UTLS) region and the mesosphere was highlighted. The current limb/occultation satellite programmes implemented by China (Ozone Monitoring Suite limb scanning unit (OMS-limb) and Environmental Trace Gases Monitoring Instrument with Nadir and Limb modes (EMI-NL)), Europe (ALTIUS) and the United States (Ozone Mapping Profiler Suite Limb Profiler (OMPS-LP) and SAGE-III) ensure continuity of the high-resolution vertical profiling of stratospheric ozone, water vapour and aerosols until 2030 and beyond. Although new mission architectures are under study, the anticipated termination of the microwave and infrared limb/occultation sounders Aura MLS,

SCISAT-1/Atmospheric Chemistry Experiment (ACE) and Odin remains a concern as no immediate replacements have been planned. As a consequence, a significant observational gap is expected in the high-resolution profiling of many ozone-related species and dynamical tracers.

The presentation continues with recent advances but also concerns regarding the geophysical validation of the satellite observations, an essential activity already affected by the steady decrease in the number of ground-based stations and observations. Several activities aiming to improve the trustworthiness of ground-based measurements and to tailor them to the specific needs of satellite validation are reported. Special attention is given to recent initiatives addressing the design, evolution and continuity of the monitoring networks used as a reference for satellite validation. Specific requirements of the operational validation services are highlighted, including the need for sustainable and timely data availability. Needs and opportunities for feedback to the contributing ground-based data providers are discussed.

The presentation concluded with suggestions of recommendations relevant to systematic observations for the ORM12 report.

SESSION 7: NATIONAL AND REGIONAL REPORTS ON OZONE RESEARCH AND MONITORING

Region 1: Africa (Bonfils Safari, University of Rwanda)

This synthesis report indicates the status of the implementation of the ORM11 recommendations. Some country reports have been submitted to the Ozone Secretariat and posted on the web portal of ORM12.

This report reiterates the observation made in previous reports that Africa remains a sparse region for ozone monitoring and research.

Overall, all African countries comply with the Montreal Protocol on Substances that Deplete the Ozone Layer. However, few countries show much interest in participating in ozone-related monitoring and research activities. This is mainly due to limited resources and political instability.

A great need is expressed in the few countries where Dobson spectrophotometers and UV sensors exist, to maintain and calibrate the instruments. In particular, capacity-building to enhance professional competence in monitoring, data processing and research is needed as well. This requires strong and continued support from the General Trust Fund and WMO/GAW.

It is encouraging to note that some countries have recently made efforts to equip their observational stations with instruments measuring total column ozone: Burkina Faso equipped with a Dobson and the Comoros equipped with a SAOZ. These two instruments were acquired thanks to the General Trust Fund and WMO.

Regarding the monitoring of ODSs, only one station exists in Africa – the Rwanda Climate Observatory. Currently, the Medusa of the Mount Mugogo AGAGE station, located in Rwanda, has been put into operation through a collaborative effort with the Massachusetts Institute of Technology (MIT) and Scripps Institution of Oceanography (SIO).

Country reports show that little effort is being made in terms of cooperation and twinning opportunities. A few countries, like Algeria and Egypt, and recently Burkina Faso, the Comoros and Rwanda, show new developments in cooperation and twinning, and this has given results.

List of countries that provided their reports:

- Algeria
- Burkina Faso
- Burundi
- Comoros
- Egypt
- Mauritania
- Mauritius
- Nigeria
- Rwanda
- Tanzania
- Senegal
- Uganda.

Region 2: Asia
(Toshinori Aoyagi, Japan Meteorological Agency)

Eight countries submitted their national reports for ORM12: Bangladesh, China, India, Iraq, Japan, Nepal, Russian Federation and Sri Lanka. Systematic observations to evaluate the changing state of the ozone layer, targeting not only ozone itself but also UV, ODSs and other ozone-related matters, should be continued in cooperation with international monitoring networks, such as WMO/GAW and NDACC. Many Members in Region 2 need financial/technical support to increase capabilities for researching/monitoring ozone, UV and so on. Support for developing countries for the refurbishment or calibration of existing instruments is an urgent need in Region 2.

Observational activities

In terms of ozone observations, classical Dobson instruments are decreasing in number; however, some Pandora systems seem to have been newly installed. There are several instruments that need calibration. As for UV radiation observation, Brewer spectrophotometers are used in China, Japan and the Russian Federation. A number of broad-band UV radiometers are operated in India and the Russian Federation. Measurements of ODSs and related substances controlled by the Montreal Protocol are limited. In China, however, the number of observing and sampling stations of ODSs seems to have been increasing recently.

Analysis, research and noting progress after the 11th Meeting of the Ozone Research Managers of the parties to the Vienna Convention for the Protection of the Ozone Layer

The trend analyses of total ozone and UV radiation involve discrepancies among Members. There are some reports on research activities, such as in situ ground monitoring efforts on ODSs, newly launched satellites and atmospheric chemistry modelling systems.

Future plans

Bangladesh is hoping for a tower renovation, new observatory and ODS laboratory. China is planning to study and develop ODSs/HFCs, compare them with international standards and progress estimation of ODSs/HFCs utilizing transport models. India reported that some of its Dobson and Brewer instruments should be refurbished or calibrated. Iraq reported a plan to facilitate continuous data collection by providing high-end land stations and monitoring equipment. Japan indicated the intention of the Japan Meteorological Agency (JMA) to host the Regional Intercomparison of Dobson Spectrophotometers for Asia in September 2025. Japan also reported that certain amounts of financial support will be needed to support developing countries' participation in the intercomparison. Nepal appeals for the necessity to plan for establishing the observational activities for UV measurement. The Russian Federation reported its plan for continuing and enhancing observations utilizing light detection and ranging (LIDAR), satellites and so on. The National Ozone Unit of Sri Lanka will promote observation of ozone and UV radiation.

Region 3: South America

(Damaris Kirsch Pinheiro, Federal University of Santa Maria, Brazil)

Efforts during the period 2021–2024 in Region 3 have been centred on the maintenance of the working networks through calibration campaigns of both local and regional character.

- The main achievement was the First Ibero-American Brewer Ozone Spectrophotometers Intercomparison Campaign,¹² which took place in Santa Maria, from 19 February to 8 March 2024.
- The Campaign was divided into three parts: the first week was dedicated to fixing and updating the instrumentation, the second week involved the conduct of a training course for operators and the final week was dedicated to the calibration itself.
- Ten Brewer and one Dobson instruments from Argentina, Bolivia, Brazil, Chile and Ecuador participated in the intercomparison, with the global reference provided by the GAW Regional Brewer Calibration Centre-Europe (RBCC-E) operated by the Izaña Atmospheric Research Center (CIAI).¹³ All instruments are now integrated into EUBREWNET.
- Thirty-five participants attended the activity, including experts, operators and PhD and master's students from the postgraduate meteorology programme of the Federal University of Santa Maria (UFSM).¹⁴

Planned and potential activities for the period 2024–2027 are centred on the principal complementary activities that would provide a good monitoring base across the region:

¹² I Campaña Iberoamericana de Calibración e Intercomparación de Instrumentos para la Medida de Ozono Total y Radiación Solar Ultravioleta

¹³ CIAI: Centro de Investigación Atmosférica de Izaña

¹⁴ UFSM: Universidade Federal de Santa Maria

- Next Latin American calibration of Dobson spectrophotometers to be held at the WMO South American Regional Calibration Centre (RCC III) in Buenos Aires, most likely in 2025.
- Next regional calibration of surface O₃ metres to be held in Buenos Aires, most likely in 2025/2026.
- Financing the shipment of standard solar radiometers to be recalibrated in Davos, Switzerland, during 2025/2026, and propagating this calibration into the next local and regional calibration campaigns.
- Next calibration of UV radiometers planned to be held at the local calibration centre in Buenos Aires in 2025/2026, after the recalibrated instrument return from Davos, Switzerland.
- Ozone sounding programmes in Region 3, requesting support for maintenance or reactivation, as some were supported locally for many years;
- Integration of the South American Brewer Network after the 2024 calibration.

The countries from Region 3 would like to thank the following: the General Trust Fund, the UNEP/Ozone Secretariat, WMO, AEMET, IO₃C, the Brazilian National Institute for Space Research (INPE),¹⁵ UFSM and all participating people and institutions who helped achieve the excellent results of the First Ibero-American Brewer Ozone Spectrophotometers Intercomparison Campaign.

Region 4: North America, Central America, and the Caribbean

United States

(Kenneth Jucks, National Aeronautics and Space Administration, and Stephen Montzka, National Oceanic and Atmospheric Administration)

The presentation provided a small recap of all the United States activities detailed in the submitted written United States report. It highlighted the various long-term observational activities in which the United States invests, along with several recent and ongoing suborbital campaigns looking at particular topical science areas related to ozone and the stratosphere. Of particular interest were the long-term NOAA and AGAGE observations in ODSs, long-term ozone sonde research, and contributions by the NDACC network. The field campaigns included the Stratospheric Aerosol processes, Budget and Radiative Effects (SABRE) campaign on stratospheric aerosols, the recently completed Dynamics and Chemistry of the Summer Stratosphere (DCOTSS) and Asian Summer Monsoon Chemical and Climate Impact Project (ACCLIP) campaigns looking at monsoonal stratospheric transport in North America and Asia, and the newly selected NASA Earth Venture Suborbital program Pyrocumulonimbus Experiment (PYREX) campaign that will study pyro injection of smoke plumes into the stratosphere.

Canada

(Sum Chi Lee, Environment and Climate Change Canada)

Canada continues its commitment to conduct long-term observational and research activities. ECCC maintains its measurements of total column ozone, spectral UV and ozone vertical profiles across Canada, including at three Arctic sites (Alert, Eureka and Resolute Bay in Nunavut) with data submitted to WOUDC on a systematic basis. Pandora total

¹⁵ INPE: Instituto Nacional de Pesquisas Espaciais

column ozone data for Canadian sites is available from the Pandora Global Network. As the Brewer World Calibration Centre, ECCC hosted JMA in 2023 for comparison of the JMA standard instrument with the WMO world reference standard. ECCC also hosts the Brewer CCL. To move towards a joint Brewer CCL between ECCC and AEMET, the WMO Expert Team on Atmospheric Composition Measurement Quality (ET-ACMQ) formed a working group. The Brewer CCL working group's first step is to set the scientific basis for a joint Brewer CCL by describing the primary calibration theory and technical details (for example, the difference between the primary calibrations by ECCC and AEMET of their Brewer instruments in a peer-reviewed paper). This paper is one in a series of four science articles planned through this working group. A recently published paper¹⁶ describes the evaluation of environmental conditions at the Mauna Loa Observatory (MLO) and the Izaña Atmospheric Observatory (IZO)¹⁷ and the requirements to ensure the primary calibrations performed at MLO and IZO are of the same quality. These requirements were successfully put into practice during the absolute calibration of the WMO Brewer world reference standard at IZO in August 2023. Future ECCC research includes conducting an updated global ground-based ozone monitoring network survey to assess the quality of measurements (1980–2023) at individual sites. Regarding the ozonesonde records, the reason for the “drop-off” in sonde signal at the Canada stations was found to be due to a change of pump motor. The Canadian ozonesonde network switched manufacturers from EN-SCI to Science Pump Corporation in 2021.

The Canadian Network for the Detection of Atmospheric Change (CANDAC) measures ozone at the Polar Environment Atmospheric Research Laboratory (PEARL) using Fourier Transform Infrared (FTIR), ultraviolet-visible (UV-vis) and Differential Absorption Laser (DIAL) with the data contributed to NDACC and the Copernicus Atmosphere Monitoring Service (CAMS). Recent research included the studies of polar ozone loss¹⁸ and tropospheric ozone columns from models in the 2021 Arctic Monitoring and Assessment Programme (AMAP) report on short-lived climate forcers.¹⁹ The University of Toronto measures ozone at the Toronto Atmospheric Observatory by FTIR and ECCC Pandora spectrometer. Recent studies included studies of the impact of the COVID-19 pandemic on ozone²⁰ and ozone time series and trends over Toronto, Canada.²¹

The Scientific Satellite (SCISAT) and the Canadian OSIRIS instrument on board the Swedish Odin satellite continue their operations of measuring atmospheric trace gases globally, with no major changes to observational parameters. SCISAT has two instruments: the infrared

¹⁶ Zhao, X.; Fioletov, V.; Redondas, A. et al. The Site-specific Primary Calibration Conditions for the Brewer Spectrophotometer. *Atmospheric Measurement Techniques* **2023**, *16*, 2273–2295. <https://doi.org/10.5194/amt-16-2273-2023>.

¹⁷ Centro de Investigación Atmosférica de Izaña

¹⁸ Pazmiño, A.; Goutail, F.; Godin-Beekmann, S. et al. Trends in Polar Ozone Loss since 1989: Potential Sign of Recovery in the Arctic Ozone Column. *Atmospheric Chemistry and Physics* **2023**, *23*, 15655–15670. <https://doi.org/10.5194/acp-23-15655-2023>.

¹⁹ Flood, V.A.; Strong, K.; Whaley, C.H. et al. Evaluating Modelled Tropospheric Columns of CH₄, CO, and O₃ in the Arctic using Ground-based Fourier Transform Infrared (FTIR) Measurements. *Atmospheric Chemistry and Physics* **2024**, *24*, 1079–1118. <https://doi.org/10.5194/acp-24-1079-2024>.

