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Vienna Convention issues: report of the eleventh 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 eleventh meeting

Note by the Secretariat

1. The second part of the eleventh meeting of the Ozone Research Managers of the Parties to the Vienna Convention for the Protection of the Ozone Layer was held online from 19 to 23 July 2021.[1] At that meeting, the Ozone Research Managers made several recommendations, which fall into the following five categories:

(1) Research needs;

(2) Systematic observations;

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

(4) Data archiving and stewardship;

(5) 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 twelfth meeting of the Conference of the Parties to the Vienna Convention (part II), under agenda item 4 (b).[2] The full report of the Ozone Research Managers will be available to the Conference of the Parties as a background document.

* UNEP/OzL.Conv.12(II)/1–UNEP/OzL.Pro.33/1.

[1] The first part of the eleventh meeting of the Ozone Research Managers was held in October 2020 and covered only issues related to gaps in the global coverage of atmospheric monitoring of controlled substances.

[2] Part I of the twelfth meeting of the Conference of the Parties was held in November 2020 and was dedicated solely to consideration of the budget of the Trust Fund for the Vienna Convention for 2020 and 2021.

Annex

Recommendations of the Ozone Research Managers at their eleventh meeting

I. Research needs

1. Measurements of ozone and ozone-depleting substances (ODS) and their replacements remain the cornerstone of stratospheric ozone research. These measurements are required to monitor the success of the Montreal Protocol on Substances that Deplete the Ozone Layer, to assess new influences and to allow process-based studies of ozone evolution in a changing climate. The understanding gained from the measurements and process-based studies are crucial to the development of atmospheric models, which are the primary tools for investigating future scenarios of stratospheric ozone.

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

2. The delegates to the eleventh meeting of the Ozone Research Managers (ORM) continue to endorse the general recommendations for research needs provided by delegates to the tenth meeting of the Ozone Research Managers. The delegates to the eleventh meeting of the Ozone Research Managers continue to endorse the general recommendations for research needs provided by delegates to the tenth meeting of the Ozone Research Managers, which covered (a) chemistry-climate interactions and monitoring the Montreal Protocol; (b) processes influencing stratospheric evolution and links to climate; and (c) ultraviolet (UV) changes and other impacts of ODS changes. In the following, the delegates highlight a subset of topics for particular focus as research priorities for the next three years. The delegates note that these topics will be covered in depth in *Scientific Assessment of Ozone Depletion: 2022*, being prepared for publication by the United Nations Environment Programme (UNEP) and the World Meteorological Organization (WMO).

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

(a) The recent research into the unexpected trichlorofluoromethane (CFC-11) emissions underlines the value of improved estimates of ODS emissions globally. This goal should be achieved by (i) expanding the top-down emission capability to cover much more of the Earth's surface and (ii) refining the bottom-up emission estimates globally and regionally in conjunction with improved reporting of production. Using the two in combination will provide substantial synergistic improvements to the quality of emission estimates of ODS and their replacements.

(b) An increasingly large fraction of the total atmospheric ODS amount comes from the shorter-lived ODS of both anthropogenic and natural origin. Monitoring and understanding their atmospheric emissions will provide underpinning information for any control strategies limiting future ODS concentrations.

2. Hydrofluorocarbons

(a) Concentrations of hydrofluorocarbons (HFCs) continue to grow in the atmosphere. The Kigali Amendment to the Montreal Protocol limits the production and use of many of the HFCs, thereby contributing to the protection of the climate system. Monitoring the success of the Kigali Amendment requires the atmospheric evolution of HFC concentrations to be monitored. It is essential that good geographic coverage of high-quality, systematic measurements be obtained to allow sectoral and regional emission information to be inferred.

(b) The climate effects of HFCs require further research and evaluation, which will be closely coordinated with work on other non-carbon-dioxide (non-CO_2) climate forcers (e.g., methane (CH_4) and nitrous oxide (N_2O)), all of which will affect the future stratosphere.

3. Stratospheric ozone – climate coupling

(a) It is now well established that the future evolution of the stratospheric ozone layer will depend not just on the decline of ODS concentrations, but also on how climate will affect stratospheric temperatures and circulation. While models predict a strengthening of the stratospheric overturning circulation (the Brewer-Dobson circulation, BDC) under increased greenhouse gas (GHG) concentrations, studies (including studies using tracer data) are required to test projections of the increased strength of the BDC. The recent unusual behaviour of the quasi-biennial oscillation (QBO) also needs to be understood. Further research combining state-of-the-art chemistry-climate models and reference-quality, altitude-resolved data records is needed. This will explain past changes and will provide an improved understanding of, and a firmer basis for, future projections of composition and climate.

(b) Research that refines our understanding of inter-annual and long-term variability in loss and transport of long-lived gases will lead to better global emission estimates on these same scales.

