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**United Nations  
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**Ozone Research Managers of the  
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Protection of the Ozone Layer  
Eleventh meeting**

**Identification of gaps in the global coverage of atmospheric  
monitoring of controlled substances and options to enhance  
such monitoring****Note by the Secretariat**

1. The annex to the present note sets out a paper prepared by the Scientific Assessment Panel in cooperation with experts in the atmospheric monitoring of substances controlled under the Montreal Protocol on Substances that Deplete the Ozone Layer, entitled “Closing the gaps in top-down regional emissions quantification: needs and action plan”. The paper will be presented at the eleventh meeting of the Ozone Research Managers, to serve as a basis for discussion in response to decision XXXI/3 on unexpected emissions of CFC-11 and institutional processes to be enhanced to strengthen the effective implementation and enforcement of the Montreal Protocol. In paragraph 8 of that decision, the parties requested the Scientific Assessment Panel to work with the Ozone Research Managers at their meeting in 2020 to identify gaps in the global coverage of atmospheric monitoring of controlled substances and to provide options for ways to enhance such monitoring, as well as exploring options for informing the parties of preliminary information indicating unexpected emissions of controlled substances, for consideration by the Thirty-Second Meeting of the Parties to the Montreal Protocol and by the Conference of Parties to the Vienna Convention at its twelfth meeting.
2. The paper will be presented and discussed during session 4 of the eleventh meeting of the Ozone Research Managers.<sup>1</sup> The paper, with inputs, if any, from the Ozone Research Managers, will also be presented to the Open-ended Working Group of the Parties to the Montreal Protocol at its forty-second meeting.

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\*The information contained in this document has not yet been considered by the eleventh meeting of the Ozone Research Managers.

<sup>1</sup> UNEP/OzL/Conv.ResMgr/11/1.

## Annex

### **Closing the Gaps in Top-Down Regional Emissions Quantification: Needs and Action Plan<sup>1</sup>**

Scientific Assessment Panel “White Paper” for the 11<sup>th</sup> Meeting of the Ozone Research Managers

#### **Executive Summary**

The recent finding of unexpected atmospheric emissions of the ozone-depleting substance trichlorofluoromethane (CFC-11) has made it imperative to expand ways to find, quantify, and attribute emissions of substances controlled under the Montreal Protocol. Such an activity would enable the parties to take actions, at country, regional, and international levels to assure compliance, and safeguard the ozone layer and mitigate climate change. An approach based on atmospheric measurements at judiciously chosen locations using *in-situ* instrumentation and collection and analyses of flask samples, on ensuring calibration and transparency of the measured data, and on inverse emissions modelling, is envisioned to address this issue. The main elements of a pathway to accomplish these goals are laid out in this document.

#### **Introduction**

Following the identification of unexpected emissions of trichlorofluoromethane (CFC-11) during the past decade, the parties to the Montreal Protocol on Substances that Deplete the Ozone Layer decided at their Thirty-First Meeting (decision XXXI/3, paragraph 8): “To request the Scientific Assessment Panel to work with the Ozone Research Managers at their meeting in 2020 to identify gaps in global coverage of atmospheric monitoring of controlled substances and to provide options on ways to enhance such monitoring as well as exploring options for informing the parties of preliminary information indicating unexpected emissions of controlled substances for the consideration of the Thirty-Second Meeting of Parties and the Twelfth Conference of Parties, in 2020.” This “white paper” supports this decision by addressing key scientific and technical components of enhancing regional-scale “top-down” controlled substance emissions identification and quantification based on direct atmospheric observations coupled with inverse modelling.

As the discovery of unexpected CFC-11 emissions has shown, ongoing measurements of atmospheric composition at remote baseline stations play a crucial role in identifying and quantifying significant global emissions of the many substances controlled under the Montreal Protocol. Other measurement capabilities such as satellite-derived and ground-based measurements of the entire or partial atmospheric column abundances of some of these controlled substances also play significant roles in this understanding. However, the identification of specific regions of unexpected emissions of any controlled substance, and the quantification of these regional emissions, are needed to enable the parties to take action in the event of such findings. While remote “background”, atmospheric column and upper atmosphere measurements remain essential to understanding the global emissions and budgets of controlled substances, and to the discovery of unexpected emissions, they cannot resolve the regional emissions of the full range of controlled substances and their temporal changes that are needed by the parties. This white paper is aimed at the specific goal of identifying and quantifying regional emissions of those substances that are identified from global observations to be of importance to the parties.