²⁰ Ortega, I.; Gaubert, B.; Hannigan, J.W. et al. Anomalies of O₃, CO, C₂H₂, H₂CO, and C₂H₆ Detected with Multiple Ground-based Fourier-transform Infrared Spectrometers and Assessed with Model Simulation in 2020: COVID-19 Lockdowns versus Natural Variability. *Elementa: Science of the Anthropocene* **2023**, *11*, 00015. <https://doi.org/10.1525/elementa.2023.00015>.

²¹ Yamanouchi, S.; Conway, S.; Strong, K. et al. Network for the Detection of Atmospheric Composition Change (NDACC) Fourier Transform Infrared (FTIR) Trace Gas Measurements at the University of Toronto Atmospheric Observatory from 2002 to 2020. *Earth System Science Data* **2023**, *15*, 3387–3418. <https://doi.org/10.5194/essd-15-3387-2023>.

ACE-FTS that measures the atmospheric profiles of nearly 70 different species and isotopologues, and the Measurements of Aerosol Extinction in the Stratosphere and Troposphere Retrieved by Occultation (MAESTRO) instrument focusing on visible-near infrared to measure the profiles of ozone, water vapour and nitrogen dioxide (NO₂). Both instruments have been measuring continuously since February 2004 (now a 20-year dataset). Latest ACE-FTS (v5.2) has added HFC-32, HFC-125, HFC-134a and HFC-143a. Research with the ACE-FTS included recently published work showing the significant slowing of the rate of increase of chlorodifluoromethane (HCFC-22) since 2012. New MAESTRO processing has improved ozone. The OSIRIS instrument continues to measure ozone, NO₂ and aerosol extinction with a ~2 km vertical resolution and good accuracy, and long-term stability of altitude registration over its vertical range of 7–90 km. OSIRIS v7.3 Level 2 data (2023) comprises aerosols, ozone, NO₂ and a new stratospheric temperature data product. Ozone has been merged to create Level 3 data products known as Stratospheric Aerosol and Gas Experiment II (SAGE-II)–OSIRIS–SAGE-III (SOS)/ISS and SAGE-II–OSIRIS–OMPS-LP (SOO) and includes the v1.3.0 OMPS-LP tomographic ozone data product.

Output from the Canadian Middle Atmosphere Model (CMAM) has been submitted for the Chemistry–Climate Modelling Initiative (CCMI) 2022 set of experiments that provide updated ozone projections for the 2026 Scientific Assessment of Ozone Depletion. CMAM simulations are also being produced for a multi-model study of the Hunga Tonga–Hunga Ha'apai eruption.

In November 2021, operational ozone assimilation and forecasting was activated as part of the ECCC global weather forecasting system using the assimilation of multiple satellite ozone sources. Operational ozone products are 10-day hourly total column ozone and 3D ozone field analysis and forecasts generated twice daily. Additional ozone observations could be assimilated operationally. At the same time, a new UV index forecasting package was also introduced with global ozone prediction as part of the ECCC global, regional and high-resolution weather forecasting systems. It provides global to high-resolution clear-sky and all-sky UV index forecast fields (hourly for global and regional resolutions). Work is under way to extend the UV index product range available to the public and make it available for research.

Canada continues its commitment to support developing countries to carry out systematic observations of the ozone layer. Funds from the current Canadian Brewer Trust Fund, a multi-year contribution agreement between ECCC and WMO (2021–2025), were used for the following activities between 2021 and early 2024: purchase of Brewer components for maintenance and repair of instruments; instrument repair, service, and calibration; and the 2024 South American Brewer Spectrophotometer Network repair and intercomparison in Santa Maria, Brazil.

***Central America, Mexico and the Caribbean
(Héctor R. Estévez Pérez, Institute of Geophysics, Michoacán Unit, National Autonomous University of Mexico)***

The presentation summarizes the national reports of activities carried out by Belize, Costa Rica, Dominica and Mexico for ORM12.

Belize

The national report of this country highlights the following points:

- Observational activities: A national network of automatic weather stations, with 27 of them housing measurements of global solar radiation.

- Compliance with the Montreal Protocol and its Amendments (London, Copenhagen, Montreal and Beijing Amendments, and ratification of the Kigali Amendment) and obtaining the Global Montreal Protocol Award for Customs and Enforcement Officers in 2019.
- Planned priorities are to enhance the country's ground stations, collaborate with several international research institutions for data collection and analysis, and make use of emerging technologies like remote sensing and atmospheric modelling to advance atmospheric research studies.
- Regarding needs and recommendations, Belize is interested in the deployment of a monitoring station dedicated to gathering data on emissions of pollutants linked with damage to the ozone layer, and enhancing its capacity to monitor ODS levels, track atmospheric changes and evaluate the effectiveness of ozone protection measures.

Costa Rica

The national report of this country highlights the following points:

- Observational activities: A national solarimetric network with a number of parameters (global solar radiation, photosynthetically active radiation (PAR) and UVB) and, in the cities of San José, Cartago and Alajuela, ultraviolet E radiation (UVE) instruments.
- Ozonesondes in San José (water vapour, sulfur dioxide (SO₂) and O₃), conducted twice a month as part of a collaboration with NOAA activities, with associated data participating in the SHADOZ and NDACC networks.²²
- Results from observations and analysis: Analysis of the Alajuela station's data will start in 2024.
- Theory, modelling, and other ozone-related research developed a daily forecast of UV index for the public from application of a national study and climate forecast from a Weather Research and Forecasting Model (WRF) for each climate region.
- Dissemination of results, projects, collaboration, twinning and capacity-building: In 2014, a method was developed to estimate UV index from UVB sensor data. The method is still being used by the forecast department of the National Meteorological Institute of Costa Rica (IMN)²³ to generate daily maximum UV index. A research article entitled *Medición y cálculo del índice ultravioleta en Costa Rica* was published.²⁴
- Projects, collaboration, twinning and capacity-building: IMN accepted the invitation from the National Autonomous University of Mexico (UNAM)²⁵ to be part of the "UV-B solar radiation monitoring in Central America and the Caribbean as an indirect way to gain knowledge on the condition and behaviour of the ozone layer" project, developed with other countries of Central America and the Caribbean region. Costa

²² <https://acd-ext.gsfc.nasa.gov/Projects/Ticosonde/index.html>

²³ IMN: Instituto Meteorológico Nacional de Costa Rica

²⁴ Hernández, K.E.; Morera, R.R.; Wright, J.G. Medición y cálculo del índice ultravioleta en Costa Rica. *Tópicos meteorológicos y oceanográficos* **2014**, *13*, 41–45.
<https://www.kerwa.ucr.ac.cr/server/api/core/bitstreams/7928aded-39a8-4496-ae2e-65d6d6e94ba6/content>.

²⁵ UNAM: Universidad Nacional Autónoma de México

Rica has a good relationship with the WMO Regional Association IV representative, because this office is located in the IMN building. This helped reduce the gap between the national ozone officer and IMN.

- Implementation of the recommendations of ORM11: Costa Rica will join the regional project with Mexico, providing UVB measurements in the Central American area.
- Future plans: Costa Rica is working on adding the UVE parameter to its stations and implementing an hourly forecast aimed at the public, as well as working on the acquisition of stratospheric ozone with indirect techniques.
- Needs and recommendations: Costa Rica needs support for:
 - Calibration activities, like calibration equipment and capacity development.
 - Acquisition of a pyrhelimeter sensor with respective calibration activities.
 - Development of a multi-solar sensor measurement site.
 - Development of new projects related to ozone and radiation topics.
 - Development of new products for the public.
 - Storing and working with satellite images.

Dominica

The representative of Dominica commented, by email communication, that national activities are currently focused on basic weather forecasting; however, the country is interested in gaining equipment and necessary training to begin ozone research.

Mexico

The national report of this country highlights the following points:

- Observational activities: Stratospheric ozone with Dobson-Beck 098, ground-based UVB radiation from the Mexican Solarimetric Service (SSM)²⁶ network; measurement of O₃ and NO₂ with Pandora instruments.
- Results from observations and analysis: Three sources of information – Aura OMI and Dobson-Beck 098 for ozone values, and ground-based UVB radiation data with a Solar Light 501A biometer – have been used to observe the behaviour of UVB according to variations in stratospheric ozone concentrations.
- Dissemination of results: Stratospheric ozone measurements are reported to the WOUDC and the SSM promotes awareness of the risks of overexposure to UV radiation through its Facebook page.
- Projects, collaboration, twinning and capacity-building: “UV-B solar radiation monitoring in Central America and the Caribbean as an indirect way to gain knowledge on the condition and behaviour of the ozone layer” project, funded by the Trust Fund.

²⁶ SSM: Servicio Solarimétrico Mexicano

- Implementation of the recommendations of ORM11: Commitment to continue with both ozone and UVB measurements, as well as exploring the acquisition of new instruments.
- Future plans: Maintaining ozone and UVB infrastructure, as well as running and seeking collaborations to conduct research.
- Needs and recommendations: Proposing strategies to manage the continuity of intercomparisons for Dobson instruments and establishing contact with working groups that allow the development of research activities using the data available to the SSM.

Final conclusions

Considering the points expressed in the proposed guide for national reports, it can be seen that the different countries in the area have different needs, while all of them are working on the application of policies aimed at the control and eradication of ODSs through Customs control in compliance with the Montreal Protocol requirements.

Covering the infrastructure needs for the measurement of parameters such as UVB, ozone and ODSs is a complex problem; although it requires commitment by the corresponding entities of each country, it needs the support of international organizations, given the high costs of instrumentation to carry out the work of measurement, monitoring and research in the intertropical zone, which has great spatial and temporal dynamics.

Equally important is the preparation of personnel in each country to develop measurement and research on the ozone layer and UV. In this case, collaboration among the countries in the area is needed for the exchange of ideas and generation of projects to fund measurement and research activities, as well as exchange programmes for the preparation of technicians and researchers to face new environmental challenges in the region.

Region 5: South-West Pacific (*Matt Tully, Australian Bureau of Meteorology*)

In general, the South-West Pacific has a very low coverage of ozone observations compared with many other parts of the world. Long-running Dobson programmes have continued in Australia, New Zealand and the Philippines. Brewers are also operated in Indonesia, Malaysia and Singapore. The Australian Bureau of Meteorology (BOM) has also recently installed Brewers at each of the Australian Dobson sites, as well as supporting the Brewer in Hobart operated by the University of Tasmania. Australia, New Zealand and the Philippines have all recently attempted to purchase new Brewers from Kipp & Zonen but have been unable to do so owing to the current suspension of production. Ozonesonde programmes include four SHADOZ sites (Kuala Lumpur; Watukosek, Indonesia; Suva; and Pago Pago) plus three long-running mid-latitude sites (Broadmeadows, Australia; Lauder, New Zealand; and Macquarie Island). FTSs as part of NDACC are operated at Wollongong, Australia, and Lauder, New Zealand, with Lauder additionally hosting an ozone LIDAR and microwave radiometer.

Atmospheric concentrations of ODSs and their replacements are measured at Kennaook/Cape Grim, Australia, which contributes to both the AGAGE and NOAA networks and samples both background southern hemisphere conditions in air travelling over the Southern Ocean and polluted air from mainland Australia (Melbourne).

Both developing and developed countries in the region expressed a need for continued support for new and existing measurement programmes. The suspension of Brewer production is a major concern and resumption of production is strongly urged. Support for chemistry–climate modelling is also needed, with real doubt as to whether chemistry–climate modelling in both Australia and New Zealand will be able to continue at all.

Research needs include further work on better understanding the long-term changes in southern hemisphere tropical and mid-latitude ozone, the impacts on stratospheric ozone of major bushfires and the Hunga Tonga–Hunga Ha'apai eruption, coupling between the Antarctic ozone hole and southern hemisphere surface climate and weather, and clarifying UTLS ozone changes in the southern hemisphere.

Polar regions – Antarctica and the Arctic
(Thomas McElroy, York University, Canada)

The levels of the polar ozone column have been tracked for more than 60 years. Measurements have been maintained at 17 stations in the northern hemisphere and 13 stations in the southern hemisphere. These measurements have provided historical perspective on ozone change and also provided data that led to understanding the chemistry involved in ozone depletion. Some of the longest and most valuable ozone records are from the Arctic stations, with particular importance attached to the more than 60-year record from the station at Resolute Bay in the Canadian High Arctic. Ozone profiles have also been recorded at Arctic stations for more than 30 years.

The major uncertainties in predicting the impacts of climate change are related to uncertainty in aerosol and ozone.²⁷ Recovery of the Antarctic ozone hole over the past four years has been slower than expected but is taking place. Polar ozone depletion affects mid-latitude ozone as well when air mixes equatorward as the winter vortex breaks up, increasing UVB. Increased GHGs in the upper atmosphere cool the ozone layer. Lowering stratospheric temperatures in the late winter and early spring may increase ozone depletion (climate change affects ozone depletion). Upper tropospheric ozone acts as a GHG (tropospheric ozone changes affect climate). Continued monitoring of polar ozone and aerosol is imperative.

