BAMS
In Box

Global Atmospheric Composition Observations

The Heart of Vital Climate and Environmental Action

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ABSTRACT: Further long-term investments in high-quality, research-driven, fit-for-purpose observations of atmospheric composition are needed globally to meet urgent societal needs related to weather, climate, air quality, and other environmental issues. Challenges include maintaining current observing systems in the face of eroding budgets for long-term monitoring and filling the geographical gaps for key constituents needed for sound services and policies. The observing systems can be bolstered through science-for-services applications, by embracing interoperable observation systems and standardized metadata, and ensuring that the data are findable, accessible, interoperable, and reusable. There is an urgent need to move from opportunities-driven one-component observations to more systematic, planned multifunctional infrastructure, where the observational data flow is coupled with Earth system models to serve both operational and research purposes. This approach fosters a community where user experience feeds back into the research components and where mature research results are translated into operational applications. This will lead to faster exploration and exploitation of atmospheric composition information and more impactful applications for science and society. We discuss here the urgent need to (i) achieve global coverage, (ii) harmonize infrastructure operations, (iii) establish focused policies, and (iv) strengthen coordination of atmospheric composition infrastructure.

KEYWORDS: Atmosphere; Air quality; Atmosphere-land interaction; Biosphere-atmosphere interaction; In situ atmospheric observations; Remote sensing

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High-quality global atmospheric composition observations are needed to support health assessments, document trends in greenhouse gas and criteria air pollutant emissions, monitor compliance with conventions and protocols, and underpin new policy measures for climate mitigation and adaptation. Forecasting air quality, sand and dust storms, volcanic ash, and biomass smoke plumes are examples of expanding operational services that require atmospheric composition observations alongside traditional weather information. Unfortunately, the current observing networks for atmospheric composition in many parts of the world are inadequate to support environmental regulations and provision of society-relevant services.

Our current atmospheric observation systems grew out of scientific curiosity and in response to specific environmental issues such as acid rain, deterioration of regional and local air quality, and stratospheric ozone depletion. These investigations led to the establishment of various long-term measurement stations by nations, universities, agencies, and research consortia. By the late 1960s, the World Meteorological Organization (WMO) recognized the need for a global program to coordinate measurements of atmospheric composition, as it had been doing for weather and climate. Initially, WMO had two major global atmospheric chemistry thrusts: (i) to measure baseline atmospheric composition and deposition and (ii) along with the United Nations Environment Program (UNEP), to observe, understand, and report on stratospheric ozone depletion. In 1989, these activities were consolidated along with others into the WMO Global Atmosphere Watch (GAW) program in response to growing concerns related to human impacts on weather and climate.

The GAW program provides a coordinating mechanism for observational networks, which include ground-based observations, satellite retrievals, and observations from aircraft, ship, and balloon platforms. These observational networks typically focus on specific issues, e.g., climate change (greenhouse gases and aerosols), stratospheric ozone depletion (UV and ozone-depleting chemicals), acid and nutrient deposition (precipitation chemistry and deposition), changing oxidizing capacity of the atmosphere (reactive gases), and health (aerosol). The good news is that today measurements of hundreds of trace gases, aerosol physical properties and chemical composition, and particle deposition rates obtained by the various networks and organized within the GAW framework provide a large amount of quality-assured, openly archived data. These data play key roles in supporting international conventions and scientific assessments like the Montreal Protocol and its supporting

Ozone Assessments, the Convention on Long-Range Transboundary Air Pollution, the Intergovernmental Panel on Climate Change, the Tropospheric Ozone Assessment Report, and other national and subnational assessments and programs.

However, there are significant deficiencies in atmospheric composition networks in terms of geographic coverage, the suite of variables measured, and prompt exchange of data. This is not surprising considering the diversity of institutions funding and implementing atmospheric composition observations. Compelling arguments are made for critical investments in each individual application network, as recently suggested by Weiss et al. (2021) for ozone-depleting chemicals. However, environmental problems caused by changes in atmospheric chemical composition are interlinked, as are the roles played by various atmospheric chemicals. For example, tropospheric ozone is both an important air pollutant and a short-lived climate forcer. Most ozone-depleting chemicals (e.g., chlorofluorocarbons and some of their replacements, nitrous oxide) are also powerful warming agents, and aerosols, depending upon their size and chemical makeup, affect both human health, weather, and climate.

