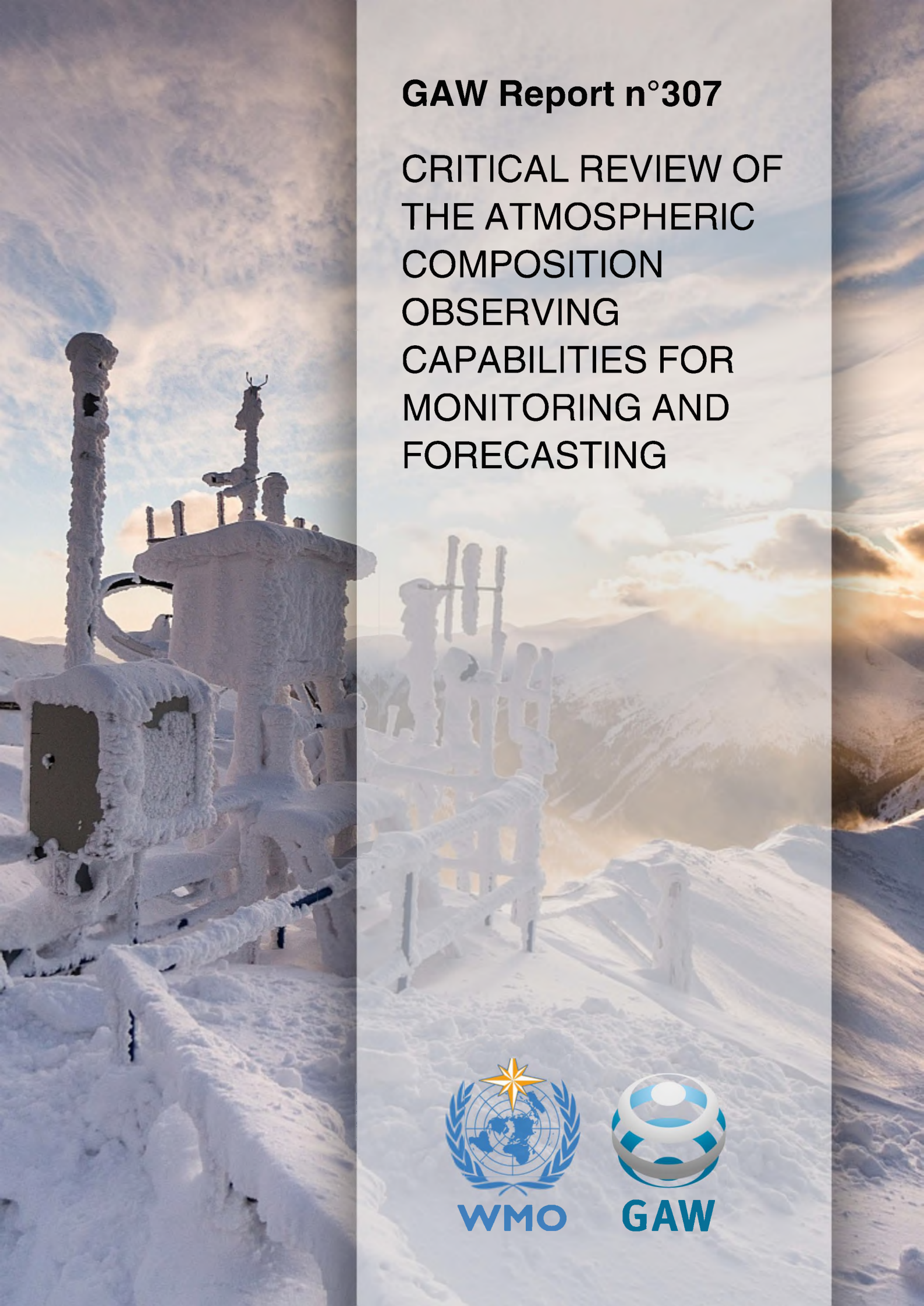

GAW Report n°307

CRITICAL REVIEW OF THE ATMOSPHERIC COMPOSITION OBSERVING CAPABILITIES FOR MONITORING AND FORECASTING

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CRITICAL REVIEW OF THE ATMOSPHERIC COMPOSITION OBSERVING CAPABILITIES FOR MONITORING AND FORECASTING