The 1999–2023 South Pole data show a +8 DU per decade trend, excluding 2002 and 2019, which were dynamically active years and significantly distort the trend. Ozone decline towards the Antarctic maximum depletion (“the ozone hole”) is correlated with the increase in equivalent effective stratospheric chlorine (EESC), which represents the impact of all depleting chemicals added together. If the same sensitivity is applied during the recovery period, the measured recovery rate is about 20% lower than the calculated rate. Peak depletion occurred in the 1991–2006 period. 2023 was the sixteenth lowest ozone value in 44 years. The recovery of the ozone hole on an annual basis appears to have slowed somewhat with time, probably from dynamical changes that may be related to climate change.

The 2022 Hunga Tonga–Hunga Ha'apai volcanic eruption had a measurable impact on ozone in the Antarctic, mostly due to water vapour injection into the stratosphere. However, the magnitude of the change is within the range of natural variability. The major impact on climate is from the reflection of more solar radiation back into space.

The science of ozone depletion and climate change must be clearly and simply communicated. Most politicians are not equipped to make scientific judgments. The most

²⁷ Based on the work of the IPCC

probable outcomes should be communicated, not a collection of choices. Politics demands that elected representatives be sensitive to many influences, possibly not weighted by the level of intrinsic importance.

Region 6: Europe

European Union: Copernicus Atmosphere Monitoring Service (Richard Engelen, European Centre for Medium-Range Weather Forecasts)

CAMS is one of six services that form Copernicus, the European Union Earth observation programme, which monitors our planet and its environment. Copernicus offers information services based on satellite Earth observation, in situ (non-satellite) data, and Earth system modelling. As part of its service portfolio, CAMS monitors the ozone layer on a daily basis, providing information on, for instance, the extent and magnitude of the ozone hole each year as it develops and recovers. CAMS also provides a historical record from 2003 to the present based on its global reanalysis that combines observations with the CAMS global models describing the composition of the atmosphere. Combining the CAMS global reanalysis with information from the European Centre for Medium-Range Weather Forecasts (ECMWF) Reanalysis v5 (ERA5) meteorological reanalysis allows us to extend this record even further back in time to 1979.

In addition to this, on a daily basis, CAMS monitors and forecasts the UV index, which is a measure of the amount of UV radiation reaching the surface of the Earth, taking into account the effect of ozone, clouds and aerosol particles. In June 2023, the CAMS global monitoring and forecasting system was upgraded to include comprehensive stratospheric chemistry with the Belgian Assimilation System for Chemical Observations (BASCOE) chemical scheme. This enables the provision of data for most of the relevant chemical species related to ozone layer destruction, allowing better interpretation of the observed ozone concentrations. All CAMS data are freely available in support of policy monitoring as well as scientific research.

Northern Europe (Thomas Carlund, Swedish Meteorological and Hydrological Institute)

On this occasion (ORM12), Northern Europe consists of the following countries: Denmark, Estonia, Finland, Lithuania, Norway and Sweden. For each country the current/recent observation schedule is described, including sites and instrumentation. The focus is on the observation of ozone and UV radiation. However, some countries also measure other gaseous components related to ozone depletion and/or tropospheric warming. Depending on the filed reports, some results from recent years have also been included.

Western, Central and Eastern Europe (Stefan Reimann, Swiss Federal Laboratories for Materials Science and Technology)

The efforts of several European countries were presented in terms of remote measurements of ozone and radiation as well as for remote and in situ measurements of ODSs. Currently, Western, Central and Eastern Europe have very good coverage of all measurement parameters. Many recommendations from ORM11 were addressed, such as maintaining observations for ozone, UV and climate; doing research on ozone, UV and climate; and providing services and building capacities.

Europe has a dense network of total ozone measurements and of ozonesonde measurements for the analysis of height-dependent ozone concentrations. Furthermore, LIDAR, microwave radiometry and FTIR measurements are used. Total ozone is measured at several sites in Europe (for example, Davos, Switzerland; Hohenpeißenberg, Germany; and Uccle, Belgium). The negative ozone trend from the past has stopped, but still a

considerable year-to-year deviation is observed. Thereby, the longest time series worldwide for ozone measurements is from Arosa/Davos, Switzerland, with 100 years of continuous measurements performed as at 2025.

In addition, several European countries are working together to enhance the consistency of total ozone observations, using Dobson and Brewer instruments. Here, the long-term seasonal difference between Brewer and Dobson measurement systems could be minimized by applying new ozone absorption cross sections.

Europe has also the world's densest network for the continuous measurements of ODSs. The network analyses the decline of ODSs and provides the regional estimations of still ongoing small emissions. Extending the current monitoring of the main ODSs to more areas of the world should be a priority and should be a focus for building capacities.

In the near future, there is a challenge that a shortage of satellite missions for making limb-based observations could occur. Several currently operational space-borne instruments are around their design lifetimes: MLS, ACE-FTS, OSIRIS and Odin Sub-Millimeter Radiometer (SMR). With the loss of these current limb-viewing capabilities, vertically resolved global measurements of many trace gases will no longer be available. In terms of future measurement capabilities, a novel, high-resolution Changing-Atmosphere Infrared Tomography (CAIRT) Explorer is currently a candidate instrument for an ESA Earth Explorer mission.

Furthermore, ongoing climate change warrants closer international collaboration on interactions between ozone and climate changes to determine the ozone recovery date and evolution of policy instruments to reduce GHGs.

Southern Europe (Alkis Bais, Aristotle University of Thessaloniki, Greece)

The report for South-East Europe that was presented to ORM12 summarized the monitoring activities of four countries and presented relevant results. South-East Europe comprises several countries with important activities in respect of stratospheric ozone and UV radiation, however not all of them submitted national reports. Specifically, reports were submitted by Armenia, Spain and Türkiye, while countries with known long-term ozone and UV monitoring, such as Greece, Italy and Portugal, did not submit reports. However, most of them continue submitting at least total ozone measurements to WOUDC.

Since 2000, Armenia has operated a Dobson spectrophotometer (no. 44) in Amberd, which was last calibrated in 2017, with a new calibration scheduled in 2024. Total ozone data are submitted to WOUDC regularly (latest submission in February 2024).

Since 2006, Türkiye has operated a Brewer Mark III spectrophotometer (no. 188) in Ankara, which provides total ozone and UVB spectral measurements and was last calibrated in 2013. It is uncertain whether this instrument continues operating, since the national report states 2018 as the last year of operation and total ozone data have been submitted to WOUDC only up to December 2015. Ozone profile data with electrochemical concentration cell (ECC) ozonesondes were collected in Ankara during the period 2006–2013.

Spain is one of the most active countries in monitoring stratospheric ozone and UV radiation. The ozone network comprises nine stations operating 1 Dobson, 10 Brewers, 2 Norwegian Institute for Air Research irradiance meter (NILU-UV),²⁸ 1 Differential Optical

²⁸ NILU: Norsk Institutt for Luftforskning

Absorption Spectroscopy (DOAS) and 1 FTIR instruments, and is managed by AEMET and the National Institute for Aerospace Technology, Spain (INTA).²⁹ The UV network comprises 45 stations equipped mainly with broad-band radiometers, which are distributed over the entire country. The quality assurance of the UV data is supported by two calibration centres. The two agencies, AEMET and INTA, are in close research collaboration with Spanish universities.

Since 1992, ozone soundings have been regularly launched (weekly) from Madrid and Santa Cruz, Brazil (changed to Puerto de la Cruz, Spain, since 2011). Since 1999, a long-term ozone sounding programme between INTA and the Argentine National Antarctic Directorate/Argentine Antarctic Institute (DNA/IAA,^{30,31} Argentina) has been running at Belgrano station in Argentina (78°S).

Spain has also been very active in maintaining calibration activities, offering to calibrate instruments from other countries. In November 2003, the WMO/GAW RBCC-E was established at the IZO. RBCC-E owns a full set of calibration and reference-maintenance equipment composed of three Brewer spectroradiometers (the IZO triad). RBCC-E transfers the calibration from the World Reference Triad in Toronto, Canada, and, since 2011, maintains its own absolute calibration obtained by the Langley extrapolation method. Brewer intercomparisons are held annually, alternating between Arosa, Switzerland, and INTA in Huelva, Spain. Finally, AEMET supports and maintains the databases of EUBREWNET.

Greece runs a total of three ozone monitoring stations in Thessaloniki and in Athens at two different institutes. In Thessaloniki, the Laboratory of Atmospheric Physics at the Aristotle University of Thessaloniki has operated a Brewer Mark II (no. 005) since 1982, a Brewer Mark III since 1993 and a Pandora 240 since 2022. Two additional DOAS/multi-axis DOAS (MAX-DOAS) systems have also been operating since 2013 and are capable of providing, among others, total ozone measurements. Data from Brewer no. 005, which was last calibrated in 2021, are regularly submitted to WOUDC and are used in various satellite validation studies. Spectral UV measurements have been provided by Brewer Mark II since 1993 and are used, among others, in the validation of UV index and spectral irradiance products of CAMS.

SESSION 8: DISCUSSION ON AND ADOPTION OF RECOMMENDATIONS

Recommendations arising from the meeting were discussed under five topics. For each topic, selected resource persons made a short introductory presentation based on the attendees' presentations, followed by discussion. Rapporteurs for each topic led the drafting of the recommendations on the basis of the discussions. The national reports formed an important basis for the discussions and the recommendations. The resource persons and rapporteurs were as follows:

- Research needs: Introduction by Lucy Carpenter (United Kingdom) and David Fahey (United States), SAP Co-Chairs; Rapporteur: Ken Jucks (United States), SAP Co-Chair;

²⁹ INTA: Instituto Nacional de Técnica Aeroespacial

³⁰ DNA: Dirección Nacional Antártica

³¹ IAA: Instituto Antártico Argentino

- Systematic observations: Introduction by Sophie Godin-Beekmann (France) and Damaris Kirsch Pinheiro (Brazil); Rapporteur: Stefan Reimann (Switzerland);
- Gaps in the global coverage of atmospheric monitoring of controlled substances, and options to enhance such monitoring: Introduction by A.R. Ravishankara (United States) and Ray Weiss (United States); Rapporteur: Stephen Montzka (United States);
- Data archiving and stewardship: Introduction by Martine De Mazière (Belgium) and Tove Svendby (Norway); Rapporteurs: Alberto Redondas (Spain) and Victoria Sofieva (Finland);
- Capacity-building: Introduction by Samuel Paré (Burkina Faso) and Sergio Moreno (Switzerland); Rapporteur: Irina Petropavlovskikh (United States).

The following section on overarching goals introduces the final recommendations in the areas of research needs, systematic observations, gaps in the global coverage of atmospheric monitoring and controlled substances, data archiving and stewardship, and capacity-building.

Recommendations

I. Research needs

The Montreal Protocol on Substances that Deplete the Ozone Layer has successfully controlled the production and consumption of ozone-depleting substances (ODS) and some hydrofluorocarbons (HFCs). The quadrennial scientific assessments of ozone depletion conducted for the Montreal Protocol provide updates on stratospheric ozone and the impact of ODS and climate change. Some of the highlights of the 2022 assessment report are as follows:

- Observations show that the atmospheric abundances of both total tropospheric chlorine and total tropospheric bromine from long-lived ODS have continued to decline.
- Evidence for ozone recovery consistent with these ODS declines has strengthened, especially for ozone in the upper stratosphere and over the Antarctic region.
- Evidence suggests that ozone recovery has caused changes in the observed trends of the Southern Hemisphere atmospheric circulation between the ozone depletion and recovery periods. Model simulations provide evidence that Southern Hemisphere circulation trends have responded to the recovery of Antarctic ozone due to the Montreal Protocol.
- In contrast, ozone in the lower stratosphere has not yet shown signs of recovery, for reasons that are not yet understood. Reconciling this discrepancy remains key to ensuring a full understanding of ozone recovery.
- The recent identification of unexpected trichlorofluoromethane (CFC-11) emissions led to scientific investigations across the science and technology assessment panels and policy responses. The source region for at least half of those emissions was identified and substantial emissions reductions followed.

- (f) Atmospheric observations continue to point to missing sources of carbon tetrachloride (CCl₄) emissions. Production of CCl₄ has increased in recent years due mainly to growing demand for feedstock use for production of HFCs, hydrofluoroolefins (HFOs)/hydrochlorofluoroolefins (HCFOs) and perchloroethylene.
- (g) Atmospheric observations indicate an increase or stabilization of the emissions of the relatively low-abundance chlorofluorocarbon (CFC) compounds CFC-13, CFC-112a, CFC-113a, CFC-114a and CFC-115 and confirm that Eastern Asia is a substantial source region. Cumulatively, these substances may eventually have an impact on stratospheric ozone.
- (h) Atmospheric observations confirm that chlorinated very short-lived halogenated substances (VSLS), dominated by dichloromethane (CH₂Cl₂), continue to grow and can reach the stratosphere through various rapid convection routes. While these VSLS represent a minor contribution to the chlorine entering the stratosphere, sustained emissions would continue to deplete approximately 1 Dobson unit (DU) of the annually averaged global total ozone column. Elimination of these emissions would rapidly reverse this depletion.
- (i) Calculations show that annual average surface warming from HFCs is expected to be 0.04°C in 2100 under the updated 2022 Kigali Amendment scenario, compared to 0.3–0.5°C without any control measures.
- (j) Global HFC-23 emissions derived from atmospheric observations have been substantially higher than emissions derived from activity-based estimates since around 2014; efforts to understand this emissions gap are ongoing.
- (k) The impact on the ozone layer of stratospheric aerosol injection, which has been proposed as a possible option to offset global warming, was assessed in the 2022 Scientific Assessment Panel report. Important potential consequences such as deepening of the Antarctic ozone hole and a delay in ozone recovery were identified. Many knowledge gaps and uncertainties prevent a more robust evaluation at this time.
- (l) Knowledge of the effects of ultra-violet (UV) radiation avoided due to the Montreal Protocol is improving, including in protecting human health, as well as impacts on terrestrial vegetation and the photosynthetic uptake of carbon dioxide (CO₂) by plants.
- (m) Calculations indicate that the impact of large increases in UV-B radiation on terrestrial vegetation in a world without the Montreal Protocol would have drastically reduced the photosynthetic uptake of carbon dioxide by plants, in turn increasing atmospheric carbon dioxide levels and the global mean surface temperature.

