TWELFTH MEETING OF THE OZONE RESEARCH MANAGERS (ORM12)

24 to 26 April 2024, Geneva, Switzerland

SESSION 8: DISCUSSION ON AND ADOPTION OF THE 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 and David Fahey, SAP Co-Chairs; Rapporteur – Ken Jucks, SAP Co-Chair
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> Systematic Observations: Introduction by Sophie Godin-Beekmann, France, and Damaris Kirsch Pinheiro, Brazil; Rapporteur – Stefan Reimann, Switzerland
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> Gaps in the Global Coverage of Atmospheric Monitoring of Controlled Substances, and Options to Enhance Such Monitoring: Introduction by A. R. Ravishankara and Ray Weiss, USA; Rapporteur – Stephen Montzka, USA
>
> 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, USA

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

A. Research Needs

The Montreal Protocol on Substances that Deplete the Ozone Layer has successfully controlled the production and consumption of ozone-depleting substances (ODSs) 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 ODSs and climate change. Some of the highlights from the 2022 assessment report are outlined below.

- Observations show that the atmospheric abundances of both total tropospheric chlorine and total tropospheric bromine from long-lived ODSs 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, which is not yet understood. Reconciling this discrepancy remains key to ensuring a full understanding of ozone recovery.
- The recent identification of unexpected CFC-11 emissions led to scientific investigations across the assessment panels on science and technology and policy responses. The source region for at least half of these emissions was identified and substantial emissions reductions followed.
- Atmospheric observations continue to point to missing emission sources of CCl_4. Production of CCl_4 has increased in recent years due mainly to growing demand for feedstock use for production of HFCs, HFOs/HCFOs and perchloroethylene.
- Atmospheric observations indicate an increase or stabilization of the emissions of the relatively low-abundance 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.
- Atmospheric observations confirm that chlorinated very short-lived halogenated substances (VSLS), dominated by CH_2Cl_2, 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 DU of the annually averaged global total ozone column. Elimination of these emissions would rapidly reverse this depletion.
- 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.
- Global HFC-23 emissions derived from atmospheric observations are substantially higher than emissions derived from activity-based estimates since around 2014; efforts to understand this emissions gap are in progress.
- 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.
- 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.
- Knowledge of the effects of avoided UV radiation 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 by plants.

Key research needs recommendations arising from the 12th ORM:

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 in 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 (TCO) 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 (ORMs) throughout the globe. For example, increased variance in the timeseries of stratospheric ozone abundances at certain locations will make trend analysis more difficult, and more extreme events may present more challenging conditions to maintain 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 observations from ground-based, airborne, and space-based observations. Consistent modelling of these trends is also an essential element of the assessments.

   1.1. Continue advancing synthesized distributions and trends of stratospheric ozone, in collaboration with the observation networks and satellite data experts.

   1.2. Continue to improve modelling efforts to understand stratospheric ozone evolution based on the existing data sets and hence improve modelled projections of ozone. This is particularly true in the lower stratosphere where ozone abundances are controlled as much by transport as by photochemistry.

   1.3. 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.

   1.4. Assess the ozone recovery date and integrated ozone depletion (IOD) metrics and their relative strengths and weaknesses for both ozone and UV.

   1.5. Improve the understanding of trends and projections in stratospheric dynamics, for example, changes in Brewer-Dobson Circulation (BDC) and in hemispheric differences.

2) *Improve understanding of global emissions of ozone-depleting substances (ODSs) and related gases:*

   ODSs: 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 ODSs (including CFCs-13, 112a, 113a, 114a, 115, and CCl4). Some of these unexplained emissions are likely occurring as leaks of feedstocks or by-products, and the remainder is not understood.

   2.1. 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.

   2.2. Enhance monitoring of ongoing emissions at global and regional scales, especially in under sampled regions.

   2.3. Monitor Montreal Protocol compliance through continuation of time series data of ODSs and related gases.

   Feedstocks: The mass of ODSs used as feedstocks increased by 75% between 2009-2019. 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 article 5 countries. Uncertainty in the emissions from feedstock use associated with various processes limits our understanding of the impact on global emissions.

2.4. 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.