(c) Regional studies of stratospheric ozone processes remain crucial. The tropics are a key area for chemistry-climate interactions, as highlighted in the report of the tenth meeting of the Ozone Research Managers.[1] Future ozone changes in the tropics will depend on climate change, affecting changes in the tropical circulation and tropopause temperature, as well as on tropospheric chemistry. Similarly, recent changes in both the Antarctic and the Arctic stratosphere may reflect composition-climate interactions. Understanding the evolution in the Arctic is a key challenge. Future research should focus on understanding the role of climate change in the evolution of polar stratospheric ozone. Other regional foci could be defined, such as the variability of the ozone layer associated with monsoon circulations or the mountainous regions of Central Asia and the Himalayas.

4. Aviation, rockets and climate intervention

(a) Future changes are expected in the amounts and distribution of certain trace gases and in the abundance and composition of aerosol particles in the stratosphere. These changes can result from a variety of sources and processes. Natural sources include emissions from ocean and coastal regions, explosive volcanic eruptions and intense fires. Anthropogenic sources include the emissions from proposed supersonic civil transport aircraft and rocket launches. Rockets are projected to be launched with increased frequency and with a variety of propulsion systems.

(b) In leading climate intervention (also known as geoengineering) proposals, aerosol or aerosol precursors are injected into the stratosphere to increase Earth’s reflectivity (albedo) and thereby reduce the absorption of solar energy and climate forcing.

(c) Increased aerosol abundance and associated reactions on or in particles are likely to enhance global ozone depletion in processes similar to those that lead to polar ozone depletion.

II. Systematic observations

3. The science presentations for the eleventh meeting of the Ozone Research Managers and national reports emphasize the fact that systematic atmospheric composition observations remain critical for monitoring and understanding long-term changes in the ozone layer, as well as changes in atmospheric composition, circulation and climate. In order to verify the expected ozone recovery from ODS and to understand interactions with changing climate, continuing observations of key trace gases, UV radiation and parameters characterizing the role of chemical, radiative and dynamical processes will be required for many decades.

4. Global observations have shown a steady decline of ODS abundances beginning shortly after the Montreal Protocol was negotiated; however, surface observations showed unexpected emission increases of the fully controlled CFC-11 ODS after 2012. Global monitoring networks (National Oceanic and Atmospheric Administration (NOAA) and Advanced Global Atmospheric Gases Experiment (AGAGE)) linked this CFC-11 emission increase to unexpected sources in eastern China. Efforts by the parties to the Montreal Protocol apparently led to a significant reduction of CFC-11 emission levels by 2019. This CFC-11 emission issue exposed a lack of stations necessary for deriving regional emissions.

5. Observations also show that the ozone layer is recovering at the rate of one-third of the decline rate observed prior to the Montreal Protocol intervention. We are in a period that does not yet unambiguously show the response to ODS decreases and, furthermore, a period when gases other than ODS (especially CO_2, N_2O, CH_4 and H_2O) also influence global stratospheric ozone changes. Future emissions of these gases, which are not controlled under the Montreal Protocol, are quite uncertain. Their impacts are complex and interconnected, influencing both climate and chemistry in the

[1] https://ozone.unep.org/meetings/10th-meeting-ozone-research-managers/report-and-recommendations.

stratosphere. Robust long-term monitoring is therefore also essential in this period, moving towards the recovery of the ozone layer, which is expected in the latter part of this century.

6. Monitoring also needs to be expanded to include important new species and parameters (e.g., emerging ODS replacements, short-lived halogenated chemicals and tracers for atmospheric circulation). Key measurement regions include the upper troposphere / lower stratosphere (UTLS) and regions of stratosphere-troposphere exchange in the extratropics such as the monsoon circulation region, as well as the polar caps and the upper stratosphere.

7. There is growing concern for the end-life of satellites (e.g., Aura Microwave Limb Sounder (MLS)) that have been tracking some of the ODS, trace species and water vapour high-resolution profiles. There are no immediate plans to replace high-resolution limb-type satellite instruments. Therefore, the gap will have to be mitigated by the intensive use of ground-based observations; however, the current and new satellite instruments will continue ozone observations at high vertical and spatial sampling.

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

(1) Despite various difficulties, ground- and space-based measurements of ozone, 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) has played a large role in providing support, especially for the ground-based global observation networks, including providing intercomparisons, refurbishing and shipping available Dobson instruments and enabling ozonesondes, while encouraging development / validation of other instruments; however, several activities, such as calibration and intercomparison campaigns, were strongly affected by the restrictions imposed due to the coronavirus disease (COVID-19) pandemic situation. Furthermore, the limited funding for the VCTF has greatly hindered implementation of various worthy and needed efforts. This limitation has also negatively impacted capacity-building in countries operating under paragraph 1 of Article 5 of the Montreal Protocol (Article 5 countries or developing countries) and countries with economies in transition (see “Capacity-building” section).