Key research needs recommendations arising from the twelfth meeting of the Ozone Research Managers

Future projections of climate change from increased greenhouse gases and other forcing agents include, for example, significant changes in surface temperatures and precipitation patterns, and in the frequency of extreme meteorological events. The diversity and variability of these changes will increasingly affect conditions that control ozone abundances in the troposphere and stratosphere. Early research results have shown how total column

ozone amounts can vary in response to circulation changes associated with extreme temperature events and during the life cycle of a tropical cyclone.

Emerging research needs include more specific understanding of how future climate change will influence the efforts of ozone research managers across the globe. For example, increased variance in the time series of stratospheric ozone abundances at certain locations will make trend analysis more difficult, and more extreme events may present more challenging conditions for maintaining accuracy in surface and airborne ozone observations.

1. Stratospheric ozone distribution and trends

Calculating ozone trends is a major part of the scientific ozone assessments. Trends require a synthesis of the available data from ground-based, airborne and space-based observations. Consistent modelling of these trends is also an essential element of the assessments. The recommendations in this regard are:

- (a) Continue to advance synthesized distributions and trends of stratospheric ozone, in collaboration with the observation networks and satellite data experts.
- (b) Continue to improve modelling efforts in order to understand stratospheric ozone evolution based on the existing datasets and hence improve modelled projections of ozone. This is particularly applicable to the lower stratosphere, where ozone abundances are controlled as much by transport as by photochemistry.
- (c) Encourage calculations of modelled surface UV change effects based on the modelled changes in the stratosphere to ensure consistency. These calculations should be regional, especially in the tropics.
- (d) Assess the ozone recovery date and integrated ozone depletion metrics and their relative strengths and weaknesses for both ozone and UV.
- (e) Improve the understanding of trends and projections in stratospheric dynamics, such as changes in the Brewer-Dobson circulation (BDC) and in hemispheric differences.

2. Improve understanding of global emissions of ozone-depleting substances and related gases

ODS: Uncertainties in emissions from banks and gaps in the observing network are too large to determine whether all unexpected CFC-11 emissions have ceased. Unexplained emissions have been identified for other ODS (including CFC-13, CFC-112a, CFC-113a, CFC-114a, CFC-115 and CCl₄). Some of these unexplained emissions are likely occurring as leaks of feedstocks or by-products, and the remainder are not understood. The recommendations in this regard are:

- (a) Continue the analysis of ODS component budgets in order to identify and quantify emissions gaps by comparing atmospheric monitoring-derived (top-down) emissions with bottom-up modelling of emissions.
- (b) Enhance monitoring of ongoing emissions at the global and regional scales, especially in undersampled regions.

- (c) Monitor Montreal Protocol compliance through continuation of time series data of ODS and related gases.

Feedstocks: The mass of ODS used as feedstocks increased by 75 per cent between 2009 and 2019. The influence on ozone was dominated by the usage of CCl_4 , increasingly used as a feedstock in the production of HFOs. A number of minor CFCs used as feedstocks are increasing; this is at least partially linked to the massive increase in HFC production since 2000 in parties operating under paragraph 1 of Article 5 of the Montreal Protocol. Uncertainty regarding the emissions from feedstock use associated with various processes limits our understanding of the impact on global emissions. The recommendations in this regard are:

- (a) Perform regional emissions modelling in regions sensitive to feedstock emissions to assess potential locations and industries. Compare top-down emissions estimates with bottom-up information on feedstock industries, processes and emissions, utilizing production and consumption data of sufficient spatial granularity.
- (b) Expand the atmospheric measurement of minor CFCs, including their isomers, to discern the industrial production processes associated with various feedstock and by-product emissions.

VSLs: Very short-lived halogenated substances are not controlled under the Montreal Protocol and have lifetimes shorter than about six months. An increasing fraction of the total atmospheric ODS amount comes from anthropogenic chlorine-containing VSLs. While still a minor contribution (4 per cent) to stratospheric chlorine, these compounds are growing in the atmosphere and new emerging VSLs, such as 1,2-dichloroethane, have been identified.

The recommendation in this regard is to assess the impact of industry-related emissions of chlorinated VSLs by sector on stratospheric ozone and its long-term trends.

Nitrous oxide (N_2O) and hydrogen (H_2): Important concerns in terms of influences on stratospheric ozone in the coming decades include increases in N_2O and H_2 global emissions. The ozone depletion potential (ODP) of N_2O emissions in 2020 was more than twice as large as that of the ODP-weighted emissions from all CFCs in 2020. The increased use of ammonia to replace fossil fuels, for example in shipping, could lead to increased N_2O emissions. Increases in atmospheric H_2 could arise in the decarbonization of the fossil fuel industry.

The recommendation in this regard is to evaluate updated scenarios of future emissions of N_2O and H_2 for potential changes in stratospheric ozone abundances.

3. Hydrofluorocarbons/hydrofluoroolefins

The Kigali Amendment to the Montreal Protocol aimed at phasing down some HFCs is projected to limit surface warming due to HFCs to about 0.04°C by 2100, compared to expected warming of $0.3\text{--}0.5^\circ\text{C}$ in the absence of any control measures. In the near future, global emissions and atmospheric abundances of most HFCs will increase in response to HCFC phase-out actions. The use of low-global-warming-potential HFCs and HFOs, along with improvements in energy efficiency in HFC applications, will minimize the climate impact of the HCFC phase-out. The large differences in HFC bottom-up and

top-down annual emissions are unexplained at present. The recommendations in this regard are:

- (a) Compare observationally derived HFC emissions with bottom-up emissions to monitor the phase-down of HFCs under the Kigali Amendment.
- (b) Evaluate the present and projected contributions of HFC/HFO emissions to climate forcing.
- (c) Verify emissions of ODS and non-CO₂ greenhouse gases for both the Montreal Protocol and the United Nations Framework Convention on Climate Change by comparing bottom-up and top-down emissions estimates.
- (d) Investigate the gap in reported and estimated HFC-23 emissions that include reported substantial destruction amounts of HFC-23 released during HCFC-22 production.

4. Trifluoroacetic acid

Trifluoroacetic acid (TFA) is a breakdown product in the atmosphere of some HFCs, HCFCs, HFOs, HCFOs and fluoroketones. TFA formed in the atmosphere is rapidly deposited in precipitation and forms salts on reaching the surface (soil or water). The formation of TFA in the atmosphere is expected to increase in future with the transition from HFCs to HFOs and HCFOs. TFA continues to be found in the environment in concentrations sufficiently low to currently be judged very unlikely to have adverse toxicological consequences for humans and ecosystems. Monitoring and assessment of TFA concentrations and deposition rates are nevertheless advised due to uncertainties in the localized deposition of TFA and its potential effects on some untested organisms. The recommendations in this regard are:

- (a) Evaluate the contribution of HFC and HFO emissions to the formation and accumulation of TFA, including further development of understanding of the atmospheric breakdown pathways that lead to TFA formation.
- (b) Broaden the understanding of risks associated with the use of refrigerants considered as per- and polyfluoroalkyl substances (PFAS) (as defined by the Organization for Economic Co-operation and Development) and their breakdown products, especially TFA and its salts, as well as other sources of TFA.

5. Stratospheric ozone-climate coupling

Human-induced stratospheric ozone depletion has affected global climate trends, including stratospheric cooling and changes in the Southern Hemisphere summer climate. There is emerging evidence that ODS-induced ozone loss can affect extratropical surface climate variability in some years. The positive effective radiative forcing (ERF) from the greenhouse effect of emitted Montreal Protocol gases (CFC+HCFC+HFC) is partly offset by negative ERF from stratospheric ozone depletion and an associated reduction in methane ERF.³² Owing to incomplete observations, stratospheric ozone ERF estimates often rely on chemistry-climate model-simulated

³² Szopa, S.; Naik, V.; Adhikary B. et al. Short-lived Climate Forcers. In *Climate Change 2021: the Physical Science Basis* (Cambridge, United Kingdom, and New York, Cambridge University Press, 2021).

trends. Long-term changes in greenhouse gases also directly change ozone through changes in transport and stratospheric temperatures and photochemistry, both of which directly affect ozone. The specific recommendations include:

- (a) Conduct analyses that provide better understanding of stratospheric ozone-climate feedbacks and ocean and cryosphere responses to ozone forcing, to increase confidence in future model projections as ozone recovers.
- (b) Calculate the accurate ERFs required to assess changes in climate as the abundances of radiatively active gases change.
- (c) Continue the observations needed to better validate the reanalyses of the stratosphere, such as the Copernicus Atmosphere Monitoring Service and Modern-Era Retrospective Analysis for Research and Applications, Version 2, products.
- (d) Improve the understanding of polar vortex dynamical processes and formation, in particular related to potential changes in temperatures that drive the formation of polar stratospheric clouds, as well as changes in wave-driven dynamics. These processes will affect the ongoing recovery of ozone in the polar vortices.
- (e) Carry out focused modelling studies in order to better understand the coupling of stratospheric dynamics and climate-driven weather patterns, which has significance at all latitudes.

6. Exceptional events: wildfires and volcanic eruptions

Recent intense and large-scale wildfires such as those in Australia and North America have demonstrated that wildfire emissions can reach the stratosphere, influencing stratospheric composition and stratospheric ozone abundances. Similarly, explosive volcanic eruptions inject sulfur gases and ash into the lower stratosphere. For example, the 2022 Hunga Tonga-Hunga Ha'apai eruption injected substantial amounts of sulfur and water vapour well into the lower stratosphere.:

The recommendation in this regard is to conduct timely observations and interpretative studies of such exceptional events to improve understanding of the effects of aerosols and trace gas perturbations on the composition and chemistry of the stratosphere, especially stratospheric ozone.

7. Supersonic aviation, space activity and climate intervention

Stratospheric aerosol and ozone abundances are also potentially influenced by other human activities that are drawing increased attention. New proposals exist for a supersonic civil aviation fleet that would emit nitrogen oxides and other gases in the stratosphere. Present day rocket launches that bring satellites to orbit and the return of space hardware to the lower atmosphere both emit gases and aerosols in the stratosphere. Future projections of space activity show substantial growth in space activity and associated emissions. Climate intervention proposals to offset the rise in global temperatures from greenhouse gases include the injection of aerosols or aerosol precursors in the lower stratosphere that would reflect more sunlight to space. The 2022 assessment report of the Scientific Assessment Panel showed that stratospheric aerosol injection to limit temperature increases in the coming decades would likely deepen the Antarctic ozone hole and delay ozone recovery. The recommendations in this regard are:

- (a) Evaluate the impact on ozone of future aircraft fleets, increases in space activity and climate intervention in the stratosphere by incorporating proposed scenarios into climate/chemistry models that include stratospheric chemistry and dynamics.
- (b) Improve the incorporation of stratospheric aerosol and gas processes related to such activities into stratospheric modelling of future ozone abundances and conduct laboratory studies to improve the characterization of those processes.

II. Systematic observations

Presentations and discussions during the twelfth meeting of the Ozone Research Managers made it clear that systematic observations are critical for monitoring and understanding long-term changes in the ozone layer, as well as changes in atmospheric composition, circulation and climate. Verification of the expected ozone recovery must be accompanied by many decades of observation of key gases (ODS, greenhouse gases, ozone column) and UV radiation and their connection to climate change.

Although the Montreal Protocol has led to a steady decline in ODS, we are still in a period where the recovery of the ozone layer has not been shown to take place unambiguously in response to ODS decreases. As the period of unexpected emissions of CFC-11 in Eastern China has shown, even the verification of emissions of fully controlled substance remains a necessity. In fact, important gaps in the global representativity of global observation capacity still exist, which limits the ability to detect the sources of such ODS.

Furthermore, we are in a period when gases other than ODS (especially CO₂, N₂O, CH₄ and H₂O) have an influence on global stratospheric ozone changes, and the future emissions of such gases, which are not controlled under the Montreal Protocol, are quite uncertain. Therefore, robust long-term monitoring is essential also in this period, moving towards the recovery of the ozone layer, which is expected in the latter part of this century. Such long-term measurements need to be of sufficiently high quality to allow unambiguous analyses.