2.5. 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 (VSLSs) are not controlled under the Montreal Protocol and have lifetimes shorter than about 6 months. An increasing fraction of the total atmospheric ODS amount comes from anthropogenic chlorine containing VSLSs. While still a minor contribution (4%) to stratospheric chlorine, these compounds are still growing in the atmosphere and some new emerging VSLS, such as 1,2-dichloroethane, have been identified.

2.6. Assess the impact of industry-related emissions by sector of chlorinated VSLSs on stratospheric ozone and its long-term trends.

Nitrous oxide (N_2O) and hydrogen (H_2): Important concerns about 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 from 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 hydrogen (H_2) could arise in the decarbonization of the fossil fuel industry.

2.7. Evaluate updated scenarios of future emissions of N_2O and H_2 for potential changes in stratospheric ozone abundances.

3) *Hydrofluorocarbons (HFCs)/Hydrofluoroolefins (HFOs):*

The Kigali Amendment to the Montreal Protocol to phase down some HFCs is projected to limit surface warming due to HFCs to about 0.4 ºC by 2100 compared to a warming of 0.3–0.5 ºC expected without any control measures. In the near future, global emissions and atmospheric abundances of most HFCs will increase in response to HCFC phaseout actions. The use of low-GWP HFCs and HFOs will minimize the climate impact of the HCFC phaseout in addition to improvements in energy efficiency in HFC applications. The large differences in HFC bottom-up and top-down annual emissions are unexplained at present.

3.1. Compare observationally derived HFC emissions with bottom-up emissions to monitor the phasedown of HFCs under the Kigali amendment.

3.2. Evaluate the present and projected contributions of HFC/HFO emissions to climate forcing.

3.3. Verify emissions of ODSs and (non-CO2) GHGs for both the Montreal Protocol and UNFCCC by comparing bottom-up with top-down emission estimates.

3.4. Investigate the gap in reported and estimated HFC-23 emissions that include reports of substantial destruction amounts of HFC-23 released during HCFC-22 production.

4) *Trifluoroacetic acid (TFA):*

Trifluoroacetic acid (TFA) is a breakdown product in the atmosphere of some HFCs, HCFCs, HFOs, hydrochlorofluoroolefins (HCFOs) and fluoroketones. TFA formed in the atmosphere is rapidly deposited in precipitation and, on reaching the surface (soil or water), forms salts. 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 sufficiently low concentrations that are currently 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.

4.1. 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 which lead to TFA formation.

4.2. Broaden understanding of other sources and risks associated with TFA.

5) *Stratospheric ozone – Climate coupling:*

Human-induced stratospheric ozone depletion has impacted 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 [IPCC AR6 WGI Ch6]. Owing to incomplete observations, stratospheric ozone ERF estimates often rely on chemistry-climate model simulated 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:

5.1. Analyses which 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.

5.2. Calculation of accurate ERFs that are required for assessments of changes in climate as the abundances of radiatively active gases change.

5.3. Continuation of observations that are needed to better validate the reanalyses of the stratosphere, such as the CAMS or MERRA-2 products.

5.4. 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 (PSCs) as well as changes in wave driven dynamics. These processes will affect the ongoing recovery of ozone in the polar vortices.

5.5. Focused modelling studies 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 recent 2022 Hunga Tonga-Hunga Ha'apai eruption injected substantial amounts of sulfur and water vapour well into the lower stratosphere.

6.1. Conduct timely observations and interpretative studies of such exceptional events to improve the 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 which would reflect more sunlight to space. The 2022 SAP assessment report showed that stratospheric aerosol injection to limit temperature increases in the coming decades would likely deepen the Antarctic ozone hole and delay ozone recovery.

7.1. Evaluate the impact on ozone of future aircraft fleets, increases in space activities and climate intervention in the stratosphere by incorporating proposed scenarios into climate/chemistry models that include stratospheric chemistry and dynamics.

7.2. Improve the incorporation of stratospheric aerosol and gas processes related to these activities into stratospheric modelling of future ozone abundances and conduct laboratory studies to improve the characterization of these processes.

B. Systematic Observations

Presentations and discussions during ORM12 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. The verification of the expected ozone recovery must be accompanied by observations of key gases (ODSs, greenhouse gases, ozone column) and UV radiation for many decades and their connection to climate change.