(2) The limb-observing component of the Ozone Mapping and Profiler Suite (OMPS) on the current Suomi National Polar-orbiting Partnership (Suomi-NPP) platform, and the planned continuation on the second Joint Polar Satellite System (JPSS-2) platform; the current deployment of the Stratospheric Aerosol and Gas Experiment III (SAGE III) solar occultation instrument on the International Space Station (ISS); and the planned Atmospheric Limb Tracker for the Investigation of the Upcoming Stratosphere (ALTIUS) satellite mission have reduced the imminent gap in atmospheric limb-sounding instruments for ozone, aerosol and water vapour; however, as indicated in the key recommendations below, a significant loss of limb measurement capabilities is still expected for many other important gases.

(3) Some Dobson and Brewer instruments have been refurbished and installed in Article 5 countries; however, some are not yet in regular operation. More support, such as via the VCTF, might remedy this.

(4) New UV ozone absorption cross sections have been agreed upon and are now used in some applications. Several recent publications have demonstrated that the main differences between Dobson and Brewer can be reconciled when applying the new ozone cross sections and temperature corrections. It leads to the homogenization of Dobson and Brewer records.

(5) Substantial progress has been made with understanding and improving the historical ozonesonde records within the Ozonesonde Data Quality Assessment (O3S-DQA) activity. The Assessment of Standard Operating Procedures for Ozone Sondes (ASOPOS) 2.0 report: Updated Guidelines for Global Ozonesonde Operations is being finalized and will be published by WMO in 2021.

(6) Global stratospheric aerosol records have been re-evaluated and homogenized, and the recently deployed SAGE III/ISS instrument has demonstrated its ability to continue global observations of volcanic aerosols and the impact of fires on the stratosphere. In addition, the OMPS Limb Profiler observations provide information on the aerosol vertical distributions; however, there are uncertainties associated with the accuracy of the altitude registration. In combination with other satellite information, OMPS Limb Profilers can detect the fire aerosols in the UTLS (work in progress). The Tropospheric Monitoring Instrument (TROPOMI) has the ability to

detect aerosols from fires and determine the top altitude of aerosol elevation. MLS was able to detect fire tracers in the UTLS.

(7) Progress has 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 Atmospheric 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 (e.g., 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; 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); WOUDC; Southern Hemisphere Additional Ozonesondes (SHADOZ); and the NDACC links). Further progress in these directions is encouraged.

(8) New and more modern instrument types are being tested and integrated into ground-based networks, participating in intercomparison campaigns with established instruments like Brewer. Examples are the new Differential Optical Absorption Spectroscopy (DOAS)-type instruments, Pandora and Multi Axis-DOAS (MAX-DOAS) spectrometers for ozone, and Air-Core samplers on small balloons for other trace gases.

(9) Substantial progress has been made in assessing and improving the quality of long-term ozone profile records from satellites. Key to this were intercomparisons of all existing data sources and much-improved approaches to merging the records from different individual instruments. Several improved records are now available, but comprehensive assessment of all the uncertainty sources for these long-term records is still required. Activities in this direction are under way (e.g., in the joint Global Atmosphere Watch / Stratosphere-Troposphere Processes and their Role in Climate (GAW/SPARC) Long-term Ozone Trends and Uncertainties in the Stratosphere (LOTUS) and SPARC Towards Unified Error Reporting (TUNER) activities).

(10) It is important to note the steady decline in ozonesonde profile observations since the report of the tenth meeting of the Ozone Research Managers. This is a warning sign for decline in availability of the highly resolved ground-based observations for satellite and model verification and trend analyses.

(11) Ozone observations uncovered deficiencies in the general circulation models for capturing geographical distribution of the decline in low stratospheric ozone that point 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 eleventh meeting of the Ozone Research Managers

(1) The eleventh meeting of the Ozone Research Managers recommends increasing funding for the VCTF. Increase resources for continuing ground-based stations, especially for stations producing long-term records of ozone, trace gases and UV. These observations provide fundamental information to the Montreal Protocol parties to ensure that ozone recovery continues and to minimize associated climate change. The steady decrease in the number of stations, mainly in the tropics and Southern Hemisphere, including profile measurements, is endangering the independent monitoring of trends and the capturing of unexpected events, as well as our ability to validate satellite data records. 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. In addition, support from the VCTF is needed.

(2) Restore and expand regular, long-term monitoring where scientific needs are clearly identified. Key regions are those of troposphere-stratosphere exchange, such as monsoon regions, Southeast Asia, the maritime continent and mountainous regions (e.g., Andes, Himalayas and Central Asia). Ozone and UV measurements also should be targeted to data-sparse areas such as South America, Africa and Asia and in the inter-tropical region for accurate detection of BDC changes and other transport phenomena (see specific recommendations in bulleted items under “Research needs”).

(3) Continue the implementation of new and cost-effective instruments towards harmonizing global monitoring networks for ozone and trace gases, as well as standard data processing. Examples include EUBREWNET, Pandora, DOAS / Système d’Analyse par Observations

Zénithales (SAOZ), Air-Core, ozonesondes, etc. Global partners should support current regional harmonization initiatives. In addition, the eleventh meeting of the Ozone research Managers recommends that national agencies in non-Article 5 countries (developed countries) be encouraged to donate “retired” instruments for refurbishment and redeployment by VCTF to Article 5 countries and countries with economies in transition.