Monitoring also needs to be expanded to include important new species and parameters, such as emerging ODS replacements, short-lived halogenated chemicals (short-lived substances and VSLS), and tracers for atmospheric circulation and other transport phenomena. Key measurement regions include the Upper Troposphere/Lower Stratosphere (UTLS) region and regions of stratosphere-troposphere exchange in the extra-tropics such as monsoon circulations, as well as the polar caps and the upper stratosphere.

While current and new satellite instruments will continue ozone observations at high-resolution and spatial sampling, there is a growing concern for the end-of-life of satellites (e.g., Aura Microwave Limb Sounder) that have been tracking some of the ODS, trace species and water vapour high-resolution profiles for the last two decades. There are no immediate plans to replace the necessary limb microwave and infrared satellite instruments. Therefore, follow-on satellite missions should be developed, and the gap will have to be mitigated by intensive use of ground-based observations.

A. Key systematic observations achievements since the eleventh meeting of the Ozone Research Managers

Despite various difficulties, ground- and space-based measurements of ozone, UV radiation, most relevant trace gases, temperature and stratospheric aerosol have continued over the last years. The General Trust Fund for Financing Activities on Research and Systematic Observations Relevant to the Vienna Convention for the Protection of the Ozone Layer has played a large role in providing support to developing countries and countries with

economies in transition, especially for the ground-based global observation networks, including providing intercomparisons, refurbishing and shipping available Dobson/Brewer instruments and enabling ozonesondes, while encouraging the development/validation of other instruments.

A number of Dobson and Brewer instruments have been refurbished, installed and calibrated in developing countries, although some are not yet in regular operation. More support, such as via the General Trust Fund for Financing Activities on Research and Systematic Observations Relevant to the Vienna Convention, might remedy this.

Substantial progress has been made in improving the historical ozonesonde records within the Harmonization and Evaluation of Ground-based Instruments for Free-Tropospheric Ozone Measurements focus working group Ozonesonde Data Quality Assessment activity. Updated guidelines for global ozonesonde operations were published by the World Meteorological Organization (WMO) in 2021.³³

Steady progress has been made in terms of timely delivery of ozone and ozone-related data from ground-based stations and in the use of these data for validation of services such as the Copernicus Atmosphere Monitoring Service, as well as for satellite validation. These activities went hand-in-hand with better characterization of uncertainties in all data sources, with improved practices and standards, resulting in improved data quality (e.g., the Assessment of Standard Operating Procedures for Ozonesondes 2.0 report; the Jülich Ozone Sonde Intercomparison Experiment campaign and publications; the Network for the Detection of Atmospheric Composition Change (NDACC) rapid delivery data for Copernicus and operational satellite validation; the Aerosol, Clouds and Trace Gases Research Infrastructure; European Brewer Network (EUBREWNET) error characterization analyses; linking of the EUBREWNET data with the World Ozone and Ultraviolet Radiation Data Centre). Further progress in these directions is encouraged.

New instrument types such as Pandora and base transceiver station spectrometers are being tested and integrated into ground-based networks, participating in intercomparison campaigns with established instruments like Dobson and Brewer spectrometers and UV-visible differential optical absorption spectrometers (DOAS). Further integration of the new instruments within established global network for long-time comparison is encouraged.

New long-term total ozone and ozone profiles from satellite observations have been made available, including both zonal and gridded data. Ozone trends from these global records were used in the most recent WMO ozone assessment.

Ozone observations uncovered deficiencies in the general circulation models that capture geographical distribution of the decline in low stratospheric ozone, pointing to the need for improved understanding of BDC processes and how they are represented in the models.

³³ WMO. *Ozonesonde Measurement Principles and Best Operational Practices – ASOPOS 2.0 (Assessment of Standard Operating Procedures for Ozonesondes)* (GAW Report No. 268). (Geneva, 2021).

B. Key systematic observations recommendations arising from the twelfth meeting of the Ozone Research Managers

The recommendations are as follows:

- (a) The Ozone Research Managers strongly propose that the funding for the General Trust Fund for Financing Activities on Research and Systematic Observations Relevant to the Vienna Convention be substantially increased. Increased resources should be used to support the continued operation of ground-based stations, especially stations that produce long-term records of ozone, trace gases and UV in undersampled areas such as Central America, South America, Africa and Asia.
- (b) The decrease in the number of stations and observations, most critical in the tropics as well as in polar areas and the Southern Hemisphere, including profile measurements, is endangering the independent monitoring of trends and the capturing of unexpected events, and has already started affecting our ability to validate satellite data records in key areas and altitude ranges. Special encouragement of national science agencies, meteorological agencies and other institutions is needed from the parties and the WMO Global Atmosphere Watch (GAW) programme to assure continued and high-quality measurements and to support data processing and regular reprocessing as needs arise.
- (c) Strengthen regular, long-term monitoring where scientific needs are clearly identified. Key regions are those where troposphere-stratosphere exchange occurs, such as monsoon regions, Southeast Asia, the maritime continent and mountainous regions (e.g., the Andes, the Himalayas and Central Asia), and the tropical region for accurate detection of BDC changes and other transport phenomena.
- (d) Continue to expand, where necessary, variables for qualifying important connections between large-scale circulation and changes in ozone, climate and atmospheric transport. In particular, the expected changes in the global meridional BDC and events like the breakup of the quasi-biennial oscillation require appropriate temperature, winds and trace-gas profiles, especially of dynamical tracers like N₂O and sulfur hexafluoride, as well as ozone, aerosols and water vapour. Observations are particularly needed for the analysis and improvement of the BDC derived from data assimilation systems. This should include cost-effective instrumentation, such as AirCore.
- (e) The maintenance of total ozone column measurements using Brewer and Dobson spectrometers is crucial to ensure the stability of the Global Ozone Observing System, including satellites. For this purpose, national agencies should work together with the manufacturers of Brewer instruments. In parallel, new instruments should be developed for future operation (see subparagraph (f) below). It is recommended that training and twinning activities in connection with Brewer and Dobson instruments be optimized to ensure the sustainability of long-term measurements, especially in undersampled regions. In addition, replacement parts could potentially be partly funded under the General Trust Fund for Financing Activities on Research and Systematic Observations Relevant to the Vienna Convention and distribution could be supported by regional calibration centres.

- (f) Continue the evaluation and accelerate implementation of new and cost-effective instruments with a view to harmonizing global monitoring networks for ozone, as well as standardizing data processing. Examples of networks include EUBREWNET, Système d'Analyse par Observations Zénithales (SAOZ – Zenith Observation Analysis System) and Pandonia, as well as networks of base transceiver stations and multi-axis differential optical absorption spectroscopy UV-visible spectrometer instruments. Key stations covering different latitudes and various climatic conditions should be identified for the transition from older to newer instrumentation, as well as integration of new measurements into existing global networks and their long-term validation. In addition, the Ozone Research Managers recommend that national agencies in developed countries be encouraged to donate “retired” instruments for refurbishment and redeployment by the General Trust Fund for Financing Activities on Research and Systematic Observations Relevant to the Vienna Convention to developing countries and countries with economies in transition.
- (g) Maintain ozonesonde observations and make sonde data publicly available. Ozonesondes are one of the pillars of the measurements of stratospheric ozone. Strive to increase the number of ozonesonde launches and stations in undersampled regions. In addition, maintain and expand systematic observations of ozone and related trace gases in the UTLS region by aircraft.
- (h) The continuation of limb emission and infrared solar occultation observations from space remains critical. Such observations are needed to maintain the global vertical profiles of ozone and many ozone and climate-related trace gases that are essential to an understanding of why ozone is changing as observed. There is now an urgent need to extend such observations until technical limits are reached. This is important for ensuring data continuity and increasing the possibility of data overlap with the potential new mission architectures that are now being considered for development by various space agencies. Without such observations, assimilated data and related services for policymakers will degrade, the detection and interpretation of changes in atmospheric circulation and altitude-dependent abundances of gases impacting ozone will be hampered, and events like the severe 2011 and 2020 Arctic ozone depletion will not be properly understood.
- (i) Increase efforts to monitor stratospheric vertical profiles of ODS and source gases, especially N₂O, CH₄ and water vapour, to understand their changing fluxes to this region and better assess their impact. Even as most concentrations of ODS are declining, others are becoming more important for their impact on the ozone layer and climate change. With several key satellite observations ending, balloon (and ground-based) observations should be started to provide additional continuity up to the middle stratosphere. This will be crucial for the transition to the next satellite missions.
- (j) Observe profiles of concentrations, size distributions and chemical composition of stratospheric aerosols and polar stratospheric clouds, both from ground-based and satellite-based instruments. Such profiles are crucial for properly simulating the stratospheric ozone layer. Natural and human-influenced processes that contribute to the stratospheric aerosol, along with volcanos and pyro-convection, need to be monitored, and their evolution understood.

- (k) Ensure trustworthiness of measurement data via global and regional calibration facilities, quality assurance systems and standard processing. This includes full support for the WMO GAW programmes and endorsement of the programmes by the parties to the Vienna Convention, which requires active collaboration between data providers, data archives and data users. Storing data in a public archive based on the principle of making the data findable, accessible, interoperable and reusable (FAIR) is strongly encouraged. An effort should be made to render surface UV and ozone data available in near-real time.
- (l) Implement the new, agreed upon, more accurate UV ozone absorption cross-sections for retrieving stratospheric ozone data from UV measurements. Ensure that the transition will lead to a fully traceable connection between existing and new data, which explicitly includes past data reanalysis. Furthermore, this requires updating operational software, data processing and versioning of the data for archival purposes. It will also require accounting for ozone layer temperatures and recalculation of the historic records for archiving at the World Ozone and Ultraviolet Radiation Data Centre under the guidance of the WMO GAW scientific advisory groups on UV radiation and ozone.
- (m) Observe concentration profiles, size distributions and composition of stratospheric aerosols from volcanoes, wildfires, rockets and lofted pollution, and continue the observation of aerosols using ground-based lidar and extend measurements to new balloon-borne optical particle spectrometers, replacing the backscatter-sonde measurements.

III. Gaps in the global coverage of atmospheric monitoring of controlled substances, and options to enhance such monitoring

Recognizing the importance of the issues raised in the white paper entitled "Closing the gaps in top-down regional emissions quantification: needs and action plan",³⁴ prepared in 2020 by the Scientific Assessment Panel and experts in monitoring of substances controlled under the Montreal Protocol, the Conference of the Parties, at its twelfth meeting, in 2021, endorsed the recommendations arising from the eleventh meeting of the Ozone Research Managers on gaps in the global coverage of atmospheric monitoring of controlled substances and options to enhance such monitoring. Further consideration of the issue by the Thirty-Third Meeting of the Parties and the Thirty-Fifth Meeting of the Parties led to the adoption of decision XXXIII/4 in 2021 and decision XXXV/14 in 2023 on enhancing the global and regional atmospheric monitoring of controlled substances. In those decisions, the parties to the Montreal Protocol sought further information on the costs associated with enhancing atmospheric monitoring, potential monitoring station locations and options for sustainable funding for the establishment of new regional monitoring capacities.

The Ozone Research Managers:

- (a) Commend China for starting an extensive monitoring programme in its region;
- (b) Recognize the progress that the pilot project in Bangladesh funded by the European Union and supported by the Government of the United Kingdom has made since 2020 in enhancing the observational capacity for halocarbon measurements in South Asia;

³⁴ <https://ozone.unep.org/system/files/documents/ORM11-II-4E.pdf>

- (c) Also recognize recent efforts to add measurements of controlled and related gases in other locations;
- (d) Note that the value of in-kind contributions for greatly reducing costs and accelerating the implementation associated with adding new observations to a measurement network was aptly demonstrated by the European-Union-funded pilot project with the commitment of the Government of Bangladesh;
- (e) Recognize that highly specialized instrumentation has become available for measuring gases controlled under the Montreal Protocol and related substances, some of which are present in the atmosphere at extremely low levels, and underscore the value of measures taken to ensure sustained, high-performance operations using established calibration scales;
- (f) Recognize that the white paper endorsed by the Ozone Research Managers at their eleventh meeting and the outcomes of that meeting continue to be highly relevant, setting an important goal for the parties and providing guidance for decisions by the parties and their individual actions for achieving it, including by providing elements for developing, where needed and in view of the availability of resources and timelines, stepwise approaches, such as starting with the identification of emissive regions not currently characterized by existing sampling and modelling to identify measurement locations that capture those emissions, followed by the possibility of survey-based flask sampling and possibly leading to more frequent measurements, including the installation of high-frequency measurement stations.