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CONTENTS

1. INTRODUCTION

Monitoring of atmospheric composition covers applications related to evaluating distributions and changes in atmospheric composition, both temporally and spatially, on regional to global scales. Such applications support scientific assessments and process studies and require measurement reproducibility, small data uncertainty, long-term stability, and global or regional data representativeness, while efficient data delivery can help ensure timely access to the observations. These monitoring applications include support for treaty monitoring, the assessment of trends in composition and emissions/fluxes, the early detection of unexpected anomalies in composition, and the production of climatologies and re-analyses. Data are often used in products such as the WMO Global Atmosphere Watch Ozone and Greenhouse Gas Bulletins and the State of Climate Services for Health report, and they provide the Essential Climate Variables (ECVs) related to atmospheric composition for the Global Climate Observing System (GCOS).

Forecasting atmospheric composition changes and their induced environmental phenomena covers forecasting applications from global to regional scales, with horizontal resolutions like global Numerical Weather Prediction (approx. 10 km and coarser), and with stringent timeliness requirements (near-real-time). The uncertainty of these forecasted atmospheric composition changes can be higher than in the case of monitoring. These applications include support for operations such as air quality and chemical weather forecasts, sand and dust storm warnings, wildfire plume dispersion, and haze-fog prediction. There are clear connections and synergies with many of the Numerical Weather Prediction applications. Although the new guidelines of the Rolling Review of Requirements have created new categorizations of the application areas, it is important to highlight that the requirements for monitoring and forecasting are different. This report will consider both application areas, noting that there are similarities in the observational requirements, but that these may vary depending on the application area.

This document provides a holistic vision of the gaps in observations for all the focal areas of the Global Atmosphere Watch (GAW) Programme: aerosols, long-lived greenhouse gases, stratospheric ozone and vertical ozone profiles, reactive gases (including tropospheric ozone, NO_x, CO, VOCs and SO_2), total atmospheric deposition, and UV radiation.

The variables covered by this document are part of the list of variables included in the application 2.6 of the Observing Systems Capability Analysis and Review Tool (OSCAR): Atmospheric Composition Forecasting and Monitoring. That database is the official repository of requirements for the observation of geophysical variables in support of WMO Programmes and Co-sponsored Programmes.

2. APPLICATION AREAS

2.1 Key variables and their prioritization

2.1.1 Aerosols

Atmospheric aerosols are solid or liquid particles suspended in the air. The impact of aerosols on the atmosphere is widely acknowledged as one of the most significant and uncertain aspects of climate change projections. There is growing concern for the impact of aerosols on human health and interest from many sectors such as weather prediction, the green energy industry (regarding their influence on solar energy reaching the ground) and the commercial aircraft industry (regarding the impact of volcanic ash and dust storms on operations and aircraft performance).

High-quality aerosol monitoring and specific threshold measurements are vital to the detection of trends in global distributions of chemical constituents in the atmosphere. More specifically, a key objective is to determine the spatio-temporal distribution of aerosol properties related to climate forcing and air quality on multi-decadal timescales and on regional, hemispheric, and global spatial scales. Achieving this objective requires support for GAW monitoring stations through the provision of recommendations for aerosol property measurements, mainly for the purposes of climate monitoring (GAW Report No. 227, 2016).

Measurements of the aerosol vertical profile, geographical extent and composition of polar stratospheric clouds (PSC) and of other stratospheric aerosols, including sulfate aerosols of volcanic origin, on which chlorine and bromine reservoir compounds are converted into reactive free radicals, are highly desired for monitoring ozone depleting substances (ODS), (see Section 2.1.3), as well as co-located measurements of the temperature profile.