#### ***Vulnerabilities of Bottom-Up Emissions Quantification***

The Montreal Protocol was designed to use reporting by various parties to evaluate compliance with the treaty terms. The vulnerabilities of relying solely upon “bottom-up” inventory reporting for the quantification of production of controlled substances are exemplified by recent findings on the unexpected emissions of CFC-11, the production and consumption of which has been banned globally since 2010. Atmospheric CFC-11 observations from a small set of globally distributed and judiciously located “background” stations were used to provide a “top-down” emission estimates based upon the known rates of atmospheric losses (*i.e.* the atmospheric lifetime) and modelled atmospheric mixing rates. A global CFC-11 emissions increase was thereby detected when the rate of decrease in the global CFC-11 abundance slowed significantly beginning around 2013<sup>1</sup>. This was accompanied by an increase in CFC-11 abundance differences between the Northern and Southern Hemispheres,

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<sup>1</sup> The paper is presented as submitted by the Scientific Assessment Panel of the Montreal Protocol.

indicating the existence of unexpectedly high CFC-11 emissions in the Northern Hemisphere, totalling about 10 gigagrams (Gg) per year, that were most likely associated with new unreported production<sup>3</sup>. Also beginning in 2013, short-term enrichments of atmospheric CFC-11 and other industrial gases were measured in air arriving at Hawaii along trajectories that had passed over eastern Asia, suggesting that this region was a source of these unexpected CFC-11 emissions<sup>1</sup>.

### ***Global versus Regional Quantification***

The discovery of increased global CFC-11 emissions was followed by a separate regional study based on high-frequency atmospheric CFC-11 measurements at Gosan, Jeju Island, and at Hateruma Island, both located east of China<sup>2</sup>. Observation stations that are located within approximately 2000 km of emission sources and receive air from those sources are sensitive to the effects of these emissions in raising atmospheric abundances above clean air “background” values and can be used to identify regional emission patterns and quantify their magnitudes. This regional analysis technique uses models of atmospheric transport based on global weather models, combined with measured variations in atmospheric CFC-11 abundance. As multiple events or plumes affected by these emissions reach the measurement stations from different directions, the wind information can be used to trace emissions backward to their source region(s). Using this technique CFC-11 emissions and their year-to-year changes have been mapped across a “footprint” covering eastern China, Korea and southern Japan.

This work has shown that CFC-11 emissions from eastern China increased by about 7 Gg per year. The measured CFC-11 emissions came mainly from two eastern Chinese provinces, while no significant changes were found within the other regions affecting these measurements. Currently, there is insufficient global coverage of measurement stations to identify the locations from which the balance of these unexpected CFC-11 emissions may have originated, but we do know from existing measurements that they are unlikely to have come from western Europe or central North America. We also know from the global measurements that they originated primarily in the Northern Hemisphere. Because of the lack of broader coverage, the sum of the available regional CFC-11 emissions estimates during this period does not fully account for the global “top-down” emissions estimate.

### ***Emissions Quantification for Controlled Substances***

In addition to the case of unexpected CFC-11 emissions, there are other controlled substances for which current combined inventories of “bottom-up” national and regional production are difficult to reconcile with “top-down” global emissions determined from atmospheric measurements and estimated lifetimes. These include carbon tetrachloride<sup>5</sup>, which is used as a feedstock to manufacture CFC-11 and other chlorine-containing compounds, as well as several other halogenated compounds controlled under the Montreal Protocol<sup>3</sup>. It is important to know the origins of any unexpected current or future emissions of any substance controlled by the Montreal Protocol.

Under the Kigali Amendment, the Montreal Protocol is also assuming regulatory responsibility for the production and consumption of the HFCs, which do not deplete stratospheric ozone but are global warming gases. Monitoring regional compliance with the phase-down requirements of the Kigali Amendment requires expanding atmospheric measurement capabilities into the regions of the world where HFC uses are increasing rapidly.