Key gaps in monitoring recommendations arising from the twelfth meeting of the Ozone Research Managers

The Ozone Research Managers,

- (a) Noting that the workshop on costs of atmospheric monitoring of gases controlled under the Montreal Protocol³⁵ was a good first step, recommend that the parties to the Vienna Convention consider assessing the number and locations of sites needed for additional measurements, and the data analyses tools (e.g., observing system simulation experiments and inverse modelling) needed to meet the current and future needs of the Montreal Protocol;
- (b) Recommend that the parties to the Vienna Convention and the Montreal Protocol work together with the Montreal Protocol's Scientific Assessment Panel and Technology and Economic Assessment Panel and the Ozone Research Managers to increase the number of measurement locations suitable for capturing a larger fraction of total global emissions of controlled and relevant substances, especially from undersampled regions of the world, such as Southeast Asia, South Asia, the Middle East, Africa, Eastern Europe and South America;
- (c) Endorse the findings of the workshop on costs of atmospheric monitoring of gases controlled under the Montreal Protocol, which delineated the options and costs associated with filling gaps in the observational network using a range of different approaches;

³⁵ https://ozone.unep.org/system/files/documents/Monitoring_Costs_Workshop_Outcomes.pdf

- (d) Realizing that the financing of new measurements could be achieved with a range of approaches, including cost-sharing, in-kind contributions and funds supplied by the parties through various mechanisms, recommend, as a matter of urgency, that parties to the Vienna Convention and the Montreal Protocol agree on funding regimes to sustain measurement activities. Before such a mechanism is operational, the General Trust Fund for Financing Activities on Research and Systematic Observations relevant to the Vienna Convention could be a viable mechanism for funding such activities, as identified by the Ozone Research Managers in consultation with the Montreal Protocol's Scientific Assessment Panel and Environmental Effects Assessment Panel (decision VC VI/2, para. 4) for the improvement of the observational network and relevant research. This trust fund mechanism could be viable if additional funds were available for such purposes.
- (e) Acknowledge the importance of contributions from all global and regional controlled substance monitoring programmes, and strongly recommends that they be supported in a sustained manner, including through effective cross-programme (e.g., greenhouse gas monitoring efforts) sharing and integration, as well as for calibration standards, data accessibility and emissions model development;
- (f) Recommend that only data that have been assessed and reviewed be considered suitable for providing the accurate emission information needed for decision support, and that parties to the Vienna Convention acknowledge the importance of data archiving and curation and open data access for use in producing decision support and research.

IV. Data archiving and stewardship

A. Key data archiving and stewardship achievements since the eleventh meeting of the Ozone Research Managers

1. Several data centres/data providers now ensure enhanced, more timely availability of ground-based, satellite and modelling data.
2. Central data processing systems are taken further in several monitoring networks, such as EUBREWNET, for selected NDACC-type data and Pandora data, within the framework of Aerosols, Clouds and Trace Gases Research Infrastructure and Fiducial Reference Measurements for Ground-Based DOAS Air-Quality Observations programmes.
3. Progress has been made on enhanced linkage among data centres and on metadata exchange.
4. Progress has been made on data publishing with an associated digital object identifier (DOI).
5. Data centres have made progress in providing data in several accepted standard formats and in providing different traceable data versions.

B. Key data archiving and stewardship recommendations arising from the twelfth meeting of the Ozone Research Managers

The recommendations are as follows:

- (a) Continue to encourage data providers and observation campaign managers to submit the data to established databases in a timely manner according to the applications. We recommend that central data portals (e.g., the WMO World Data Centres) provide visibility and linkage to the ensemble of ozone research-related data. This would enhance data discovery and thus the possibility of making better synergistic use of all the data, and would increase the effectiveness and appreciation of data acquisition efforts. We suggest that the WMO World Data Centres continue to foster enhanced coordination/collaboration between data centres on data formats, especially on the availability and interoperability of the metadata and data in their respective focus areas.
- (b) The Ozone Research Managers encourage the use of the instrument-based central processing systems, including for the storage of the raw data and metadata and calibration data. This will enhance reproducibility and traceability, facilitate reprocessing and improve uncertainty evaluation and data harmonization, as well as automated or timely data submission and use. The Ozone Research Managers emphasize the importance of including all metadata that are required for data use, attribution and discovery. The availability of metadata is also essential when data are converted to the standards of data centres (e.g., for converting profile data reporting from pressure to altitude grid). The requirements for metadata reporting (format and content) should be agreed in the respective communities. Global Climate Observing System recommendations on metadata should be considered.
- (c) The curation of data, metadata and processing algorithms, including historical data, is strongly encouraged. In particular, the curated data should include all metadata and ancillary data. Sufficient resources should be allocated for digitizing and curating historical data for ozone and related species as well as ancillary data (e.g., laboratory spectroscopic data, station information), where available, before the information and knowledge get lost, in order to include the data in modern database systems.
- (d) Data availability according to FAIR data principles is encouraged. This is supported by the assignment of a DOI and data license to the data sets. Data publishing with an associated DOI is encouraged to provide data to the scientific community and give recognition to scientists and the funding agencies providing the data. This may also offer a good solution for the archiving (including traceability) of model output or single data or versioning of data processing codes. An open data policy is recommended, albeit with the requirement to give appropriate credit and offer co-authorship for scientific publications to the data originator. It is important to ensure that such credit is given, as it is often taken as a key performance indicator. Data creators are encouraged to publish peer-reviewed publications about the datasets.
- (e) A user-friendly data format is recommended. A common data format and metadata standard facilitates the exploitation of data retrieved from different data centres. Several common data standards, such as the Network Common Data Form (NetCDF) or Generic Earth Observation Metadata Standard

Hierarchical Data Format (HDF), are used by Earth observation communities (e.g., the satellite data providers and the climate modelling community) and are supported by a number of tools for extracting and visualizing the data. It is most important that the formats enable a good structuring of the data and metadata; the “packaging” of data and metadata, whether NetCDF, HDF or something else, is less important, as there are many tools available to convert from one to the other. Data centres should make the data available in different standard formats or provide the appropriate conversion tools. Data centres should support the data providers for near-real-time or rapid delivery of the data. Satellite overpass data coincident with ground-based network stations should be readily available. Similar model datasets would be useful. Data centres need to be resourced to provide the above services to data providers and users.

V. Capacity-building

While capacity-building for ozone monitoring and research in developing countries and countries with economies in transition comes from the general commitments anchored in the Vienna Convention, it is in itself an essential component of truly successful ozone layer protection.

The atmosphere covers the globe and does not recognize national borders, thus requiring measurements with full global coverage for proper scientific understanding of ozone. To be full participants in the ozone protection regime that includes the Vienna Convention and the Montreal Protocol, all countries need to be partners in our ever-growing scientific understanding, and the global need is for all countries to make contributions to research efforts, particularly in the decades to come.

One of the main goals of capacity-building is the enhancement of ozone monitoring networks such as that of the GAW programme, and the creation of local scientific communities that contribute to global ozone science. This can be achieved through partnerships that exchange knowledge between the industrialized world and developing countries. The rapid advancement of modern communications technology brings new opportunities to establish and conduct such partnerships.

In paragraph 3 (d) of decision XII(II)/1 taken by the Conference of the Parties to the Vienna Convention in 2021, parties were encouraged to accord priority in particular to support for capacity-building activities in developing countries and countries with economies in transition through the continuation and expansion of regular calibration and intercomparison campaigns and through the provision of training and assistance to enable those parties to expand their scientific capacity and participate in ozone research activities, including assessment activities under the Montreal Protocol.

A. Key capacity-building achievements since the eleventh meeting of the Ozone Research Managers

Capacity-building has been/will be provided through the implementation of the following activities approved by the Advisory Committee of the General Trust Fund for Financing Activities on Research and Systematic Observations Relevant to the Vienna Convention:

1. Completed and ongoing activities

- (a) Kyrgyzstan: technical support, information exchange for atmospheric monitoring at the shore of the high mountain lake, Issyk-Kul, 22 January 2020–30 March 2024;
- (b) Comoros: project on the establishment of an ozone observatory in Comoros, 11 May 2021–30 April 2022;
- (c) Brazil: South American Brewer Spectrometer Network, Santa Maria, Brazil, 23 February–8 March 2024.

2. Planned activities

- (a) Belarus: relocation of Dobson No. 8 (formerly deployed in Spitzbergen, Norway) to Belarus;
- (b) Burkina Faso: acquisition of a ground-based ozone column measurement instrument;
- (c) Mexico: monitoring of solar ultraviolet radiation band “B” in Central America and the Caribbean.

In response to the Ozone Secretariat’s November 2023 call for proposals inviting all developing countries and countries with economies in transition to submit project proposals for support under the General Trust Fund for Financing Activities on Research and Systematic Observations Relevant to the Vienna Convention, as of the twelfth meeting of the Ozone Research Managers, 12 parties had submitted 15 proposals, as listed in the table below. Additional project proposals may continue to be submitted for consideration and evaluation by the Advisory Committee of the Trust Fund.

<i>No.</i>	<i>Party</i>	<i>Project proposal</i>
1	Burundi	Systematic observations of atmospheric composition over Bujumbura using a Pandora spectrophotometer
2	Chile	Renovation and maintenance of stations of the ultraviolet radiation network in Chile
3	Comoros	Monitoring and measurement of the total ozone column in the Union of the Comoros
4	Ecuador	Advanced environmental monitoring: developing a real-time UV radiation mapping system for Equatorial Andean regions
		(a) Monitoring of the dynamics of ozone, ozone-depleting substances, UV radiation and air pollutants
5	Indonesia	(b) Observation of vertical distribution of ozone-depleting substances and UV radiation in Indonesia by using an aerial drone as a carrier for miniaturized samplers and portable sensors
6	Morocco	Ground-based total column observation in Africa using Pandora spectrometer
7	Mozambique	Restoration of the solar radiation and ozone measurement network in Mozambique
8	Nigeria	Long-term monitoring of anthropogenic contribution to total column ozone in two diverse climatic regions of Nigeria
9	Rwanda	Enhancing data quality in the total ozone network: a workshop initiative in Rwanda
10	Somalia	Strengthening ozone monitoring and capacity-building in Somalia
11	Uganda	Activities on research and systematic observations relevant to the Vienna Convention
		(a) Monitor column ozone and ozone profiles in the Bolivarian Republic of Venezuela, implemented by the Ministry of People Power for Eco-socialism
12	Venezuela (Bolivarian Republic of)	(b) Training plan for the internal control of refrigerant gases, aimed at officials from the Ministry of People's Power for Eco-socialism
		(c) Plan to raise awareness of the safe handling of fluorinated refrigerant gases, considered to be substances with high ozone depletion and global warming potential, in the commercial sector (supermarkets)

B. Key capacity-building recommendations arising from the twelfth meeting of the Ozone Research Managers

The recommendations are as follows:

- (a) General Trust Fund for Financing Activities on Research and Systematic Observations relevant to the Vienna Convention is the mechanism specifically established by the parties to enable relevant capacity-building activities, and it must continue to be supported. While actions taken by individual agencies are always welcome and have proved beneficial, the Trust Fund is the global means by which all developing countries can receive support and the global ozone monitoring system can be enhanced; however, the number of contributions received to date has limited the Trust Fund's impact. Expansion of funding would

enable deserving activities to be properly supported, leading to a lasting impact and the development of human potential. The Advisory Committee of the Trust Fund has developed a long-term strategy and short-term action plan for the Trust Fund. The following two recommendations require continued support of the Trust Fund:

- (i) Maintain the quality of the global ozone-observing system through the continuation and expansion of regular calibration and intercomparison campaigns. The quality of the data from the global ozone-observing networks depends on such exercises. Calibration and intercomparison campaigns also include a large transfer of knowledge and development of true partnership in science production between experts in developed and developing countries and countries with economies in transition. Offering instructional courses and workshops alongside these campaigns would provide an ideal venue for building awareness of Trust Fund opportunities, training local operators and involving the local community for capacity-building, including on scientific matters. Several ground-based total column ozone instrument (e.g., Brewer and Dobson) intercomparison activities further indicate the success of such endeavours. Given the declining number of observations in the tropics and other locations related to the loss of staff and resources (decline in agency funding, instrument repurposing, retirement), continuity planning should be increased and early-career scientists recruited.
 - (ii) Provide ongoing training opportunities for local station operators in developing and developed countries. The experience such operators gain from training, combined with valuable local knowledge, will facilitate the training of others within their countries. The participants at the eleventh meeting of the Ozone Research Managers expressed the need for more training on basic measurement techniques, data handling and analysis methods. They also expressed the desire to lower the barriers for data submission by providing training on data processing techniques and submission to data archives. Such training could be supplemented with online materials, videos, software tools and real-time communication with trainers. Virtual training sessions should also be considered, as they greatly reducing the cost of such activities. WMO can play a role in posting and providing access to the training resources for instrument operators in developing countries. Long-term support through “twinning” and having specific contact points with regional experts is essential.
- (b) Assist and encourage developing countries and countries with economies in transition, even those with limited resources, to expand their scientific capacity in order to allow them to participate actively in ozone research and assessment activities under the Montreal Protocol. Identification of points of contact and relevant stakeholders in developing countries is key to successful implementation of scientific research training activities. Participants in the twelfth meeting of the Ozone Research Managers noted training opportunities that had been successful in enabling participants from developing countries to leverage ground-based instrumentation and satellite data for scientific research.
 - (c) WMO and the Ozone Secretariat should facilitate bridging the gap between the relevant monitoring and research communities at the international level. Ozone focal points, in collaboration with the Ozone Research Managers, should improve

coordination at the national level to enhance cooperation among the relevant national entities (ministries, space agencies, departments and academia) to ensure proper coordination and enhance synergies.