Measurements of primary biological aerosols (bioaerosols: plant pollen, fungal spores, bacteria, viruses, plant debris, etc.), as well as microplastics, emerging species of the GAW IP 2024–2027, play crucial roles in environmental processes and can affect weather and climate, with direct implications for public health, agriculture and forestry industries, and society in general. Development of protocols for these species would substantially speed-up the development of the respective global monitoring capacity.

In terms of aerosol forecasting, numerical prediction of aerosol particle properties has become an important activity at many research and operational weather centers. A significant component of aerosol forecast development consists of streamlining aerosol-related observations and reducing the most important errors through model development and data assimilation (Benedetti et al., 2018).

2.1.2 Long-lived greenhouse gases

Greenhouse gases (GHG) influence the energy balance of the Earth by absorbing thermal infrared radiation emitted by the Earth's surface. Their presence in the atmosphere is of vital importance for life on Earth. However, new GHG introduced in the atmosphere by humans cause global warming. Earth System models predict future warming levels that pose an increasing threat to humanity, motivating climate policy to reduce GHG emissions, as is being implemented in the framework of the Paris agreement. Extended global greenhouse gas monitoring is needed to support this process. GHG monitoring focuses primarily on gases that are emitted by both human activities and natural processes, as opposed to compounds that change in response to such emissions (e.g. increases in atmospheric water vapour due to global warming).

Historically, research has focused on studying the large-scale carbon budget with focus on natural and anthropogenic carbon dioxide (CO_2) sources and sinks (e.g. terrestrial biosphere and oceans) (e.g. Revelle and Suess, 1957). Data were mostly collected from remote sites that were not largely impacted by anthropogenic sources. Now many other GHG (e.g. methane (CH_4), nitrous oxide (N_2O), and halocarbons), with residence times that are often long as compared with the mixing timescales of the atmosphere, are being monitored. Because of the relatively uniform global abundances of long-lived GHG in the atmosphere, measurements must be made with high precision; see e.g. GAW Report No. 255 (compared to urban applications, and the monitoring of most other atmospheric compounds; see, e.g. GAW Report No. 260, GAW Report No. 275). To comply with stringent precision and accuracy requirements the international community makes a significant effort to maintain and share common standards for use in the global network. GHG data from satellites have become available since 1991 in the stratosphere and over the past 20 years in the troposphere. Satellites have been collecting data globally including from regions that are sparsely sampled by the surface global reference network. Global ground-based networks continue serving as the basis of GHG monitoring as well as a reference for the necessary validation of the different satellite programmes. Data are utilized to estimate sources and sinks via atmospheric inversions. Recently, atmospheric inversions have been examined as a tool for providing flux estimates at policy relevant scales, such as countries and subnational scales (e.g. Henne et al., 2016; Deng et al. 2022; Bryne et al., 2023) beyond conventional continental and subcontinental scales.

Quantifying urban emissions has also become one of the major objectives in carbon science and climate mitigation applications. For example, the use of atmospheric data has been identified as an approach for evaluating inventories and/or generating independent GHG information (e.g. Pacala et al. 2010; IPCC 2019; NASEM 2022; GAW Report No. 275). Urban data have been collected in several global cities (likely many more if scientifically uncoordinated networks are included) and from intensive regional/local networks, and they are examined to better quantify urban emissions. Several forward-looking urban pilot studies (Indianapolis, Paris, Los Angeles, Washington DC/Baltimore, etc.) have collected and examined GHG data from urban sites to quantify emissions. It is important to note that urban requirements for observations are different from monitoring applications and that they are unique to each city and its objectives/approaches.

2.1.3 Stratospheric ozone and vertical ozone profiles

Stratospheric ozone is a naturally occurring gas that protects life on Earth from harmful solar ultraviolet radiation (see also Section 2.1.6). However, some anthropogenically produced gases can destroy the ozone layer in the polar regions during springtime (the Antarctic and arctic ozone holes) and globally on long timescales. Therefore, protecting the ozone layer is of great importance to the international community that is mandated by the Vienna Convention for the Protection of the Ozone Layer and the Montreal Protocol.