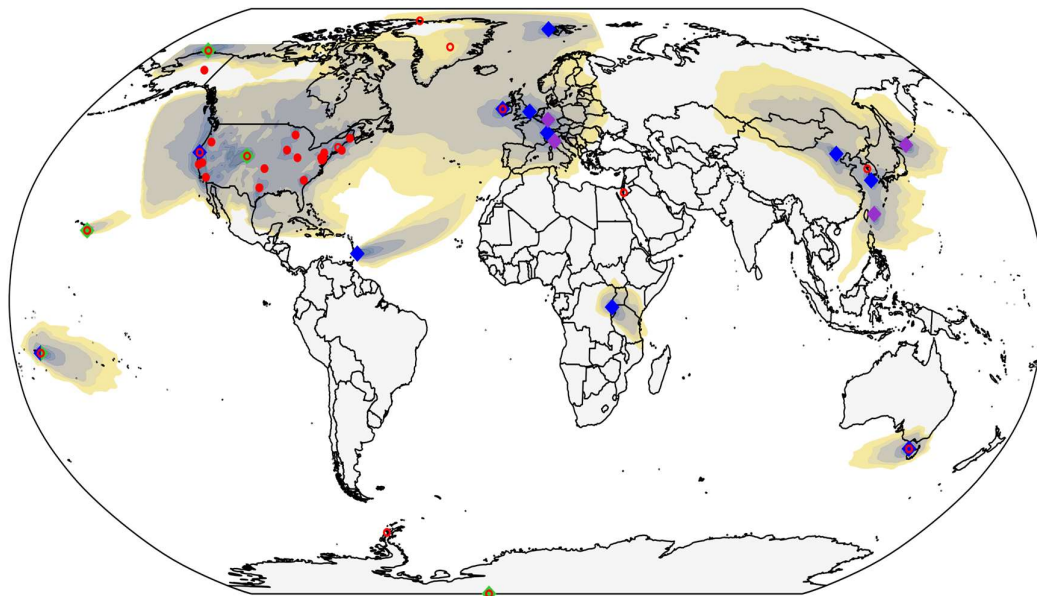
### **Current Capabilities and their Limitations**

Many observational networks contribute to the measurement of the atmospheric distributions and trends of substances that are now controlled by the Montreal Protocol. They include international collaborations such as the Network for the Detection of Atmospheric Composition Change (NDACC) using optical methods, civil-aviation and government-sponsored aircraft measurement programmes, and various satellite measurement programmes. They also include ground-based observational networks, such as those of the international Advanced Global Atmospheric Gases Experiment (AGAGE) consortium and the US National Oceanographic and Atmospheric Administration (NOAA) which have played direct roles in the discovery and identification of unexpected CFC-11 emissions.

Since the 1970s, the international AGAGE and US NOAA networks have focused on ground-based *in-situ* and flask sample measurements for determining global concentrations, trends, lifetimes and emissions of a wide range of controlled substances and other trace gases based on measurements at remote “background” locations. More recent expansions of both networks have enabled an added emphasis on measurements in areas that are sensitive to regional emissions. The Korean Gosan AGAGE and the Japanese Hateruma AGAGE-affiliated stations (cited above), and higher-density North American NOAA flask-sampling locations, are examples of this added emphasis that have made these networks capable of discovering and quantifying emissions in areas not previously sampled. The

added regional measurements, when coupled with inverse modelling, provide a powerful tool to identify and quantify regional emissions, as has been shown by many recent studies.

The current locations of high-frequency measurement stations and daily flask sampling sites for both of these networks are shown in Figure 1, together with the “footprint” regions in which their measurements are sensitive to quantifying emissions by inverse modelling. As is exemplified by the successes of the recent findings for CFC-11, important areas such as eastern Asia, middle North America, and western Europe are well-sampled by existing measurement locations. In contrast, coverage of eastern Europe, western, southern and central Asia, all of South America, portions of North America, large parts of Southeast Asia, Australia and New Zealand, and most of Africa is largely absent.



**Figure 1.** Map of Advanced Global Atmospheric Gases Experiment (AGAGE) high-frequency measurement stations (blue diamonds), AGAGE affiliated high-frequency measurement stations (purple diamonds), National Oceanic and Atmospheric Administration (NOAA) high-frequency measurement stations (green diamonds), NOAA daily flask-sampling locations (red filled circles) and NOAA weekly flask-sampling locations (red open circles) for monitoring atmospheric substances controlled by the Montreal Protocol. Modelled<sup>2,4</sup> annual “footprint” sensitivities are shown for the plotted high-frequency *in-situ* measurement and daily flask sampling locations (except for the South Pole, central Alaska, and parts of the Beaufort Sea north of Alaska). Sensitivity contours begin at the approximate limit where quantitative estimates of emissions can be made and increase exponentially toward the station locations.