(4) Continue limb emission and infrared solar occultation observations from space. This is necessary for global vertical profiles of many ozone and climate-related trace gases. Without such observations, assimilated data and related services for policymakers will degrade, the detection and interpretation of changes in atmospheric circulation will be hampered and events like the severe 2011 and 2020 Arctic ozone depletion will not be properly understood.

(5) 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 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.

(6) Increase efforts to monitor vertical profiles of source gases, especially N_2O, CH_4 and water vapour, through the troposphere and stratosphere to understand their changing fluxes 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. In the light of a probable gap in satellite observations of these gases, how balloon (and ground-based) observations can help to fill the gap up to the middle stratosphere should be investigated.

(7) Observe profiles of concentrations, size distributions and composition of stratospheric aerosols. They are crucial for properly simulating the stratospheric ozone layer. Natural processes that contribute to the Junge layer, along with volcanos and pyro-convection, need to be monitored, and their evolution understood.

(8) Ensure trustworthiness of data via global and regional calibration facilities and quality assurance systems. This includes full support for the WMO GAW programmes and their endorsement by the parties to the Vienna Convention, including the establishment of a data curators committee in support of WOUDC, which requires active collaboration between data providers, data archives and data users.

(9) Implement incorporation of new ozone cross sections and temperature corrections by all established ground-based networks. 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. In order to move forward, curation of data that will guide homogenization and reprocessing of data is needed. The Dobson operations guide needs to be thoroughly updated and published at WMO.

(10) Enhance monitoring of ongoing emissions to check for consistency with the Montreal Protocol for long-lived ODSs and HFCs controlled under the Protocol, so that ongoing emissions can be monitored to check for compliance with the Protocol (see specific recommendations in the bullet points under “Gaps in the global coverage of atmospheric monitoring of controlled substances and options to enhance such monitoring”).

(11) Include measurements of very short-lived halogen-containing substances (VSLS) of interest to the Montreal Protocol (VSLS and hydrofluoroolefins (HFOs), including their degradation products) in baseline monitoring programmes at global and regional scales. Systematic observations should include different altitudes, as transport of VSLSs and their halogenated degradation products into the stratosphere is not yet measured regularly.

C. The eleventh meeting of the Ozone Research Managers recommends the following actions for observations, data analyses and curation of data related to ozone depletion:

(1) Assure and increase funding for continuous observations, analyses and curation of data.

(2) Continue efforts for supporting ongoing and new observations of ozone, GHG, ODS, HFCs, VSLS, aerosols, related chemical composition, and meteorological parameters on national and

global scales, especially in Article 5 countries. Support from the VCTF is needed. Therefore, the delegates recommend increasing funding for the VCTF.

(3) Open access to observation data (including metadata and calibration information) is required for intercomparability of networks and data analyses. Stations need to be supported to provide such data.

(4) Data analyses are critical for interpretation of observations, driving future research and informing policy makers.

(5) Provide support for the long-term curation of the archived data, requiring active collaboration between data providers, data archives and data users.

(6) Develop common tools, formats and centralized processing for the near-real time ozone data submission to improve forecasts.

(7) Encourage the twinning of observation stations in Article 5 and non-Article 5 countries (see further recommendations under “Capacity-building”).

(8) Identify extra financial sources to support regional network calibration and data homogenization initiatives (e.g., calibration of the South America Brewer instruments, reprocessing Indian ozonesonde records, operational software upgrades).

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

8. The draft white paper, “Closing the Gaps in Top-Down Regional Emissions Quantification: Needs and Action Plan”, prepared on behalf of the Scientific Assessment Panel with extensive consultation among a broad range of members of the ozone research community and the assessment panel members, was presented and discussed at length during part I of the eleventh meeting of the Ozone Research Managers, held online on 7 and 8 October 2020. Details of the presentation and the ensuing discussions are included, together with further background information, in the report of the Ozone Research Managers for the meeting (UNEP/OzL/Conv.ResMgr/11(I)/2).

9. The presentation summarized current methods for measuring atmospheric abundances of substances controlled by the Montreal Protocol and determining regional emission rates from atmospheric data, emphasizing the methods that played important roles in the recent discoveries and mapping of unexpected CFC-11 emissions. A key component of the white paper is a global map showing the very limited regions from which the current measurement stations can quantify regional-scale emissions. The costs and criteria for expanding observations at stations using flask sampling and high-frequency in situ instrumentation were presented, as were methods for modelling the regional emissions sensitivity for potential new measurement locations.

10. The discussions that followed in October 2020 focused mainly on the range of available methods for sampling and measuring these substances in the atmosphere, and their relative advantages and disadvantages. Several minor edits to the draft white paper were recommended. The most significant one was to include sensitivity units for the modelled “footprint” contours for existing observations in the regional sensitivity map. The document was then revised accordingly, and the resulting final version (UNEP/OzL/Conv.ResMgr/11(II)/4) was posted for consideration during part II of the eleventh meeting of the Ozone Research Managers, held online from 19 to 23 July 2021.