The Montreal Protocol and its amendments requires monitoring of total column and stratospheric profile measurements of ozone, several reactive gases, and aerosols to ensure compliance and for tracking its impacts. In order to attribute ozone (O_3) short and long-term variability in the stratosphere to natural and anthropogenic sources there is a need to measure various chemical compounds participating in catalytic cycles controlling O_3 under normal conditions and under activation of ozone depleting chlorine and bromine free radicals: nitrogen dioxide (NO_2), water vapour (H_2O), chlorine and bromine monoxides (ClO and BrO), and chlorine and nitrogen reservoir compounds (hydrogen chloride (HCl), chlorine nitrate ($ClONO_2$), nitric acid (HNO_3)). The necessary measurements of ozone depleting substances (ODS), such as halocarbons, some of which are regulated by the Montreal Protocol, and of N_2O, the main source of stratospheric NO_2, were addressed above in Section 2.1.2.

In a changing climate, combining analyses of processes impacting atmosphere, oceans, land surface, and biosphere are needed for the proper interpretation of reactive gas measurements in the troposphere and stratosphere. Thus, it requires observations of long-lived tracers and the "age of air" (a proxy for stratospheric mean meridional circulation). These observations are necessary to disentangle Montreal Protocol effects from changes in atmospheric general circulation and in exchanges between the upper troposphere and the lower stratosphere (UTLS). They are also needed to better constrain chemical transport models (CTM) with budgets and compact relationships of tracers, and to evaluate the influence of atmospheric circulation on changes in carbon uptake by oceans. Measurements of long-lived tracers like carbonyl sulfide (OCS), nitrous oxide (N_2O) and methane (CH_4) are helpful for tropospheric monitoring and forecasting, while hydrogen chloride (HCl), hydrogen fluoride (HF) and nitric acid (HNO_3) are useful tracers in the stratosphere. The age of air can be assessed from observations of e.g. carbon dioxide (observation requirements are addressed both here and in The 2022 GCOS Implementation Plan (GCOS-244)) and sulfur hexafluoride (SF_6).

2.1.4 Reactive gases

Reactive gases are key players in a wide variety of thematic domains, from air quality and the oxidizing capacity of the atmosphere to the stratospheric ozone and climate forcing themes. The group of reactive gases encompasses chemical compounds of diverse composition, which have a high (photo-)chemical reactivity and, accordingly, a relatively short lifetime – typically from a few weeks/months to a few seconds. They are either emitted directly into the atmosphere or produced by chemical reactions or photodissociation. Several of them exhibit a diurnal cycle of photochemical origin, controlled by solar radiation and interactions with changing emissions daily. As reactive gases travel from their region of emission or production, they may become diluted, deposited, chemically destroyed, or enhanced through continued photochemical production. Their concentration and mixing scales through the troposphere varies with their lifetime, the presence of other reactive gases with which they react, and meteorological conditions. Therefore, the observational requirements may vary by compound or compound family, by type of atmospheric environment (e.g. presence of other reactive gases and in particular the hydroxyl radical (OH^*) which controls many chemical processes), and by the vertical range where observational requirements are needed: at the surface, in the troposphere, in the stratosphere, in the mesosphere, and/or as a total column. Reactive gases that are common to several thematic domains include tropospheric ozone (O_3), nitrogen oxides (NO_2, NO_x, NO_y), carbon monoxide (CO), ammonia (NH_3), several volatile organic compounds (VOCs), and sulfur dioxide (SO_2). For example, produced by reactions of its precursors (VOCs and NOx) in presence of sunlight, tropospheric ozone is both a pollutant and a contributor to the oxidizing capacity of the atmosphere; it is also a short-lived greenhouse gas whose changes due to emissions of its precursors since pre-industrial times contribute to a significant tropospheric radiative forcing which is less than that of CH_4 but larger than that of N_2O. SO_2 emissions lead to the formation of sulfate aerosols, which cause a negative radiative forcing of climate by scattering incoming solar radiation back to space, as well as indirectly influencing cloud albedo and particle size.