To date, expansions of this observational capability have been largely *ad hoc* in character. They have been driven by a combination of the scientific interests and needs of individual investigators to study Montreal Protocol and climate gases, by the funding interests and policy priorities of host and supporting entities, and by the existence of necessary infrastructures and logistic support. There is clearly a need for a more coordinated international approach to meeting the needs of the parties by identifying and prioritising the filling of the most important regional gaps.

### Filling the Gaps

Existing observational networks provide a foundation upon which to build an increased observational capacity for monitoring of controlled substance emissions and closing existing gaps. Expansion of these networks requires considering a range of issues discussed below.

#### *High-Frequency In-Situ and Flask-Sampling Measurements*

High-frequency time-series *in situ* measurement stations (Figure 2), combined with atmospheric transport “inverse” modelling, enable the mapping of emissions across regions of up to a few thousand kilometres in scale. Optimal locations for high-frequency (*e.g.* hourly) measurement stations are generally downwind of emission regions (in the climatological air flow sense) and away from polluted urban sites. This ensures that a station samples air masses from areas of interest without being overwhelmed by local sources. These high-frequency measurement instruments are generally not easily deployed for intensive field campaigns and are most useful when operated continuously at fixed monitoring station locations for extended periods.



**Figure 2.** Atmospheric monitoring station at Mace Head, Ireland. AGAGE high-frequency measurements of substances controlled by the Montreal Protocol are made by automated gas chromatography with mass-spectrometric detection (GC/MS) on air pumped from the central tower. The upper right inset shows a similar GC/MS instrument at the Gosan monitoring station, Jeju Island, South Korea. The upper left inset shows a NOAA automated 12-flask air sampling system used to collect samples at stations around the world for subsequent GC/MS analysis in the central NOAA laboratory.

Flask sampling locations (Figure 2) have also enabled the mapping of emission locations and magnitudes across regions with the use of inverse modelling techniques. While daily flask sampling may provide lower resolution for modelling emissions around any one site compared to higher-frequency measurements from an *in-situ* instrument, multiple flask collection sites can provide extensive geographic coverage for estimating emissions. Flask sampling at many locations or in airborne programmes also can provide exploratory geographic coverage in presently unsampled or under-sampled areas of interest at lower cost. Flask samples collected at *in situ* high-frequency measurement stations can also be used to assess potential biases among different measurement programmes. And larger flask samples can be archived for future measurements with advanced technologies that exceed current capabilities, thereby enabling the detection of new compounds and the measurement of isotopic composition to diagnose sources and mechanisms of production and destruction.

Combining high-frequency *in-situ* measurements with a program of measurements of flask samples in central laboratories can significantly strengthen the robustness and reliability of an integrated measurement network. Existing long-term internal and external collaborations involving a number of international and national research enterprises, including AGAGE and NOAA, have clearly proven the benefits of such an integrated observational approach.

### ***Methods for Measuring Atmospheric Abundances***

Most observations of Montreal Protocol substances in the atmosphere rely upon tested and well-established cryogenic preconcentration methods, with analysis by gas chromatography with mass spectrometric detection (GC/MS). Although technical implementation details and methods vary with time and among programs, this is the general analytical approach used in the AGAGE network of high-frequency *in situ* automated measurement stations<sup>6</sup>, and in the NOAA measurements of flask samples in their central laboratory<sup>1</sup>. The more abundant CFCs, carbon tetrachloride and a range of other substances relevant to the Montreal Protocol can also be measured at high frequency by *in-situ* gas chromatography with electron capture detection (GC/ECD) instruments, as is also done at some NOAA and AGAGE stations. The GC/MS methods have the advantage of being able to measure all the substances controlled by the Montreal Protocol, including the HFCs and certain by-products of controlled substance manufacturing that are not themselves controlled but provide important clues to the origins of controlled substances.