11. The presentation at part II of the eleventh meeting focused on summarizing the status of the white paper and advances in exploring potential measurements sites via Observational System Simulation Experiments (OSSEs). Mr. Ray Weiss (United States of America) presented the first portion, and Mr. Ronald Prinn (United States) described the second topic. Three new OSSE simulations that computed the sensitivity maps as functions of season and the El Niño-Southern Oscillation (ENSO) were examined for potential sites suggested by various interested parties. In addition, Mr. Prinn introduced a new way to predict regions that might be adding to unexpected emissions using a machine learning method based on socioeconomic activities. This new method can be employed to help assess potential sites for new measurement stations to fill gaps in the global ODS observing system. He also presented updated observational data on recent reductions in East China CFC-11 emissions.

12. During the discussion, Mr. Stephen Montzka (United States) posed two questions, namely: (1) whether there were data that the parties might have that could assist the Scientific Assessment Panel in its deliberations regarding the optimal locations for new observational capabilities; and (2) whether the parties could provide more detailed information about past, present and potential

future uses of controlled substances, including HFCs. The second question also arose during discussions at the recent sessions of the forth-third meeting of the Open-ended Working Group of the Parties to the Montreal Protocol, following the presentations of the Scientific Assessment Panel and the Technology and Economic Assessment Panel. An effort to expand “bottom-up” research and information on such things as banks, production facilities, product usage and equipment retirement could help refine Technology and Economic Assessment Panel modelling of emission expectations and inform the positioning of future observing stations. The Ozone Research Managers could encourage such information from the parties (in-country analyses of past and future markets, consumption, sales, appliance lifetimes, etc.). This would enhance the work of the Scientific Assessment Panel and the Technology and Economic Assessment Panel in their efforts to identify and quantify gaps by comparing the atmospheric observation-based “top-down” emissions with Technology and Economic Assessment Panel modelling of emission expectations. Other efforts to improve “bottom-up” emissions mapping were also described by Mr. Philip DeCola (United States) and Mr. A. Ravishankara (United States). The delegate from Finland suggested prioritizing observations and locations based on their importance (e.g., expected “hot spots,” ozone depletion potential (ODP)- and global warming potential (GWP)-weighted emission expectations, and substances with rapidly rising trends). The delegate from Brazil raised additional points about station costs and funding sources, while the Belgian delegate inquired about whether column observations could be used for emissions estimates. In response to costing, it was noted that rough costing was addressed in the white paper, while funding sources were outside the purview of the ORM. Emission estimates on regional scales from column observations are currently not derivable, but research is encouraged.

13. On the basis of the above information and discussions, draft recommendations of the Ozone Research Managers were proposed and discussed, leading to the adoption of the final recommendations.

Key white paper recommendations arising from the eleventh meeting of the Ozone Research Managers

14. Based on the discussions of the white paper (UNEP/OzL/Conv.ResMgr/11(II)4), the Ozone Research Managers:

(a) Endorse the white paper, and forward it to the Vienna Convention and Montreal Protocol parties for their consideration.

(b) Note that the activities and methodologies outlined in the white paper provide a sound basis for addressing the gaps in monitoring of controlled substances;

(c) Emphasize the importance of continued monitoring of controlled substances (i.e., ODS and HFCs) and the need to address gaps for early detection of emissions and their sources;

(d) Emphasize that filling in the gaps in monitoring is resource-intensive, and considerable sustained funding would be required;

(e) Note that a pilot project with European Commission funding will be undertaken by the Ozone Secretariat to implement some of the recommendations in the white paper, that the Ozone Research Managers are grateful to the European Union for such financing, and that additional resources would allow expansion of the initiative;

(f) Recognize the importance of contributions from all global and regional controlled-substance monitoring programmes, and strongly urge their sustained support with effective cross-programme sharing and integration, including for calibration standards, data accessibility and emissions model development;

(g) Prioritize locating any new sites and the chemicals to be measured based on expectations derived from the work of the Technology and Economic Assessment Panel, the Scientific Assessment Panel and other contributors as to where, what and how much is likely to be emitted in the future.

IV. Data archiving and stewardship

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

(1) Central data processing systems are taken further or being set up in several monitoring networks, such as EUBREWNET, for selected NDACC-type data and Pandora data in the framework of ACTRIS; the European Space Agency (ESA) Fiducial Reference Measurements for Ground-Based DOAS Air-Quality Observations (FRM4DOAS) programme; the NASA Making Earth System Data Records for Use in Research Environments (MEaSUREs) projects for harmonized satellite data sets; and others. They ensure harmonized data processing and quality assurance across the networks, operational data delivery and re-processing capabilities with full traceability. More data centres have implemented the option to store and provide access to multiple data versions with full traceability (e.g., NDACC and EUBREWNET). These efforts should be expanded to more networks and more target observational variables. WOUDC needs resources for central data processing. A similar approach to that used in EUBREWNET still remains a desirable application to the Dobson network.