An emerging observational need is to acquire additional co-located measurements of reactive gases like NO_2 and CO, of GHG like CO_2 and CH_4, and of vegetation related variables like solar induced fluorescence (SIF) for better attribution of emission sources, for coherent validation of new generation satellites that simultaneously measure several of these gases for the same purposes, and for evaluation of related modelling and emission inventory assessments.
The observation of NH_3 is also gaining importance, as this molecule plays an important role in the Earth's nitrogen cycle which has been dramatically modified by human activities. NH_3 has been measured globally by satellites since 2006, which requires proper geophysical validation against ground-based network measurements of reference.

Despite not pertaining to the category of reactive gases, the measurement of long-lived tracers is highly desired for the proper interpretation of reactive gas measurements in several thematic applications.

2.1.5 Total atmospheric deposition

Atmospheric constituents are removed from the atmosphere by both dry and wet deposition processes, each requiring observation of different variables.

While the deposition of certain nutrients (e.g. nitrogen containing species) can sometimes contribute positively to ecosystem productivity, excess deposition of nitrogen, sulfur, ozone, and other constituents can have negative impacts that threaten ecosystem function and biodiversity. Given the ecosystem impacts, total atmospheric deposition has wide-ranging consequences for food security, climate, and human health.

For wet deposition, a chemical flux can be directly estimated from observations of precipitation composition and precipitation volume. For dry deposition, the mass concentration or mixing ratio of relevant trace gases and aerosol constituents are observed and must be combined with dry deposition parameterization schemes to infer the flux. Thus, there is overlap between key variables for dry deposition and other sections in this document (e.g. "Aerosols", and "Reactive Gases"). For example, species that contribute to dry deposition of nitrogen include HNO_3, NH_3, NO_2, and aerosol ammonium (NH_4+) and nitrate (NO_3-). Minor, but regionally important species include other reduced and oxidized forms of nitrogen, including organic nitrates. Dry deposition estimates of O_3 likewise require observations of O_3 near the surface. To infer the dry deposition flux, required supporting measurements include land cover and land use variables, meteorological parameters, and leaf area indices.

2.1.6 UV radiation

Solar ultraviolet radiation affects both terrestrial and aquatic ecosystems (UNEP, 2019).
The biological effectiveness of solar ultraviolet (UV) radiation depends on the wavelength.
The short wavelengths are the most effective and dangerous for humans, plants, and animals as they can for example induce DNA damage and increase the risk of skin cancer. However, solar UV radiation has also positive effects by initiating the formation of vitamin D in the skin. In the atmosphere, UV radiation drives chemical reactions affecting air quality and climate. UV radiation is also responsible for the degradation of materials and is the key driver of microplastic formation.

The stratospheric ozone layer protects the Earth from the most dangerous UV wavelengths by effectively absorbing the shortest wavelengths. Since the 1980s, increases in global UV radiation have been observed due to stratospheric ozone depletion (e.g. WMO, 2011a). However, due to the success of the Montreal Protocol, changes in UV radiation levels have been small during the last 25 years, and changes in UV radiation outside polar regions have been mainly driven by variations in clouds, aerosols, and surface reflectivity (EEAP, 2023).

2.2 Spatial and Temporal variability of variables and identified key gaps

For climate applications, the most important parameters are described in The 2022 GCOS ECVs Requirements (GCOS 245). Here we describe the requirements for atmospheric composition monitoring and forecasting, which is a superset of the GCOS variables. Requirements for the following parameters are described as measurement thresholds (T) (minimum requirement to ensure data usefulness) and goals (G) (ideal requirement, no improvement needed) to assess their contribution to the characterization of Earth's climate. However, such thresholds can be different for specific applications (e.g. trend detection, radiative forcing and climate studies, chemical data assimilation).

2.2.1 Aerosols

There are numerous wavelength-dependent related parameters that describe optical and physical aerosol properties (attenuation, composition, scattering, absorption etc.) that are derived either in situ, described as columnar properties or derived as a function of their location (heights) in the atmosphere (profiles).

Aerosol instruments and measurement techniques have improved greatly over recent decades. The aerosol ECVs can be monitored with either in situ methods, remote sensing techniques, or a combination of both, either directly or based on a set of proxy parameters.