### ***The Importance of Calibration***

Calibration standards and the resolution of potential differences among measurement methods play especially critical roles in emissions quantification because the inverse models depend on the absence of bias over time and between different measurement locations and programmes. The risks of error are minimized by using calibration standards that are prepared in whole air at ambient parts-per-trillion concentration levels and are free of drift during storage. Unfortunately, such standards are not typically available from the national metrology institutes or commercial vendors. To fill this need, atmospheric research programmes, including NOAA and AGAGE, independently prepare and propagate their own calibration standard scales, and regularly compare standards and field measurements to assure the robustness, consistency, comparability and accuracy of their measurements. Maintaining standards over long periods of time is a difficult task that is separate from but essential to the accurate tracking of long-term changes in atmospheric composition. It requires regular comparison and maintenance of standard scales, and periodic preparation of new primary standards over the course of the measurement record. It is also important for the compositions of calibration standards to keep pace with changes in atmospheric composition over time.

Calibration standards are not easily adapted to significant network expansion. Large volumes of standard gas are required to support the millions of measurements already carried out around the world each year. One solution to this potential capacity shortfall is for the international metrology community to take on this issue. A few national institutes have recently begun to implement ambient-level standards for a few of the measured controlled substances, but more work is required.

### ***Global and Regional Inverse Emissions Modelling***

Assessing global or regional emissions from atmospheric observations requires the use of “inverse” models that trace measured variations in composition back to their source regions and account for atmospheric mixing. These simulations, when combined with a statistical framework that accounts for uncertainties in the data and model, can be used to infer emissions from the observations.

Global inverse modelling methods, such as have been used to quantify the recent unexpected global CFC-11 emissions<sup>1</sup>, have primarily used observations from “background” monitoring stations that are far from pollution sources.

Regional inverse modelling methods have been used in areas where measurements are available in sufficient temporal and spatial density. These methods use high-resolution atmospheric transport models (typically ~10 km horizontally) that simulate the mixing of trace gases over a limited distance (typically a few thousand km). Emissions estimates are adjusted to bring the model simulation and the observations into agreement, subject to uncertainty estimates. The scale at which regional emissions can be derived is dependent on the measurement density. Because the uncertainties in these simulations are often poorly understood, it is important that the results are tested against a range of model architectures, meteorological inputs and assumptions, as has been done in the recent modelling of east Asian CFC-11 emissions<sup>2</sup>. The differences between emission estimates from individual models are often larger than the uncertainties estimated by the individual models. Therefore it is important that inverse modelling approaches are rigorously inter-compared, and that the assumptions made are transparent.

Atmospheric transport models and inverse modelling frameworks can also be used to predict the benefits of proposed new measurement sites for global or regional emissions estimates by using Observing System Simulation Experiments (OSSEs). Such simulations can estimate the improvements that can be made in estimating emissions for a given range of possible network configurations, and thus determine the optimal locations for new measurement infrastructures.

It is important to note that the sensitivity with which emissions from particular region can be modelled for a specific compound of interest depends fundamentally on a number of factors. As the length of time over which measurements are made increases, or the ability to measure regional enhancements of that compound above background values improves, minimum detectable emission rates are lowered. As noted above, the sensitivity of a particular measurement location to model a particular regional emission source also depends critically on atmospheric transport and mixing parameters, and these can vary significantly over seasons and interannually. The emission of some compounds of interest may also be seasonal. The combined effects of variations and differences in these factors can have large impacts on the sensitivities with which the emissions of a specific compound from a particular region can be modeled based on measurements at a given station or stations. The example shown in Figure 1 is the annually averaged (mostly for 2016) regional footprint sensitivity for existing measurement stations and for CFC-11 or a compound with a similar measurement capability.

## ***Integration of Observations and Data Transparency***

The need for collaborative integration of controlled substance measurements and emissions modelling is global. While the establishment of national and regional programmes for monitoring and modelling of controlled substance emissions are strongly encouraged, all such efforts are limited if they are carried out in isolation because much more can be learned through integration within a larger regional and global context.

Wherever the stations are located, and whichever approach is taken, open and transparent data sharing is imperative. Quality control, enabled by sharing of data and calibration standards, builds trust amongst nations, and comparison with others most-effectively integrates individual stations into the larger network of regional and global observations. The use of these data for estimating and quantifying source strengths, and the integrity of the results, also depend critically upon transparency and open and timely data availability.