- It has been noticed that some individual principal investigators have allocated resources to digitize and reprocess historical data according to current state-of-the-art procedures, but this effort remains limited because of the lack of resources. The Copernicus Climate Change Service (C3S) has allocated some resources to the digitization of historical meteorological data, but we have not seen a similar effort for atmospheric ozone data and related variables.

(2) Progress has been made on enhanced linkage among data centres. WOUDC has made linkages available to established data centres, including the European UV database (EUVDB) and other WMO World Data Centres, with cross-data-centre search. SHADOZ data have been formatted and ingested, and the pyshadoz open-source tool developed. NDACC and EUBREWNET file listings are indexed into the WOUDC data search, with the data discoverable from WOUDC and downloaded from NDACC and EUBREWNET, respectively. In addition, WOUDC continues to promote interoperability in support of open government, open data and open software, resulting in increased use of the data centre. There is a data centre interoperability (DCIO) project that aims to federate various Earth observation (EO) data centres for cross--centre information sharing and harmonizing metadata exchange without copying the datafiles.

(3) Data centres have made progress in providing data in several accepted standard formats. WOUDC support of open standards and interoperability allows the downloading of ozone/UV data in multiple formats and representations (CSV, XML, JSON, etc.). Station metadata are also available in the WMO Integrated Global Observing System (WIGOS) Metadata Standard. WOUDC obtains annual contributor contact validation, sends out contributor data submission reminders and provides data submission feedback (confirmation, data processing report) and metadata quality correction feedback. Data formats may work the other way, too; most data centres want data from providers in the data centre format rather than the provider format. Thus, there is progress with availability of data search, visualization and data exchange tools like OpenAPI. Nevertheless, it remains difficult to use data retrieved from different data centres synergically because they are provided in different data standards (format, metadata).

- The EUBREWNET data centre includes data from intercalibration campaigns, but the data are less prevalent from other (inter-)calibration activities or measurement campaigns. For the purpose of Copernicus satellite validation, an inventory is being made of the location and FAIRness (Findable, Accessible, Interoperable, Reusable and Reproducible) of the reference data sets, including campaign data, that are available in various data centres for the Sentinel satellite data. A similar effort covering data for ozone research might be useful.

(4) Progress has been made towards ensuring the long-term sustainability of databases. For example, the NDACC Data Host Facility (DHF) is transitioning from NOAA to NASA’s Langley Research Center (LaRC). There is a move of Total Carbon Column Observing Network (TCCON) data from the Carbon Dioxide Information Analysis Center (CDIAC) to the Jet Propulsion Laboratory (JPL). EUBREWNET is supported by AEMET (the Spanish State Meteorological Agency) and integrated with the Regional Brewer Calibration Centre for Europe (RBCC-E). Within Environment and Climate Change Canada (ECCC), WOUDC

continues to be operated by the Meteorological Service of Canada (data management and access), in collaboration with the Science and Technology Branch (scientific expertise / recommendations). WOUDC 2.0 is being developed to update the website and application programming interfaces. A beta release will be available in late 2021 / early 2022. The long--term archiving effort must be sustained.

(5) Progress has been made on data publishing with an associated digital object identifier (DOI). First-order DOIs are implemented for WOUDC data sets. NDACC and other data centres have implemented the assignment of DOI and data licenses to their data sets. Following the request from the WMO scientific advisory groups on ozone and UV for station-based DOIs, WOUDC is in discussion with the WMO Expert Team on Atmospheric Composition Data Management (ET-ACDM).

(6) WMO is working on a new data policy to advance the international exchange of Earth system data, including atmospheric composition monitoring and research data. There is interest in moving towards a unified open data policy; however, the research community recognizes the need to acknowledge the data providers.

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

(1) The delegates re-emphasize the past recommendation regarding the continuing need to develop robust automated data submission with centralized and standard processing wherever feasible, and quality assurance schemes to ensure timely – or even near-real time – submission to the appropriate data centres. In particular, all necessary information to process and reprocess data (e.g., calibration histories) should be included in the processing facility. Scientific oversight is required. Satellite overpass data and metadata with tools to determine co-locations with ground- and aircraft-based programmes should be readily accessible to the data centre, data users and data providers to allow for initial quality assessments in near-real time. Vice versa, ground station data should be readily accessible to the satellite teams. Databases should be configured to store multiple versions with full traceability.

(2) Strongly encourage the full curation of data, including historical data. In particular, the curated data should include all metadata and ancillary data. It is a redundant effort for individual users to curate the data. It is important for data centres to work with the scientists regarding what needs to be archived. A working group should be formed to discuss how data curation can be put into practice. The decision of who would lead this working group could be left up to WMO ET-ACDM. This topic is also alluded to in the “systematic observations” recommendations.

(3) Address the urgent need to allocate resources 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. The parties are encouraged to ask their research agencies to digitize and quality-control data they have retrieved and to make it freely available. A call should be sent out to stations asking if they need help digitizing their data, with a view to twinning.