Since the 1970s, the science of the environmental problems linked to atmospheric composition has matured and many policy instruments were developed and implemented. Today further investments in observational networks that measure a comprehensive suite of variables—e.g., greenhouse gases, air pollutants, and ozone-depleting chemicals—are needed to support policies aimed at reducing the collective environmental and societal impacts from air pollution (Fig. 1). There is a growing capability to couple observations from such networks to Earth system modeling, in a forecast mode where near-real-time data flow is required, and in reanalysis and research modes, where careful data collection and screening are essential. Examples include efforts from the Integrated Carbon Observation System (ICOS), the Aerosol, Clouds and Trace Gases Research Infrastructure (ACTRIS), the In-Service, Airborne Global Observation System (IAGOS), the Copernicus Climate Change Service (C3S), and the Network for Detection of Atmospheric Composition Change (NDACC). Through efforts such as these, observations underpin both environmental services and research applications.

Fig. 1. Elements of the boreal forest station Hyytiälä in Finland that measures the controlling variables in this ecosystem. It is an example of a comprehensive global Earth observatory (Kulmala 2018). As in other ICOS and ACTRIS stations across Europe, measurements cover variables in the atmosphere, biosphere, soil, and lake, which characterize water and energy flow and exchange, atmospheric chemistry, micrometeorology and cloud microphysics, water and nutrient content of soil and gas exchange with the atmosphere and the biosphere, and other processes. The observatory supports several platforms (some of these outdoor and laboratory instruments are illustrated).

This in turn leads to systematic validation and improvement of forecast model quality, identification of regions where additional observation sites are needed, generation of new research questions, and improved services.

What we need today is to build upon past accomplishments and advances in space-based assets, low-cost sensors, data management, model development, and computing capability to achieve a global comprehensive atmospheric composition observing and analysis infrastructure. This concept was laid out by WMO and the European Space Agency in the assessment of the status of the Integrated Global Atmospheric Chemistry Observing system for the major weather, climate, and air quality variables (Barrie et al. 2004), and was advanced by Kulmala (2018) and Weatherhead et al. (2018) for the climate system. We support this concept and underscore the urgency in realizing it.

The infrastructure includes ground-based in situ observations from both research grade instruments and low-cost sensors, ground-based remote sensing capabilities, mobile platform observations, and space-based instruments. This infrastructure also includes modeling and assimilation elements in an Earth system framework, along with the data management and discovery functions that enable a variety of atmospheric composition services, with all the elements embedded within a "research to operations to research" approach. This infrastructure also includes people with the requisite skills and the capacity-building and regional engagement elements necessary to sustain it.

The infrastructure for analysis of atmospheric composition has improved considerably over the past 20 years. This includes substantial developments in the observational capabilities from surface-based, aircraft, and satellite systems, including low-cost sensors, as well as enhancements in the Earth system modeling capabilities at both global and regional scales. These operational and research infrastructures are providing valuable predictions and reanalysis products. Furthermore, advances in the fundamental aspects of atmospheric chemistry achieved by the research community through international efforts such as the international Commission on Atmospheric Chemistry and Global Pollution and the International Global Atmospheric Chemistry project have provided a basis for the development and implementation of these operational aspects.

However, while many of the elements of this global observing system exist today, they are fragmented in bits and pieces. There are several critical elements that need to be addressed.

1) Achieve global multiconstituents coverage: We need to fill gaps in geographical coverage of observations, as there are large parts of the globe with few measurements of atmospheric composition, e.g., the oceans, high-latitude regions, and many developing countries. Often, in regions where observations are available, only a few components are measured. We also need to enhance observations of the vertical distribution of atmospheric compounds worldwide to better link observations from space to surface measurements and to provide information on plumes of volcanic ash and smoke for transportation safety.
2) Harmonize infrastructure operations: We need to develop standards and tools to advance the use of observations and provide open access and interoperable reliable data. This includes extending standards and metadata that can capture more diverse data streams and extend quality assurance and quality control approaches and tools to new data sources so that services can be improved and updated routinely.
3) Establish focused policies: Clear policies that recognize the critical role played by data providers and users are needed to draw attention to the importance of obtaining and sharing data. Similar policies exist in the weather domain at the international level, and within some infrastructures (e.g., ICOS, ACTRIS, IAGOS) that address the basic expectations of countries in terms of observations taken and how the data should be shared.

Policies are also needed to underpin the importance and impact of atmospheric composition infrastructure more strongly on achieving goals of international protocols and conventions.

