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Vienna Convention issues: report of the twelfth meeting of the Ozone Research Managers of the Parties to the Vienna Convention

Recommendations of the Ozone Research Managers of the Parties to the Vienna Convention at their twelfth meeting

Note by the Secretariat

1. The twelfth meeting of the Ozone Research Managers of the Parties to the Vienna Convention for the Protection of the Ozone Layer was held from 24 to 26 April 2024 at the headquarters of the World Meteorological Organization in Geneva. At that meeting, the Ozone Research Managers made a number of recommendations, which fall into the following five categories:

(a) Research needs;

(b) Systematic observations;

(c) Gaps in the global coverage of atmospheric monitoring of controlled substances and options to enhance such monitoring;

(d) Data archiving and stewardship;

(e) Capacity-building.

2. The recommendations are reproduced in the annex to the present note with light editing by the Ozone Secretariat. They are relevant to the discussions on the status of the General Trust Fund for Financing Activities on Research and Systematic Observations Relevant to the Vienna Convention, to be held during the combined thirteenth meeting of the Conference of the Parties to the Vienna Convention and Thirty-Sixth Meeting of the Parties to the Montreal Protocol on Substances that Deplete the Ozone Layer, under agenda item 5 of the provisional agenda for the preparatory segment. The full report of the Ozone Research Managers will be available to the Conference of the Parties at its thirteenth meeting as a background document.

* UNEP/OzL.Conv.13/1–UNEP/OzL.Pro.36/1.

Annex

Recommendations of the Ozone Research Managers at their twelfth meeting

I. Research needs

1. 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:

(a) Observations show that the atmospheric abundances of both total tropospheric chlorine and total tropospheric bromine from long-lived ODS have continued to decline.

(b) Evidence for ozone recovery consistent with these ODS declines has strengthened, especially for ozone in the upper stratosphere and over the Antarctic region.

(c) 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.

(d) 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.

(e) 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 (CCl_4) emissions. Production of CCl_4 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 (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 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 (CO_2) 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

2. 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.

3. 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

4. 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 data sets 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

5. 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 CCl_4). 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.

6. 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.

7. 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.

8. 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

9. The Kigali Amendment to the Montreal Protocol aimed at phasing down some HFCs is projected to limit surface warming due to HFCs to about 0.04ºC by 2100, compared to expected warming of 0.3–0.5ºC 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-CO_2 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

10. 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

11. 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.[1] 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:

(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

12. 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

13. 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

[1] Szopa, S., V. Naik, B. and others, "Short-Lived Climate Forcers", in *Climate Change 2021: The Physical Science Basis* (Cambridge and New York, Cambridge University Press, 2021).

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

14. 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.

15. 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.

16. Furthermore, we are in a period when gases other than ODS (especially CO_2, N_2O, CH_4 and H_2O) 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.

17. 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.

18. 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

19. 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.

20. 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.

21. 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.[2]

22. 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.

23. 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.

24. 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.

25. 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.

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

26. 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 N_2O and sulfur hexafluoride, as well as ozone, aerosols and water vapour. Observations

[2] World Meteorological Organization, "Ozonesonde Measurement Principles and Best Operational Practices – ASOPOS 2.0 (Assessment of Standard Operating Procedures for Ozonesondes)", GAW Report No. 268 (Geneva, 2021).

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 N_2O, CH_4 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

27. 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",[3] 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.

28. 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;

(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.

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

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

29. The Ozone Research Managers,

(a) Noting that the workshop on costs of atmospheric monitoring of gases controlled under the Montreal Protocol[4] 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;

(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

30. Several data centres/data providers now ensure enhanced, more timely availability of ground-based, satellite and modelling data.

31. 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.

32. Progress has been made on enhanced linkage among data centres and on metadata exchange.

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

34. Data centres have made progress in providing data in several accepted standard formats and in providing different traceable data versions.

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

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

35. 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

36. 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.

37. 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.

38. 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.

39. 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

40. 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.

41. 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.

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 a 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 potential, in the commercial sector (supermarkets)

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

42. 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 website[5] (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.

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