(4) Continue to encourage data providers to submit or link to established databases to avoid a proliferation of databases, and especially to avoid the loss of data after the end of a measurement or (inter)calibration campaign or project, and to enable possible reprocessing of the data.

(5) Further target enhanced linkage among data centres. This requires that data centres coordinate more and make further progress with the exchange of metadata and interoperability. Open and user-friendly formats and data access should be encouraged; data that are not open to the community should be made widely available. Different data levels (L0 to L3; merged data sets) may be required for different users. Efforts to generate homogenous long-term data records from available data sources should continue.

(6) Data centres should be able to provide data in several accepted standard formats. It should be the data centres’ responsibility to provide tools to re-format, read and view the data and, if possible, carry out initial quality checks on submitted data using scientific oversight. Other responsibilities for data centres should be clearly established. The delegates recommend that WOUDC initiate requests to the Dobson stations to collect “raw” (e.g., N-value for Dobson instruments) data for archival and centralized reprocessing purposes. WOUDC collects calibration information from Dobson calibration centres to accompany station data.

A decision about a common data format and metadata standard would facilitate the exploitation of data retrieved from different data centres. Several common data standards, like netCDF-CF or the Common Data Model (CDM), are emerging; these 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. Work should be undertaken in the WIGOS framework or with the Generic Earth Observation Metadata Standard (GEOMS) Metadata Board to identify a common standard and recommend an approach for data format conversions. A recent study determined that the various formats currently provided are the best we can do, although we still need to try to do better. In response to the user requests, WMO data centres should collaborate with other data centres (i.e., NDACC) to produce data in a common format.

(7) The creation of central data portals (e.g., at the World Data Centres) that provide visibility and linkage to the ensemble of existing data centres for ozone research-related data would enhance the possibility of making synergistic use of all the data and, as such, increase the effectiveness and valorization of data acquisition efforts.

(8) Funding agencies need to continue to recognize long-term archiving as a resource-intensive but critical part of any measurement or modelling programme. Stewardship and succession should be a consideration. Long-term data preservation (LTDP) should be supported further. For example, ESA member States have made progress in supporting the ESA LTDP programme. Solutions for the long-term sustainability of databases should be sought (e.g., CDIAC, EUBREWNET).

(9) Data availability must be implemented according to FAIR data principles. This is supported by the assignment of a DOI and data license to the data sets. Data publishing with an associated DOI (e.g., in Pangaea or Earth System Science Data (ESSD)) should be 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. An open data policy is recommended, but with the requirement to give appropriate credit to the data originator. A way must be found to ensure that these credits are given, as they are often taken as a key performance indicator for funding agencies.

(10) Central data archives for satellite data sets (e.g., the Distributed Active Archive Centre (DAAC) at NASA) linked via a central portal (e.g., the Committee on Earth Observation Satellites (CEOS) portal) must be supported on a sustainable basis. Satellite overpass data and subsets coincident with ground-based network stations must be readily available; for instance, facilities like the Aura Validation Data Centre (AVDC) and the ESA Validation Data Centre (EVDC) should be sustained.

(12) Actions should be taken by monitoring stations operating Brewer spectrophotometers or other types of spectral and broadband instruments towards increasing the submission rate of UV index data to WOUDC. Ensuring the quality of this data is imperative, as their use is directly related to effects of UV radiation on human health and ecosystems.

V. Capacity-building

15. 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 Montreal Protocol.

16. 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 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. When this occurs, local experts will exist who can communicate with regional policymakers and speak with authority on the importance of compliance with the Montreal Protocol.

17. One of the main goals of capacity-building is the enhancement of ozone-monitoring networks, such as that of 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.

18. Paragraph 3 of decision X/2 of the Conference of the Parties to the Vienna Convention states: "To accord priority to capacity-building activities, in particular the specific projects identified for priority funding under the General Trust Fund for Financing Activities on Research and Systematic Observations Relevant to the Vienna Convention, related to the inter-calibration of instruments, the training of instrument operators and increasing the number of ozone observations, especially through the relocation of available Dobson instruments".

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

1. Activities completed under the General Trust Fund for Financing Activities on Research and Systematic Observations Relevant to the Vienna Convention

Activity 10: Dobson intercomparison campaign for northern Africa, El Arenosillo, Spain, 4–15 September 2017

Activity 11: Training workshop for Brewer operators, Sydney, Australia, 4–9 September 2017

Activity 12: Joint project proposal by WMO/Global Atmosphere Watch and Southern Hemisphere Additional Ozonesondes: Jülich Ozone Sonde Intercomparison Experiment 2017, Jülich, Germany, 9–20 October and 23 October–3 November 2017

Activity 13a: Kenya: Capacity-building on data management and instrument calibration: part 1, Hradec Králové, Czechia; and Payerne, Zürich and Dübendorf, Switzerland, 18 June–6 July 2018

Activity 13b: Kenya: Capacity-building on data management and instrument calibration: part 2, Kenya, 18–27 March 2019