4) Strengthen coordination of atmospheric composition infrastructure: This requires enhanced cooperation among the diverse groups and important existing networks involved as well as improved collaboration across agencies with international activities [e.g., WMO, UNEP, World Health Organization (WHO)] to provide near-real-time, consistent information on local and national scales.

We advocate that the path to achieving these objectives is to couple observational data flow to Earth system modeling in a manner whereby operational and the research infrastructures are synergistically bound together (Fig. 2). This is best practice for many weather and climate observations, and numerical predictions, but not as complete for atmospheric composition. This approach will help in realizing the vision for the "global Earth observatory" because it will mostly reside in the long-term, research-driven, and user-informed domain, which has the mandates—and the funding—to monitor compliance, identify and underpin unresolved environmental issues, and forecast pollution loads related to human health, agriculture, water quality, UV radiation, and climate change.

In this approach, the disciplinary boundaries between ozone layer research, climate science, deposition to Earth's surface, and air quality will fade, leading to better environmental predictions, analyses, and assessments. Furthermore, it will strengthen the interactions among the operational and research centers, which are moving away from being "weather," "climate," "marine," "air pollution," "water," or "ecosystem impact" focused to becoming

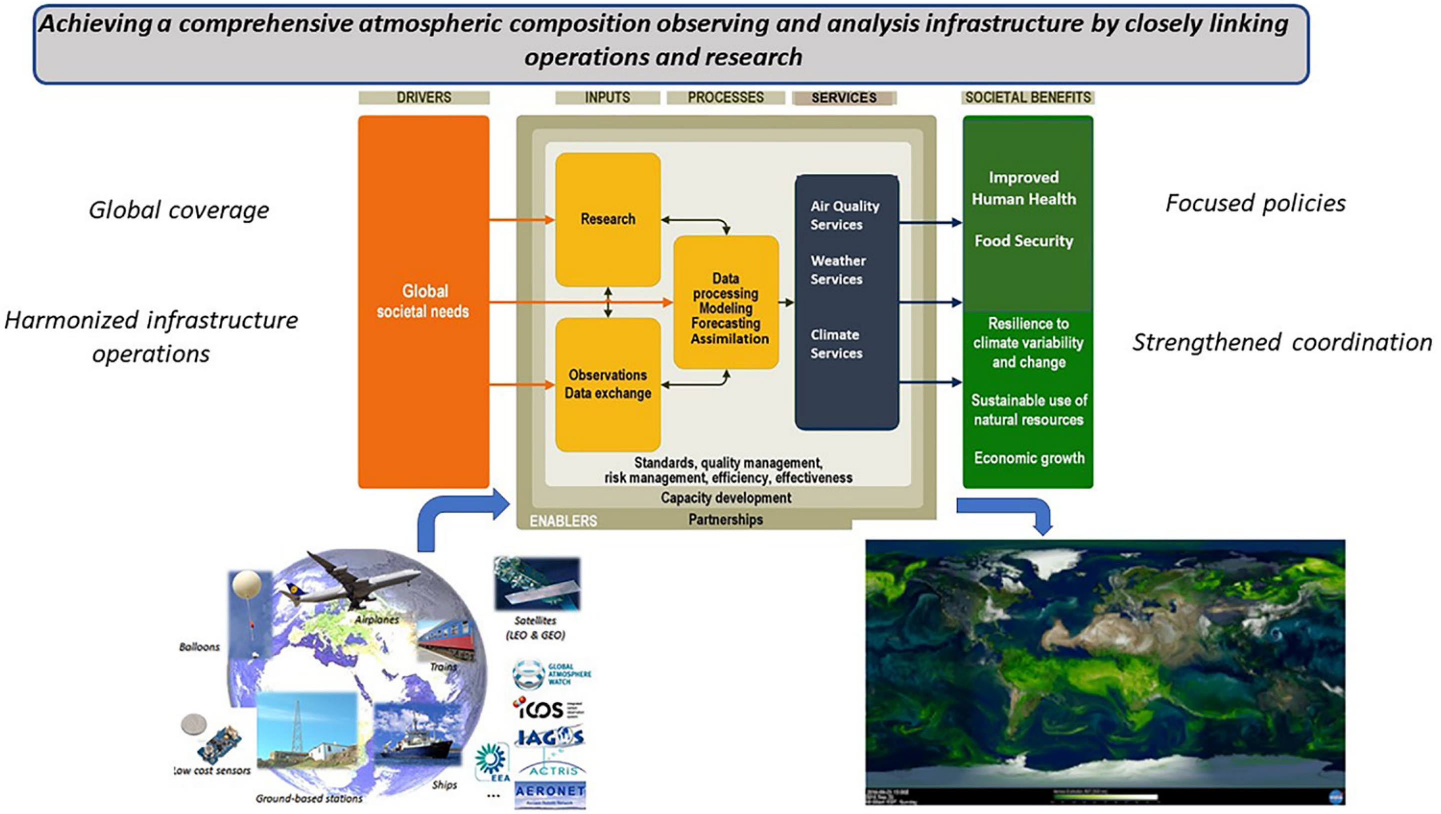

Fig. 2. A comprehensive atmospheric observing and analysis infrastructure consisting of observations of multicomponents and modeling and assimilation elements in an Earth system framework, along with the data management and discovery functions needed by society to enable a variety of atmospheric composition services. All the elements are embedded within a "research to operations to research" approach. This infrastructure also includes people with the requisite skills and the capacity-building and regional engagement elements necessary to sustain it.

more integrated Earth system oriented. This will also better coordinate and sustain the comprehensive observatories (as illustrated in Fig. 1) that today often reside in the science-for-research papers domain, by linking them together in the science-for-service domain. The resulting services will be science-based with more rapid translation of science advancements into improved operational applications.

A particularly good example of a successful interaction among research, operations, and services is the Copernicus Atmospheric Monitoring Service (CAMS) run on behalf of the European Commission by the European Centre for Medium-Range Forecasts (ECMWF). This is an operational infrastructure developed, supported, and run by a dedicated international organization and also serves as a research infrastructure on a day-to-day basis through trusted relationships with partners in academia. This pulls the research community into the pool of experience, knowledge, and direction that accumulates along with the operational use and services. In turn, it ensures the injection of new knowledge and techniques into operations.