- (d) Increase capacity-building activities by finding alternate funding sources (e.g., manufacturers, other private sector entities) and helping to support development activities. Relationships should be developed with local and regional organizations to foster the development of ozone measurement programmes.
- (e) Encourage true partnership in science among researchers in developing and developed countries. Provide fellowships to support the scientific development of individuals from developing countries, particularly students and early-career scientists, who are a critical link and will help improve the level of engagement and understanding in their respective countries. Promote creation of subregional hubs for networking by ozone-related researchers to develop research, observations and knowledge transfer. Student exchanges and knowledge transfer between developed and developing countries (twinning) are vital to building such relationships. It is also suggested that ozone focal points liaise with academia or relevant institutions from developing countries and relevant government bodies to promote stratospheric ozone-related majors in atmospheric sciences and propose consideration of the development of government support schemes to ensure a sufficient professional workforce in the future. All parties should be encouraged to use the existing resources and material available on the Ozone Secretariat website³⁶ (e.g., 20 Questions and Answers under the "Ozone and You" website tab).
- (f) The Ozone Secretariat and the OzonAction programme of the United Nations Environment Programme, through its regional networks of national ozone officers, could assist the national ozone officers in the development and implementation of monitoring and research activities, particularly those that are relevant to Montreal Protocol compliance.

CLOSURE OF THE MEETING

³⁶ <https://ozone.unep.org/>

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**WMO/UNITED NATIONS ENVIRONMENT PROGRAMME
12TH MEETING OF THE OZONE RESEARCH MANAGERS OF THE PARTIES TO THE
VIENNA CONVENTION FOR THE PROTECTION OF THE OZONE LAYER**

Annex 1: List of participants

Annex 2: Final agenda

Annex 3: Abbreviations and chemical nomenclature

ANNEX 1

WMO/UNITED NATIONS ENVIRONMENT PROGRAMME 12TH MEETING OF THE OZONE RESEARCH MANAGERS OF THE PARTIES TO THE VIENNA CONVENTION FOR THE PROTECTION OF THE OZONE LAYER

24–26 April 2024

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⁵ CNRS: Centre national de la recherche scientifique

⁶ DWD: Deutscher Wetterdienst

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¹² CIAI: Centro de Investigación Atmosférica de Izaña

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¹⁴ EMPA: Eidgenössische Materialprüfungs- und Forschungsanstalt

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Ms Lucy Carpenter

¹⁵ DLR: Deutsches Zentrum für Luft- und Raumfahrt e.V.

¹⁶ KMI-IRM: Koninklijk Meteorologisch Instituut van België/Royal Météorologique de Belgique

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ANNEX 2

**WMO/UNITED NATIONS ENVIRONMENT PROGRAMME
12TH MEETING OF THE OZONE RESEARCH MANAGERS
OF THE PARTIES TO THE VIENNA CONVENTION FOR THE
PROTECTION OF THE OZONE LAYER
24–26 April 2024**

FINAL AGENDA

24 April (Wednesday)

- 09:00 – 09:45 Opening of the Meeting
- Opening statement, *Meg Seki, Executive Secretary, Ozone Secretariat*
 - Welcome statement, *Paolo Laj, World Meteorological Organization (WMO)*
 - The 2022 WMO/UNEP Scientific Assessment of Ozone Depletion, *David Fahey and Bonfils Safari, Co-Chairs of the Scientific Assessment Panel (SAP)*
 - Overview of the interface between the Scientific Assessment, the Ozone Research Managers (ORM) recommendations and the resultant decisions of the twelfth meeting of the Conference of the Parties to the Vienna Convention, *Hector Estevez and Kenneth Jucks, ORM11 Co-Chairs*

09:45 – 09:55 Election of the Co-Chairs of the 12th meeting of the ORM (ORM12)

09:55 – 10:00 Adoption of the ORM12 agenda

Session 1: Issues related to the General Trust Fund for Research and Systematic Observations

- 10:00 – 10:30 Work under the Trust Fund
- The status of the Trust Fund, *Sophia Mylona, Ozone Secretariat*
 - Report on activities under the Trust Fund, *John Rimmer, WMO*
 - Report of the Advisory Committee of the Trust Fund, *Sophie Godin-Beekmann, Advisory Committee Chair*
- 10:30 – 10:50 Discussion
- 10:50 – 11:10 Clarification of the tasks and roles of discussion leaders, rapporteurs and experts in the breakout groups to frame recommendations on: Research needs; Systematic observations; Gaps in the global coverage of atmospheric monitoring of controlled substances and options to enhance such monitoring; Data archiving and stewardship; Capacity building.
- 11:10 – 11:30 *Coffee/tea break*

Session 2: The state of the ozone layer and factors impacting the speed of its recovery

- 11:30 – 11:50 Updates on the state of the ozone layer, *Wolfgang Steinbrecht, German Meteorological Office (DWD)*
- 11:50 – 12:10 Benefits of the Montreal Protocol: effects on climate, UV radiation, and stratospheric ozone, *Janet Bornman, Environmental Effects Assessment Panel (EEAP) Co-Chair*
- 12:10 – 12:30 Emerging issues of interest to the parties, *Lucy Carpenter, SAP Co-Chair and Bella Maranion, Technology and Economic Assessment Panel (TEAP) Co-Chair*
- 12:30 – 14:00 *Lunch*

Session 3: Interactions between ozone layer depletion, climate change and related emerging issues

- 14:00 – 14:20 Links between stratospheric ozone and climate, *Amanda Maycock, University of Leeds, United Kingdom*
- 14:20 – 14:40 Trends of hydrochlorofluorocarbons (HCFCs) and hydrofluorocarbons (HFCs) controlled under the Montreal Protocol and other substances that affect the ozone layer and climate, *Guus Velders, Dutch National Institute for Public Health and the Environment (RIVM)*
- 14:40 – 15:00 Stratospheric aerosol injection and the ozone layer, *David Fahey, National Oceanic and Atmospheric Administration (NOAA)*
- 15:00 – 15:30 Discussion

Session 4: International monitoring programmes for ozone and UV

- 15:30 – 15:50 The International Ozone Commission (IO₃C), *Irina Petropavlovskikh, IO₃C*
- 15:50 – 16:10 The WMO Global Atmosphere Watch Ozone Observing System, *Matt Tully, Chair of the WMO Scientific Advisory Committee (SAG) on Ozone and UV radiation*
- 16:10 – 16:30 The Network for the Detection of Atmospheric Composition Change (NDACC), *Martine De Mazière, Royal Belgian Institute for Space Aeronomy (BIRA-IASB)*
- 16:30 – 16:50 *Coffee/tea break*
- 16:50 – 17:10 The Brewer Networks and their future, *Alberto Redondas, Meteorological State Agency (AEMET) and John Rimmer, WMO*
- 17:10 – 17:30 International ozonesonde activities, *Roeland Van Malderen, Royal Meteorological Institute of Belgium*

- 17:30 – 17:50 Atmospheric Processes And their Role in Climate (APARC), *Michaela Hegglin, Institute of Energy and Climate Research, Germany*
- 17:50 – 18:10 The World Ozone and Ultraviolet Radiation Data Centre (WOUDC) - Data reporting and archiving, *Sum Chi Lee, Environment and Climate Change Canada*
- 18:10 – 18:30 Discussion
- 18:30 – 20:00 Cocktail Reception (WMO Attic, 9th floor)**

25 April (Thursday)

Session 5: International monitoring programmes on substances controlled by the Montreal Protocol

- 09:00 – 09:20 Ground-based networks for measuring ozone- and climate-related trace gases and current state of the atmosphere, *Stephen Montzka, NOAA*
- 09:20 – 09:40 Gaps in the global coverage of atmospheric monitoring of controlled substances and options on ways to enhance such monitoring, *Paul Newman, NASA/A.R. Ravishankara, Colorado State University/Ray Weiss, Scripps Institution of Oceanography*
- 09:40 – 10:00 Discussion

Session 6: Satellite research and monitoring

- 10:00 – 11:00 Ozone layer and climate observations from space: Status of activities and challenges ahead
- North American Satellite Programmes: National Aeronautics and Space Administration (NASA), NOAA, Canadian Space Agency (CSA) and Other Agencies, *Kenneth Jucks, NASA and Marcus Dejmek, CSA*
 - European Space Agency (ESA) Activities, *Michael Eisinger, ESA*
 - The development and application of satellite remote sensing for total ozone column in China, *Pengfei Ma, Center for Satellite Application, Ministry of Environment and Ecology of China*
 - CEOS AC-VC¹ ozone harmonization projects, *Diego Loyola, German Aerospace Centre (DLR)*
- 11:00 – 11:15 Summary of the key issues in space-based measurements: Identification of future needs and opportunities, *Jean-Christopher Lambert, BIRA-IASB*
- 11:15 – 11:40 Discussion

¹ CEOS AC-VC: Committee on Earth Observation Satellites, Atmospheric Composition Virtual Constellation

Session 7: National and regional reports on ozone research and monitoring

- 11:40 – 12:00 **Region 1:** Africa, *Bonfils Safari, University of Rwanda*
- 12:00 – 12:20 **Region 2:** Asia, *Toshinori Aoyagi, Japan Meteorological Agency (JMA)*
- 12:20 – 12:40 **Region 3:** South America, *Damaris Kirsch Pinheiro, Federal University of Santa Maria, Brazil*
- 12:40 – 14:00 Lunch
- 14:00 – 15:00 **Region 4:** North America, Central America, and the Caribbean
- USA, *Kenneth Jucks, NASA, and Stephen Montzka, NOAA*
 - Canada, *Sum Chi Lee, Environment and Climate Change Canada*
 - Central America, Mexico and the Caribbean, *Hector R Estévez Pérez, Geophysics Institute, National Autonomous University of Mexico (IGUM – UNAM)*
- 15:00 – 15:20 **Region 5:** South-West Pacific, *Matt Tully, Australian Bureau of Meteorology*
- 15:20 – 15:40 **Polar regions**
- Antarctica and the Arctic, *Thomas McElroy, York University, Canada*
- 15:40 – 16:00 *Coffee/tea break*
- 16:00 – 17:00 **Region 6:** Europe
- European Union: Copernicus Atmosphere Monitoring Service, *Richard Engelen, European Centre for Medium-Range Weather Forecasts (ECMWF)*
 - Northern Europe, *Thomas Carlund, Swedish Meteorological and Hydrological Institute (SMHI)*
 - Western, Central and Eastern Europe, *Stefan Reimann, Swiss Federal Laboratories for Materials Science and Technology (EMPA)*
 - Southern Europe, *Alkis Bais, Aristotle University of Thessaloniki, Greece*
- 17:00 – 18:30 **Discussion and formation of breakout groups to frame initial recommendations**
- Review of research areas
 - Systematic observations of ozone
 - Gaps in the global coverage of atmospheric monitoring of controlled substances and options to enhance such monitoring
 - Data archiving and stewardship
 - Capacity building.

26 April (Friday)

Session 8: Discussion on and adoption of recommendations

- 09:00 – 09:45 **Research needs:** Presentation of initial draft by Lucy Carpenter and David Fahey, Ken Jucks, Rapporteur
- 09:45 – 10:30 **Systematic observations:** Presentation of initial draft by Sophie Godin-Beekmann and Damaris Kirsch Pinheiro Stefan Reimann, Rapporteur
- 10:30 – 11:15 **Gaps in the global coverage of atmospheric monitoring of controlled substances and options to enhance such monitoring:** Presentation of initial draft by A.R. Ravishankara and Ray Weiss Stephen Montzka, Rapporteur
- 11:15 – 11:30 *Coffee/tea break*
- 11:30 – 12:15 **Data archiving and stewardship:** Presentation of initial draft by Martine De Mazière and Tove Svendby Alberto Redondas and Victoria Sofieva, Rapporteurs
- 12:15 – 13:00 **Capacity building:** Presentation of initial draft by Presentation of initial draft by Samuel Paré and Sergio Moreno Irina Petropavlovskikh, Rapporteur
- 13:00 – 14:30 *Lunch*
- 14:30 – 17:00 Discussion and adoption of the recommendations
- 17:00 – 17:30 Other matters
- 17:30 **Closure of the meeting**
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ANNEX 3

WMO/UNITED NATIONS ENVIRONMENT PROGRAMME 12TH MEETING OF THE OZONE RESEARCH MANAGERS OF THE PARTIES TO THE VIENNA CONVENTION FOR THE PROTECTION OF THE OZONE LAYER

24–26 APRIL 2024

ABBREVIATIONS AND CHEMICAL NOMENCLATURE

ABBREVIATIONS

ACCLIP	Asian Summer Monsoon Chemical and Climate Impact Project
ACE	Atmospheric Chemistry Experiment
ACTRIS	Aerosol, Clouds and Trace Gases Research Infrastructure
AC-VC	Atmospheric Composition Virtual Constellation
AEMET	State Meteorological Agency, Spain ¹
AGAGE	Advanced Global Atmospheric Gases Experiment
ALTIUS	Atmospheric Limb Tracker for the Investigation of the Upcoming Stratosphere
AMAP	Arctic Monitoring and Assessment Programme
AOS	Atmosphere Observing System
APARC	Atmospheric Processes And their Role in Climate
API	application programming interface
AR6	Sixth Assessment Report
ASOPOS	Assessment of Standard Operating Procedures for Ozonesondes
BAMS	Bulletin of the American Meteorological Society
BASCOE	Belgian Assimilation System for Chemical Observations
BDC	Brewer–Dobson circulation
BESOS	Balloon Experiment on Standards for Ozone Sondes
BIRA-IASB	Royal Belgian Institute for Space Aeronomy ²
BOM	Australian Bureau of Meteorology
CAIRT	Changing-Atmosphere Infrared Tomography
CAMS	Copernicus Atmosphere Monitoring Service
CANDAC	Canadian Network for the Detection of Atmospheric Change