Although the Montreal protocol has led to a steady decline in the ODSs, 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 sources of CFC-11 in eastern China has shown, even the verification of emissions of fully controlled substance is still a necessity. In fact, important gaps in the global representativity of global observation capacities still exist, which limits the ability to detect sources of these ODSs.

Furthermore, a period when gases other than ODSs (especially CO_2, N_2O, CH_4, and H_2O) have an influence on global stratospheric ozone changes, the future emissions of these gases 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 so as to provide for unambiguous analyses.

Monitoring also needs to be expanded to include important new species and parameters, e.g. emerging ODS replacements, short-lived halogenated chemicals (SLS and VSLS), and tracers for atmospheric circulation and other transport phenomena. Key measurement regions include the UTLS, 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 vertical and spatial sampling there is a growing concern for the end-life of satellites (e.g. Aura MLS) that have been tracking some of the ODSs, 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 the intensive use of the ground-based observations.

Key systematic observations achievements since the 11th ORM:

1) 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 (VCTF-RM) has played a large role in providing support to developing countries and countries with economies in transition (CEITs), especially for the ground-based global observation networks, including providing intercomparisons, refurbishing and shipping available Dobson/Brewers instruments and enabling ozone sondes, while encouraging the development/validation of other instruments.

2) Some Dobson and Brewer instruments have been refurbished, installed and calibrated in developing countries; however, some are not yet in regular operation. More support, such as via the VCTF-RM, might remedy this.

3) Substantial progress has been made in improving the historical ozone sonde records within the HEGIFTOM ozone sonde Data Quality activity. The Assessment of Standard Operating Procedures for Ozone Sondes (ASOPOS) 2.0 report: Updated Guidelines for Global Ozonesonde Operations has been published by WMO in 2021.

4) Progress has continuously been made in terms of timely delivery of ozone and related data from ground-based stations and in the use of these data for validation of services such as the Copernicus Atmosphere Monitoring Service (CAMS), 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, and have resulted in improved data quality (for example, ASOPOS 2.0; the Jülich Ozone Sonde Intercomparison Experiment (JOSIE) campaign and publications; Network for the Detection of Atmospheric Composition Change (NDACC) rapid delivery (RD) data to Copernicus and operational satellite validation; the Aerosol, Clouds and Trace Gases Research Infrastructure (ACTRIS); European Brewer Network (EUBREWNET) error characterization analyses; link of the EUBREWNET data with the World Ozone and Ultraviolet Radiation Data Centre (WOUDC)). Further progress in these directions is encouraged.

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

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

7) Ozone observations uncovered deficiencies in the GCM models to capture geographical distribution of the decline in low stratospheric ozone that point to the need for improvement of understanding of BDC processes, and how they are represented in the models.

Key systematic observations recommendations arising from the 12th ORM:

1) The twelfth meeting of the Ozone Research Managers strongly proposes that the funding for the VCTF-RM should be substantially increased. Increased resources should be used for supporting continuing ground-based stations, especially stations which produce long-term records of ozone, trace gases and UV in under sampled areas, such as Central America, South America, Africa and Asia.

2) The decrease in the number of stations and observations, most critical in the tropics, as well as in polar areas and Southern Hemisphere, including profile measurements, is endangering the independent monitoring of trends and the capturing of unexpected events, and has already started impacting our ability to validate satellite data records in key areas and altitude ranges. Special encouragement from the parties and WMO GAW to national science agencies, meteorological agencies and other institutions is needed to assure continued and high-quality measurements and to support the data processing and regular reprocessing as needs arise.

3) Strengthen regular, long-term monitoring where scientific needs are clearly identified. Key regions are those where troposphere-stratosphere exchange occur, such as monsoon regions, Southeast Asia, the maritime continent, and mountainous regions (e.g., Andes, Himalayas, and Central Asia) and in the tropical region for accurate detection of BDC changes and other transport phenomena.

4) Continue and expand, where necessary, variables for qualifying important connections between changes in ozone, climate and atmospheric transport, and large-scale circulation. In particular, the expected changes in the global meridional BDC and events like the breakup of the Quasi Biennial Oscillation (QBO), require appropriate temperature, winds and trace-gas profiles, especially of dynamical tracers like N_2O and SF_6, 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 air-core.