Long-term funding of atmospheric composition observations remains a challenge. Even with the many advances being made in terms of the observing systems, in many cases there is eroding support for long-term, ground-based measurements. For example, three of four ozone sonde stations in Japan and at least one South American NDACC station have ceased operations in the past decade (DeMazière et al. 2018). Similarly, NOAA ceased supporting two of its six atmospheric baseline observatories a few years ago. Current initiatives investing in long-term research infrastructures such as ICOS, ACTRIS, IAGOS, and integrated forecast and analysis models that use atmospheric composition observations to address major weather, climate, and environmental issues, e.g., C3S, NDACC, and WMO's Integrated Global Greenhouse Gas Information System are examples of convergence of long-term funding and operations of infrastructures that underpin both research and services. In other parts of the world less expensive observations are implemented and help in providing environmental insight through observations and model analyses. These can involve low-cost sensors (Lewis et al. 2018) and provide rough impact estimates over areas where little or no information exists. Increased efforts by WMO, UNEP, and other organizations to secure funds are required to build the measurement, modeling, and analysis capabilities in developing countries.

Private corporations are increasingly engaged in providing atmospheric composition and weather information based on low-cost sensors, space observations, and models with excellent visualization tools, and are often ahead of WMO and other public institutions in communicating information. Increased partnerships between the private sector and public institutions are needed to ensure that societal risk reduction everywhere reflects available capabilities, and that the services can be sustained daily over the long term.

A crucial step forward in addressing the critical elements identified above occurred recently with the establishment of WMO's new Unified Data Policy (WMO 2021). This policy commits WMO and its members to broadening and enhancing the free and unrestricted international exchange of Earth system data, explicitly including atmospheric composition data. Further, it establishes that members should provide without charge access to all recommended data exchanged to public research and education communities for their noncommercial activities. It also encourages users of Earth system data to honor requests for the attribution of input data wherever possible.

In closing, it is essential that further long-term investments be made in high-quality, research-driven, fit-for-purpose, multicomponent, integrated observations of atmospheric composition to meet urgent societal needs related to weather, climate, air quality, and other environmental issues. Because most funding for observations and research is provided by national entities, the international structures—WMO, UNEP, WHO, and others—need to act in concert with national and regional agencies. As a first step we call on these organizations to perform gap analyses of existing atmospheric composition infrastructures supporting research and service provision. Then efforts need to be directed at eliminating the deficiencies by more closely linking atmospheric composition observations to operational services. The coupling of observational data flow with Earth system models serving both operational and research purposes will catalyze atmospheric composition research, application, and user-community engagement where user experience feeds back into the research components, and where mature research results are translated into operational applications. The national and international efforts should ensure that the communities of research and services converge, thus leading to faster exploration and use of atmospheric composition information and more effective applications for science and society.

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