¹ AEMET: Agencia Estatal de Meteorología

² BIRA-IASB: Belgisch Instituut voor Ruimte-Aëronomie

CCI	Climate Change Initiative
CCL	Central Calibration Laboratory
CCMI	Chemistry–Climate Modelling Initiative
CEIT	country with economy in transition
CEOS	Committee on Earth Observation Satellites
CEPROCOR	Centre of Excellence in Processes and Products of Cordoba ³
CIAI	Izaña Atmospheric Research Center ⁴
CIRES	Cooperative Institute for Research in Environmental Sciences
CMAM	Canadian Middle Atmosphere Model
CNRS	National Centre for Scientific Research ⁵
CONICET	National Scientific and Technical Research Council, Argentina ⁶
COP1	1st meeting of the Conference of the Parties to the Vienna Convention for the Protection of the Ozone Layer, Helsinki, 26–28 April 1989
COP6	6th meeting of the Conference of the Parties to the Vienna Convention for the Protection of the Ozone Layer, Rome, 25–29 November 2002
COP10	10th meeting of the Conference of the Parties to the Vienna Convention for the Protection of the Ozone Layer, Paris, 17–21 November 2014
COP12	12th meeting of the Conference of the Parties to the Vienna Convention for the Protection of the Ozone Layer, online, 23–27 November 2020 and 25–29 October 2021
COP13–MOP36	combined 13th meeting of the Conference of the Parties to the Vienna Convention and the 36th Meeting of the Parties to the Montreal Protocol, Bangkok, 28 October–1 November 2024
COVID-19	coronavirus disease
CSA	Canadian Space Agency
CTBTO	Comprehensive Nuclear-Test-Ban Treaty Organization
DCOTSS	Dynamics and Chemistry of the Summer Stratosphere
DIAL	Differential Absorption Laser
DLR	German Aerospace Center ⁷

³ CEPROCOR: Centro de Excelencia en Procesos y Productos de Córdoba

⁴ CIAI: Centro de Investigación Atmosférica de Izaña

⁵ CNRS: Centre national de la recherche scientifique

⁶ CONICET: Consejo Nacional de Investigaciones Científicas y Técnicas

⁷ DLR: Deutsches Zentrum für Luft- und Raumfahrt e.V.

DNA	National Antarctic Directorate ⁸
DOAS	Differential Optical Absorption Spectroscopy
DOI	digital object identifier
DQ	Atmospheric Environment Monitoring Satellite
DWD	German Weather Service ⁹
ECC	electrochemical concentration cell
ECCC	Environment and Climate Change Canada
ECMWF	European Centre for Medium-Range Weather Forecasts
ECS	early career scientist
EEAP	Environmental Effects Assessment Panel
EESC	equivalent effective stratospheric chlorine
EMI-NL	Environmental Trace Gases Monitoring Instrument with Nadir and Limb modes
EMPA	Swiss Federal Laboratories for Materials Science and Technology ¹⁰
ERA5	European Centre for Medium-Range Weather Forecasts Reanalysis v5
ERF	effective radiative forcing
ESA	European Space Agency
ET-ACMQ	WMO Expert Team on Atmospheric Composition Measurement Quality
EUBREWNET	European Brewer Network
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites
FAIR	findable, accessible, interoperable and reusable
FMI	Finnish Meteorological Institute
FRM	Fiducial Reference Measurement
FRM4DOAS	Fiducial Reference Measurements for Ground-Based DOAS Air-Quality Observations
FSTOC	Fire Suppression Technical Options Committee
FTIR	Fourier Transform Infrared
FTOC	Flexible and Rigid Foams Technical Options Committee
FTS	Fourier Transform Spectrometer

⁸ DNA: Dirección Nacional Antártica

⁹ DWD: Deutscher Wetterdienst

¹⁰ EMPA: Eidgenössische Materialprüfungs- und Forschungsanstalt

FY-3	FengYun-3
FZJ	Forzungszentrum Jülich
GAW	Global Atmosphere Watch
GEMS	Geostationary Environment Monitoring Spectrometer
GEOMS	Generic Earth Observation Metadata Standard
GF-5	Gaofen-5
GGGW	Global Greenhouse Gas Watch
GHG	greenhouse gas
GOME	Global Ozone Monitoring Experiment
GO3OS	Global Ozone Observing System
GTO-ECV	Global Ozone Monitoring Experiment-type Total Ozone Essential Climate Variable
GWP	global warming potential
HDF	Hierarchical Data Format
HEGIFTOM	Harmonization and Evaluation of Ground-based Instruments for Free-Tropospheric Ozone Measurements
IAA	Argentine Antarctic Institute ¹¹
IAMAS	International Association of Meteorology and Atmospheric Sciences
IASI-NG	Infrared Atmospheric Sounding Interferometer-Next Generation
ICOS	Integrated Carbon Observation System
IGAC	International Global Atmospheric Chemistry
IGUM	Institute of Geophysics, Michoacán Unit ¹²
IMN	National Meteorological Institute of Costa Rica ¹³
INPE	Brazilian National Institute for Space Research ¹⁴
INTA	National Institute for Aerospace Technology, Spain ¹⁵
IO ₃ C	International Ozone Commission
IPCC	Intergovernmental Panel on Climate Change
IPO	International Project Office

¹¹ IAA: Instituto Antártico Argentino

¹² IGUM: Instituto de Geofísica, Unidad Michoacán

¹³ IMN: Instituto Meteorológico Nacional de Costa Rica

¹⁴ INPE: Instituto Nacional de Pesquisas Espaciais

¹⁵ INTA: Instituto Nacional de Técnica Aeroespacial

ISS	International Space Station
IUGG	International Union of Geodesy and Geophysics
IZO	Izaña Atmospheric Observatory ¹⁶
JMA	Japan Meteorological Agency
JOSIE	Jülich Ozone Sonde Intercomparison Experiment
JPSS	Joint Polar Satellite System
KMI-IRM	Royal Meteorological Institute of Belgium ¹⁷
KNMI	Royal Netherlands Meteorological Institute ¹⁸
LaRC	Langley Research Center
LEO	low Earth orbit
LIDAR	light detection and ranging
LOTUS	Long-term Ozone Trends and Uncertainties in the Stratosphere
MAESTRO	Measurements of Aerosol Extinction in the Stratosphere and Troposphere Retrieved by Occultation
MAX	multi-axis
MBTOC	Methyl Bromide Technical Options Committee
MCTOC	Medical and Chemicals Technical Options Committee
MIT	Massachusetts Institute of Technology
MLO	Mauna Loa Observatory
MLS	Microwave Limb Sounder
MOP35	35th Meeting of the Parties to the Montreal Protocol on Substances that Deplete the Ozone Layer, Nairobi, 23–27 October 2023
NASA	National Aeronautics and Space Administration
NDACC	Network for the Detection of Atmospheric Composition Change, formerly the Network for Detection of Stratospheric Change (NDSC)
NetCDF	Network Common Data Form
NILU	Norwegian Institute for Air Research ¹⁹
NILU-UV	Norwegian Institute for Air Research irradiance meter
NOAA	National Oceanic and Atmospheric Administration

¹⁶ IZO: Centro de Investigación Atmosférica de Izaña

¹⁷ KMI-IRM: Koninklijk Meteorologisch Instituut van België/Royal Météorologique de Belgique

¹⁸ KNMI: Koninklijk Nederlands Meteorologisch Instituut

¹⁹ NILU: Norsk Institutt for Luftforskning

OCTAV-UTLS	Observed Composition Trends and Variability in the Upper Troposphere and Lower Stratosphere
ODP	ozone depletion potential
ODS	ozone-depleting substance
OMI	Ozone Monitoring Instrument
OMPS	Ozone Mapping and Profiler Suite
OMPS-LP	Ozone Mapping Profiler Suite Limb Profiler
OMS-limb	Ozone Monitoring Suite limb scanning unit
ORM	Ozone Research Managers
ORM11	11th Meeting of the Ozone Research Managers of the parties to the Vienna Convention for the Protection of the Ozone Layer, online, 8–10 July 2020 and 19–23 July 2021
ORM12	12th Meeting of the Ozone Research Managers of the parties to the Vienna Convention for the Protection of the Ozone Layer, Geneva, 24–26 April 2024
OSIRIS	Optical Spectrograph and Infrared Imaging System
OSSE	Observing System Simulation Experiment
O3S-DQA	Ozonesonde Data Quality Assessment
PAR	photosynthetically active radiation
PEARL	Polar Environment Atmospheric Research Laboratory
PFAS	perfluoroalkyl and polyfluoroalkyl substance
PYREX	Pyrocumulonimbus Experiment
RBCC-E	Regional Brewer Calibration Centre-Europe
RCC III	WMO South American Regional Calibration Centre
RIVM	National Institute for Public Health and the Environment, Netherlands (Kingdom of the) ²⁰
RTOC	Refrigeration, Air Conditioning and Heat Pumps Technical Options Committee
SABRE	Stratospheric Aerosol processes, Budget and Radiative Effects
SAG	Scientific Advisory Group
SAGE-II	Stratospheric Aerosol and Gas Experiment II
SAGE-III	Stratospheric Aerosol and Gas Experiment III

²⁰ RIVM: Rijksinstituut voor Volksgezondheid en Milieu

SAI	stratospheric aerosol injection
SAOZ	Zenith Observation Analysis System ²¹
SAP	Scientific Assessment Panel
SCIAMACHY	Scanning Imaging Absorption Spectrometer for Atmospheric Cartography
SCISAT	Scientific Satellite
SCISAT-1	Scientific Satellite 1
SDG	Sustainable Development Goal
SHADOZ	Southern Hemisphere Additional Ozonesondes
SIO	Scripps Institution of Oceanography
SMHI	Swedish Meteorological and Hydrological Institute
SMR	Sub-Millimeter Radiometer
SNPP	Suomi National Polar-orbiting Partnership
SOO	Stratospheric Aerosol and Gas Experiment II–Optical Spectrograph and Infrared Imaging System–Ozone Mapping Profiler Suite Limb Profiler
SOP	standard operating procedure
SOS	Stratospheric Aerosol and Gas Experiment II–Optical Spectrograph and Infrared Imaging System–Stratospheric Aerosol and Gas Experiment III
SPARC	Stratospheric Processes and their Role in Climate
SRM	solar radiation modification
SSM	Mexican Solarimetric Service ²²
TEAP	Technology and Economic Assessment Panel
TEMPO	Tropospheric Emissions: Monitoring of Pollution
TOAR-II	Tropospheric Ozone Assessment Report, Phase II
TOC	Technical Options Committee
UFSM	Federal University of Santa Maria ²³
UNAM	National Autonomous University of Mexico ²⁴
UNEP	United Nations Environment Programme

²¹ SAOZ: Système d'Analyse par Observation Zénithale

²² SSM: Servicio Solarimétrico Mexicano

²³ UFSM: Universidade Federal de Santa Maria

²⁴ UNAM: Universidad Nacional Autónoma de México

UNFCCC	United Nations Framework Convention on Climate Change
UTLS	upper troposphere and lower stratosphere
UV	ultraviolet
UVB	ultraviolet B radiation
UVE	ultraviolet E radiation
UV-vis	ultraviolet-visible
VSLs	very short-lived substance
WCCOS	World Calibration Centre for Ozonesondes
WCRP	World Climate Research Programme
WIS 2.0	WMO Information System 2.0
WOUDC	World Ozone and Ultraviolet Radiation Data Centre
WRF	Weather Research and Forecasting Model

CHEMICAL NOMENCLATURE

CCl ₄	carbon tetrachloride, also CTC
CFC	chlorofluorocarbon
CFC-11	trichlorofluoromethane
CFC-13	chlorotrifluoromethane
CFC-112a	tetrachloro-1,1-difluoroethane
CFC-113a	trichlorotrifluoroethane
CFC-114a	1,1-dichlorotetrafluoroethane
CFC-115	chloropentafluoroethane
CH ₂ Cl ₂	dichloromethane
CH ₄	methane
CO ₂	carbon dioxide
HCFC	hydrochlorofluorocarbon
HCFC-22	chlorodifluoromethane
HCFO	hydrochlorofluoroolefin
HCl	hydrogen chloride (hydrochloric acid)
HFC	hydrofluorocarbon
HFC-23	trifluoromethane

HFC-32	difluoromethane
HFC-125	pentafluoroethane
HFC-134a	1,1,1,2-tetrafluoroethane
HFC-143a	1,1,1-trifluoroethane
HFO	hydrofluoroolefin
HNO ₃	nitric acid
H ₂	hydrogen
NO ₂	nitrogen dioxide
N ₂ O	nitrous oxide
O ₃	ozone
SO ₂	sulfur dioxide
TFA	trifluoroacetic acid

For more information, please contact:

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