5) The maintenance of total ozone column measurements using Brewers 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 (6)). It is recommended to optimize training and twinning activities in connection to Brewer and Dobson instruments to ensure the sustainability long-term measurements, especially in under sampled regions. In

addition, replacement parts could be potentially partly funded under the General Trust Fund for Financing Activities on Research and Systematic Observations Relevant to the Vienna Convention (VCTF-RM) and the distribution could be supported by regional calibration centers.

6) Continue the evaluation and accelerate implementation of new and cost-effective instruments towards harmonizing global monitoring networks for ozone, as well as standard data processing. Examples of networks include EUBREWNET, SAOZ and Pandonia as well as networks of BTS, MAX-DOAS UV visible spectrometer instruments. Key stations covering different latitudes and various climatic conditions should be identified for the transition of older to newer instrumentation, the integration of new measurements into existing global networks, and their long-term validation. In addition, the twelfth meeting of the Ozone Research Managers recommends that national agencies in developed countries be encouraged to donate "retired" instruments for refurbishment and redeployment by VCTF-RM to developing countries and countries with economies in transition.

7) Maintain ozone sonde observations and make sonde data publicly available. Ozone sondes are one of the pillars of the measurements of stratospheric ozone. Strive to increase the number of ozone sonde launches and stations in under sampled regions. In addition, maintain and expand systematic observations of ozone and related trace gases in UTLS by aircrafts.

8) The continuation of limb emission and infrared solar occultation observations from space remains very critical. This is necessary to maintain global vertical profiles of ozone together with many ozone and climate-related trace gases that are essential to understand why ozone is changing as observed. There is now an urgent need to extend such observations until technical limits are reached. This is important to ensure data continuity and to increase 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.

9) Increase efforts to monitor stratospheric vertical profiles of ODSs and source gases, especially N_2O, CH_4 and water vapour, to understand their changing fluxes to this region and to better assess their impacts. As most of the concentrations of ODS are declining, others are becoming more important for their impacts 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 from one to the next satellite missions.

10) Observe profiles of concentrations, size distributions and chemical composition of stratospheric aerosols and PSCs, both from ground-based and satellite-based instruments. They 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.

11) 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 their endorsement 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, using the FAIR principle is strongly encouraged. An effort should be made to make surface UV and ozone data available in near-real time (NRT).

12) Implement the new, agreed upon, and 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. It will also require accounting for ozone layer temperatures and recalculation of the historic records for archival at WOUDC under the guidance of the WMO GAW UV and ozone scientific advisory groups.

13) Observe concentration profiles, size distributions, and composition of stratospheric aerosols from volcanoes, wildfires, rockets, and lofted pollution and continue the observation of aerosol using ground-based Lidars and extend measurements to new balloon-borne optical particle spectrometers replacing the backscatter-sonde measurements.

C. 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",[1] 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 ORM11 recommendations on gaps in the global coverage of atmospheric monitoring of controlled substances and options to enhance such monitoring. Further consideration of this issue by the 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, parties sought further information on costs estimates associated with enhancing atmospheric monitoring, potential monitoring station locations, and options for sustainable funding to establish new regional monitoring capacities.

The ORM:

1) Commends China for starting an extensive monitoring program in their region.

2) Recognizes the progress that the EU-funded and UK-supported pilot project in Bangladesh has made since 2020 in enhancing the observational capacity for halocarbon measurements in South Asia.

3) Also recognizes efforts to recently add measurements of controlled and related gases in other locations.

4) Notes 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 EU-funded pilot project with the commitment of Bangladesh.

5) Recognizes that highly specialized instrumentation has become available for measuring gases controlled under the Montreal Protocol and related substances, some

[1] https://ozone.unep.org/system/files/documents/ORM11-II-4E.pdf.

of which are present in the atmosphere at extremely low levels and underscores the value of measures taken to ensure sustained, high-performance operations with using established calibration scales.