## **Criteria for Selecting New Observing Locations**

As noted above, atmospheric abundances of Montreal Protocol controlled substances are measured at judiciously chosen locations either by collecting flask air samples and sending them to a central analytical facility for analysis, or by measuring *in situ* at high frequency using an automated instrument installed at a measurement location. The essential criteria for establishing new measurement stations and flask sampling locations to optimise the quantification of emissions include:

- Assessing regions of the world where there are observational gaps in regional emissions monitoring (*cf.* Figure 1). Important factors to consider include population distribution, locations of certain emissive industries, and regions of high economic activity or growth.
- Identifying potential measurement station and flask sampling locations that are relatively remote from strong nearby emission sources, and that are also within about 2000 km of the regions of interest from which prevailing winds bring air to the measurement locations during most seasons. Such conditions are found: on islands, on coastlines, or in other areas that are relatively remote from population centres and industrial activities; or are achieved by measuring or sampling air pumped from tall towers such as are used for radio or television broadcasting, or by taking advantage of mountain topography to avoid local influences.
- Identifying potential station locations for on-site instrumentation that have access to logistical support, including: 1) a building or enclosure for housing the measurement equipment that has sufficient environmental control, reliable electric power, data connectivity and access for personnel and supplies; 2) availability of qualified technical personnel to operate and maintain the instrumentation and station; and 3) a long-term commitment to the work and to providing financial support. We note that flask sampling locations require lower levels of technical expertise and support than are required for high-frequency *in-situ* measurement stations.
- Determining that a particular proposed site is suitable for providing the desired regional emissions monitoring “footprint” coverage by carrying out Observing System Simulation Experiments (see above) that include seasonal and interannual variabilities in patterns of atmospheric transport.

## **Benefits, Costs and Organizational Structures**

### ***Benefits of Advancing Measurement and Modelling Capabilities***

In addition to directly strengthening the fundamental quantification of controlled substance emissions under the Montreal Protocol, there are a number of related benefits associated with expanding atmospheric measurement and modelling capabilities. Current atmospheric measurements depend on one-of-a-kind customized instrumentation that has been developed and assembled in individual research laboratories. The evolving need for expansion has already begun to create incentives for commercialization and improvement of this technology. Supporting such efforts will enable higher quality observations and improved instrument deployment and operation for the measurement of Montreal Protocol substances.

In the area of emissions modelling, there are strong synergies with other fields that employ similar or related atmospheric inverse modelling methods. These include regional air pollution studies, monitoring of nuclear activities based on atmospheric radionuclide measurements, and modelling of accidents that emit harmful substances into the atmosphere. There are also strong synergies in measurement and modelling with the quantification of emissions of high global warming potential gases, in addition to the HFCs that are addressed by the Kigali Amendment to the Montreal Protocol.

Another important direct benefit of expanding atmospheric measurement and modelling activities to new regions is the strengthening of international collaborations and capacity building, including the education of students who will be the next generation of experts in this long-term emissions quantification effort. The AGAGE network, which was begun by academic and government scientists in three nations and now includes scientists in eleven nations, is a good example of this benefit. There are also important examples of resources crossing international boundaries, such as the US and the UK supporting the AGAGE station in Barbados, and the US supporting the NOAA cooperative flask sampling program in many nations around the world.

### ***Costs of Implementation and Operation***

The establishment of a high-frequency measurement station requires a suitable air intake tower, an air-conditioned building space, reliable electric power, data connectivity, and access for personnel and supplies. Flask sampling locations require a subset of these conditions including an air intake tower, protected space and electric power. The associated costs depend greatly on the extent to which existing resources and personnel can be used. In addition, the costs of modelling proposed sites with OSSEs and maintaining a modelling capability are on the order of \$150K USD per year. Approximate costs associated with establishing measurements at a pre-existing station, based on current experience, are:

- **High-frequency observations:** The initial cost of the measurement instrumentation and ancillary equipment at an existing station is on the order of \$400K USD, and the annual operating cost is on the order of \$150K to \$350K USD (in the AGAGE example), depending greatly on the costs of personnel.
- **Flask sampling:** For weekly sampling, the costs are on the order of \$15K USD for reusable flasks and pumps, and the annual cost of shipping and analysis (without any sampling tower or flask filling personnel costs) is on the order of \$25K USD (in the NOAA example). Daily flask sampling increases the initial costs to order \$100K USD and the annual costs to order \$90K USD. Increasing flask sampling at 10 sites at a weekly frequency also generally requires personnel travel for training at a cost of \$200-250K USD. Annual costs of shipping are approximately \$200K USD. These cost totals can be accrued over time, starting in a few places and expanding year after year.