Activity 14: Dobson intercomparison campaign for Latin America and the Caribbean, Buenos Aires, Argentina, 4–22 March 2019

Activity 15: Ecuador: The Ecuadorian Highlands Ozonesondes (ECHOZ) project, Cumbayá, Ecuador, 1 March 2019–30 April 2020, ongoing through 30 June 2021 owing to COVID-19-related delays

Activity 16: Dobson intercomparison campaign for southern Africa, Irene, South Africa, 7–18 October 2019

Activity 18: Kyrgyzstan: Technical support, information exchange for atmospheric monitoring at the shore of the high mountain lake, Issyk-Kul, 22 January 2020–31 March 2024

Activity 19: Comoros: Project on the establishment of an ozone observatory in Comoros, 11 May 2021–30 April 2022. Data to be delivered to WOUDC by 1 February 2023.

2. Planned activities

19. The following activity was listed for priority funding at the ninth meeting of the Ozone Research Managers in 2014; it has been approved by the Advisory Committee for the trust fund and will be financed by the trust fund pending determination of a host developing country:

Activity 17: Relocation of available Dobson instrument

20. In response to the Ozone Secretariat's invitation to all developing countries and countries with economies in transition for the submission of project proposals, nine proposals were received in 2021, and are being considered for financing by the Advisory Committee in 2021. In addition, the funding amount for one proposal (A) is currently under negotiation. Implementation depends on the availability of funds. Feedback from the Advisory Committee's evaluations is being provided to the proposers. The proposals are:

(A) *Belarus*: Preparing for and undertaking intercomparison sessions of three instruments to monitor total ozone and ultraviolet radiation in Belarus

Brazil: South American Brewer Spectrophotometer Network

China: International integration and capacity-building for observations of controlled substances in Asian developing countries

China: International and domestic communication on ODS and HFC monitoring technology, data analysis and quality control methods

Ecuador: Expanding ozone sounding operations in Ecuador from the Andes to the Galapagos Islands: the ECHOZ-SHADOZ synergy

Ecuador: Exposure to ultraviolet radiation and dermatological effects on people linked to productive sectors of the provinces of Pichincha, Guayas, Manabi, Pastaza and Galápagos, in Ecuador

Ecuador: Implementation of the Research Centre on Solar Energy and Ozone "Mitad del Mundo"

India: Capacity-building and awareness workshop on stratospheric and tropospheric ozone measurements and calibration of ozone measuring equipment

India: Impact of trace gas emission changes on the stratospheric ozone layer and the present-day and future climate over South Asia

Mexico: Monitoring of solar ultraviolet radiation band "B" in Central America and the Caribbean

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

(1) The VCTF is the mechanism specifically established by the parties to enable global capacity-building activities, and must continue to be supported. While actions taken by individual agencies are always welcome and have proved beneficial, the VCTF 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 VCTF. Even a modest expansion of funding would enable deserving activities to be properly supported, leading to a lasting impact and development of human potential. The following two recommendations require continued support of the VCTF.

(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 from experts in developed countries to station managers in developing countries. Offering instructional courses and workshops alongside these campaigns would be the ideal venue for training local operators. The recent JOSIE-SHADOZ 2017 campaign, with VCTF support, gathered ozonesonde operators from developing countries to provide training and discussion and intercomparison of measurement techniques. Several ground-based total column ozone instrument (e.g., Brewer, Dobson) intercomparison activities further indicate the success of such endeavours.

(b) Provide ongoing training opportunities for local station operators in developing 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. The COVID-19 pandemic has revealed the viability and success of virtual meetings: for instance, the SHADOZ Network held four regional virtual meetings that included station operators and management from developing countries. Following this example will improve the level of local scientific understanding, data-taking capabilities and quality assurance. Long-term support through "twinning" and having specific contact points with regional experts is essential.

(2) Assist and encourage Article 5 countries and countries with economies in transition with limited resources to expand their scientific capacity to allow them to participate actively in ozone research activities, including 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 eleventh meeting of the Ozone Research Managers noted, as an example to follow, the success of NASA's Applied Remote Sensing Training (ARSET) in enabling its many participants from developing countries to leverage satellite data for scientific research.

(3) WMO and the Ozone Secretariat should facilitate bridging the gap between different communities. Collaboration between ozone officers and the national meteorological / space agencies in their countries should be enhanced. In many Article 5 countries, there is a noticeable disconnection between the two. The Ozone Secretariat should establish a list of ozone / UV / climate research institutions in each country to ensure that communication is effective.

(4) Increase capacity-building activities by finding alternate funding streams (e.g., manufacturers, private sector) and helping to support development activities. Relationships should be developed with local chambers of commerce and economic agencies to foster the development of ozone measurement programmes.

(5) Provide fellowships to support the scientific development of students from developing countries. These students are a critical link and will help improve the level of engagement and understanding in their respective countries. Student exchanges and knowledge transfers between developed and developing countries (twinning) are vital to building these relationships. It is also suggested that developing countries liaise with 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.