6) Recognizes that the white paper, endorsed by the ORM during its 11th meeting, and its outcomes continue to be highly relevant, setting an important goal for the parties to achieve, and provides guidance for decisions by the parties and their individual actions for achieving them, including by providing elements for developing, where needed in view of the availability of resources and timelines, stepwise approaches, for example by 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 flasks sampling, and possibly leading to more frequent measurements including the installation of high-frequency measurements.

Key gaps in monitoring recommendations arising from the 12th ORM:

The ORM:

1) Noting that the “Workshop on Costs of Atmospheric Monitoring of gases Controlled under the Montreal Protocol”[2] is a good first step, the ORM recommends that the Parties consider assessing the number and locations for additional measurements, and data analyses tools (e.g., OSSEs and inverse modelling) needed to meet the current and future needs of the Montreal Protocol.

2) Recommends that the Parties work together with SAP, ORM and TEAP to increase the number of measurement locations suitable for capturing a larger fraction of total global emissions of controlled and relevant substances, especially from under-sampled regions of the world, such as Southeast Asia, South Asia, the Middle East, Africa, Eastern Europe, and South America.

3) Endorses the findings of the “Costs Workshop” that delineated the options and costs associated with filling gaps in the observational network using a range of different approaches.

4) Realizes 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. ORM recommends, as a matter of urgency, that Parties agree on funding regimes to sustain these 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 ORM in consultation with the SAP and EEAP (VC decision 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 these purposes.

5) Acknowledges the importance of contributions from all global and regional controlled substance monitoring programmes, and strongly urges their sustained support, including effective cross-programme (for example, greenhouse gas monitoring efforts) sharing and integration, and also including for calibration standards, data accessibility and emissions model development.

[2] https://ozone.unep.org/system/files/documents/Monitoring_Costs_Workshop_Outcomes.pdf

6) Recommends that only data that have been assessed and reviewed are suitable for providing accurate emission information needed for decision support. We also recommend that parties acknowledge the importance of data archiving, curation, and open data access for use in producing decision-support and research.

D. Data Archiving and Stewardship

Key data archiving and stewardship achievements since the 11th ORM:

1) Enhanced and more timely availability of ground-based, satellite and modelling data through several data centers/ data providers.

2) Central data processing systems are taken further in several monitoring networks, such as EUBREWNET, for selected NDACC-type data, Pandora data, in the framework of ACTRIS and FRM4DOAS programmes.

3) Progress has been made on enhanced linkage among data centers and on metadata exchange.

4) Progress has been made on data publishing with an associated digital object identifier (DOI).

5) Data centers have made progress in providing data in several accepted standard formats and in providing different traceable data versions.

Key data archiving and stewardship recommendations arising from the 12th ORM:

1) Continue to encourage data providers and observation campaign managers to submit the data to established databases in a timely manner, depending on the applications. We recommend that central data portals (e.g., the World Data Centers) provide visibility and linkage to the ensemble of ozone research-related data. This would enhance data discovery and as such the possibility of making better synergistic use of all the data and increase the effectiveness and appreciation of data acquisition efforts. We suggest that the WMO World Data Centers continue to foster enhanced coordination/collaboration between data centers on data formats, especially on metadata and data availability and interoperability in their respective focus areas.

2) The delegates encourage the instrument-based central processing systems including 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 delegates emphasize the importance of including all metadata that are required for data use, attribution and data discovery. The availability of metadata is also essential when data are converted to the standards of datacenters (for example, 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. GCOS recommendations on metadata should be considered.

3) 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 for ancillary data (e.g., laboratory spectroscopic data, station information), where available and before the information and knowledge get lost, in order to include the data in modern database systems.

4) 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 to give recognition to scientists and the funding agencies for 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, but with the requirement to give appropriate credit and to offer co-authorship for scientific publications to the data originator. Ensure that these credits are given, as they are often taken as a key performance indicator. Data creators are encouraged to publish peer-reviewed publications about the datasets.

5) A user-friendly data format is recommended. A common data format and metadata standard facilitates the exploitation of data retrieved from different data centers. Several common data standards, like netCDF-CF or GEOMS HDF are used by several Earth observation communities (e.g., 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 it is netCDF or HDF or else, is less important as there are many tools available to convert from one to another. Data centers should make the data available in different standard formats or provide the appropriate conversion tools. Data centers 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 centers need to be resourced to fulfil the above services to data providers and users.