### ***Organizational Structures***

Given these costs, it is important to recruit national resources or university collaborations to support the establishment of key regional atmospheric measurement stations and related emissions modelling activities. Pilot collaborative efforts with other international and national organizations at their existing monitoring sites, such as the atmospheric monitoring network operated by the Comprehensive Test Ban Treaty Organization, could also take advantage of efficient sharing of existing resources.

International collaboration and cross-border sharing of experimental expertise and data are key components of a successful regional controlled substance emissions quantification programme. International bodies play a critical role in establishing and maintaining such collaboration by providing support for enhanced international open-access databases. These needs are currently met in-part by existing data repositories, such as the World Data Centre for Greenhouse Gases operated by the Japan Meteorological Agency under the World Meteorological Organization, that archive a broad range of atmospheric trace gas measurements including substances controlled by the Montreal Protocol. As noted above, quality assurance is of critical importance in the effective use of observational data in emissions modelling, especially when it involves using data from diverse sources. Experience has shown that these goals are best achieved through the mechanisms of open access, collaboration and peer review.

### ***Options for Initiatives to Close the Gaps***

Advancing the ability to make regional emission estimates that account for global emission totals requires adding a number of new strategically-chosen measurement locations around the globe. This is apparent from Figure 1, which shows the “footprint” areas of current measurement locations compared to the many populated and developed or developing areas that are not currently monitored. Establishing such a network and realizing its benefits is a decadal-scale project, one that can be expanded to address new regional emissions monitoring needs for certain controlled substances as they evolve. Each added measurement location strengthens the ability of the network to detect and quantify unexpected emissions. Based on the above analysis, three first initiatives are recommended:



- **Pilot project with high-frequency atmospheric measurement stations:** A specific first step is to establish at the outset two or three new high-frequency atmospheric measurement stations chosen to sample emissions from important areas that are currently under-sampled. As part of the selection process, “footprint” sensitivities of new stations are analysed by OSSE calculations to establish their specific value for regional emission detection. As noted above, since practical constraints limit the available options, and to the extent that there is a need to move quickly, the first new station locations require an existing infrastructure and the availability of financial and local logistic support and commitment. This pilot project also establishes baseline costs and addresses technologic, logistic and management structures.
- **Pilot flask sampling project:** Flask sampling sites provide for emissions monitoring in important regions that are not sampled using *in-situ* high-frequency measurement stations. These sites are guided in location, significance of emissions, and optimal sampling frequency (*e.g.* daily or weekly) by OSSE calculations. Multiple flask sampling locations distributed within larger regions provide broader geographic coverage, and individual flask sampling locations characterise smaller regions. Flask sampling also enables the evaluation of locations for future expansions of *in-situ* measurement stations, assesses local logistic and institutional capabilities to support such expansions, and assures data comparability among different measurement programmes and across larger regions.
- **Collaboration among existing and newly developed networks:** Finally, existing measurement networks such as those operated by AGAGE and NOAA, other existing ground-based measurement programmes such as those participating in the Global Atmosphere Watch of the WMO<sup>3</sup>, and those newly proposed such as by China<sup>7</sup>, are encouraged to collaborate and coordinate internationally, with exchange of technical knowledge, operational expertise, calibration standards, and, most importantly, to adopt data and model sharing, open data access and model transparency. This approach maximises, over the shortest period of time, the quality of the measurements and the credibility of their interpretations, and thus also maximises the benefit to all of the parties of the Montreal Protocol.

The first new high-frequency measurement stations and flask sampling locations established under this effort are to emphasise closing gaps in Northern Hemisphere observations. Possible locations include: South Asia with measurements in the Indian Ocean or the Himalayan foothills; Eastern Europe with measurements in eastern Scandinavia or the Baltic region; Central Asia with measurements in the central desert regions or on the Tibetan Plateau; Southeast Asia with measurements in the mountains of Vietnam or coastal southern China; and Northern Africa with measurements in the Atlas Mountains.

The three initiatives described above are suitable for implementation either in parallel or staggered, based upon: 1) available resources; 2) agreement on the location of the new high-frequency measurement stations, the approaches to implementation, and the provision of new flask sampling locations in important currently undersampled regions; 3) adoption of transparent data sharing; and 4) assured continuity of five to ten years to fully realize the fruits of this effort and its expenditures.

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