E. 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 of itself an essential component of achieving a 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 include 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 Global Atmosphere Watch Programme (GAW), and the creation of local scientific communities contributing 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 of the Conference of the Parties to the Vienna Convention in 2021, parties were encouraged, *inter alia*, 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".

Key capacity building achievements since the 11th ORM:

Capacity building has been/will be provided through the implementation of the following activities approved by the Advisory Committee of the Trust Fund:

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 call in November 2023 inviting all developing countries and countries with economies in transition to submit project proposals for support under the Trust Fund, by the time of the meeting 12 parties had submitted 15 proposals, 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.

No.	**Party**	**Project proposal**
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
5	Indonesia	(a) Monitoring of the dynamics of ozone, ozone-depleting substances, UV radiation and air pollutants
		(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
12	Venezuela (Bolivarian Republic of)	(a) Monitor column ozone and ozone profiles in the Bolivarian Republic of Venezuela, implemented by the Ministry of People Power for Eco-socialism
		(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, in the commercial sector (supermarkets)

Key capacity building recommendations arising from 12th ORM:

1) The General Trust Fund for Financing Activities on Research and Systematic Observations relevant to the Vienna Convention for the Protection of the Ozone Layer is the mechanism specifically established by the parties to enable relevant capacity-building activities and 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 are able to receive support and the global ozone monitoring system can be enhanced; however, the number of contributions received to date has limited the impact achieved by the Trust Fund. Expansion of funding would enable deserving activities to be properly supported, leading to a lasting impact and development of human potential. The Advisory Committee of the Trust Fund has developed the long-term strategy and short-term action plan for the Trust Fund. The following two recommendations require continued support of the Trust Fund.

    (a) Maintain the quality of the global ozone-observing system through the continuation and expansion of regular calibrations 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 be the ideal venue for building awareness of Trust Fund opportunities, training local operators, and involving local community for capacity building including on scientific matters. Several ground-based total column ozone instrument (for example, Brewer and Dobson) intercomparison activities further indicate the success of such endeavors. Given the declining number of observations in tropics and other locations related to the loss of staff and resources (decline in agency funding, instrument repurposing, retirement), increase continuity planning and recruit early-career scientists.

    (b) Provide ongoing training opportunities for local station operators in developing and developed countries. Experience gained 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. Participants 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, greatly reducing the cost of such activities. WMO may play a role in posting and providing access to the training resources for instrument operators in the developing countries. Long-term support through “twinning” and having specific contact points with regional experts is essential.

2) Assist and encourage developing countries and countries with economies in transition, even with limited resources, to expand their scientific capacity 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 are key to successful implementation of scientific research training activities. Participants in the twelfth meeting of the Ozone Research Managers noted successful training opportunities in enabling participants from developing countries to leverage ground-based instrumentation and satellite data for scientific research.

3) WMO and the Ozone Secretariat should facilitate bridging the gap between the relevant monitoring and research communities at the international level. Coordination at the national level should be improved by the ozone focal points, in collaboration with the ozone research managers, to enhance cooperation among the relevant national organizations (ministries, space agencies, departments and academia) to ensure proper coordination and enhance synergies.

4) Increase capacity-building activities by finding alternate funding streams (for example, manufacturers, private sector) and helping to support development activities. Relationships should be developed with local and regional organizations to foster the development of ozone measurement programmes.

5) 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 sub-regional hubs for ozone-related researchers networking to develop research, observations and transfer of knowledge. Student exchanges and knowledge transfers between developed and developing countries (twinning) are vital to building these relationships. It is also suggested that ozone focal points should liaise with academia or relevant institutions from developing countries and the relevant governmental bodies to popularize stratospheric ozone-related majors in atmospheric sciences and to propose consideration of the development of government support schemes to ensure a sufficient professional workforce in the future. Encourage all parties to use existing resources and material available on the Ozone Secretariat website[3] (e.g. 20 Questions and Answers under the “Ozone and You” website tab).

The Ozone Secretariat and the OzonAction Programme of UNEP, 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.

[3] https://ozone.unep.org/.