For climate applications, columnar properties such as aerosol optical depth (AOD) and aerosol absorption variables (e.g. Single scattering albedo) are the most important parameters for understanding the aerosol radiative effects. In addition to droplet forming aerosols in clouds (cloud condensation nuclei or CCN), the number of ice-forming aerosols in clouds (IN) would be an important parameter to quantify (Laj et al., 2020). Although the IN are mainly measured in short-term campaigns with varying instrumentation, the technical readiness is improving.

Aerosol chemical composition is typically defined as a bulk property of the total aerosol while it is often a strong function of the size. Size-dependent aerosol chemical composition information would improve the quantification of aerosol climate relevant properties and proxies. There are also emerging needs in forecasting aerosol parameters that directly relate to climate change feedback, including different bioaerosols, dust, sea-spray, elemental carbon, and other affected aerosol types (Szopa et al., 2021).

Multiwavelength Aerosol Optical Depth (AOD) quantifies the extinction of the radiation while it propagates in an aerosol layer and reflects the aerosol loading information in the view of remote sensing measurement. AOD is therefore the single most important aerosol parameter in determining the aerosol direct radiative effect (and forcing). AOD can be determined from the ground through solar attenuation measurements with sun-photometers (radiometers pointed at the Sun) at solar sub-spectral regions, where attenuation by atmospheric trace gases is negligible. Ground-based AOD measurements are more accurate than satellite-based ones, hence the first ones are used as validation points for the latter ones which have the advantage of global coverage. T and G requirements are 0.06 or 20% and 0.02 or 4%, respectively, in terms of measurement uncertainty while long-term stability is 0.04 or 10% and 0.01 or 2%. Temporal and spatial resolution T/G are 30 days/one hour and 500 km /20 km, respectively, while for forecasting activities and model assimilation timeliness T/G are 30 and one day(s). For forecasting applications, the timeliness requirement is 6 hours for threshold and one hour for goal.

Aerosol Particle Number Size Distribution (PNSD) is the particle number concentration as a function of multiple finite size ranges, which ideally extend from 15 nm to 15 μm (Goal).
A sufficient and useful threshold parameter for several climate applications is also the number of fine and coarse mode aerosol particles. PNSD can be directly measured in situ or retrieved under some assumptions from AOD-related measurements or light extinction vertical profile. PNSD, together with chemical composition, is a proxy parameter for CCN and aerosol extinction and scattering properties. Required uncertainties are defined separately for number (40 – 100%) and for size (20 – 40%). Required temporal and horizontal resolution depends on the application area. Modelling and forecasting of particle dynamic processes and transport requires better temporal resolution (one hour, G) than climate model applications (one month, G). Required horizontal resolution is between 50 km (G) and 500 km (T).

Aerosol Single Scattering Albedo (SSA) is defined as the ratio of particle light scattering coefficient to the light extinction coefficient and depends on light wavelength (the typically used value is 550 nm). Purely scattering aerosol particles (e.g. ammonium sulfate) have an SSA value of one. Absorbing aerosols have lower SSA values, for example strongly absorbing soot aerosol may have values of around 0.3 at 550 nm. SSA can be measured in situ or retrieved from remote sensing data (either integrated column or profile) under some assumptions. Required temporal resolution extends from 15 min (G) to one month (T), and horizontal resolution from 50 km (G) to 500 km (T). SSA is measured in situ and with sun-photometers which provide information on a columnar scale.

Aerosol light extinction vertical profile (Trop + Strat) is defined as the spectrally dependent sum of aerosol particle light scattering and absorption coefficients per unit of geometrical path length. Extinction profiles are retrieved by lidar observations, so they typically refer to punctual observations. In the stratosphere, extinction profiles can also be inverted from limb and occultation soundings from satellite. Effective vertical resolution and uncertainties are strongly dependent on the aerosol load. Required temporal resolution extends from one day (G) to 90 days (T) in the troposphere and 5 days (G) to 30 days (T) in the stratosphere (so that minor / medium volcanic eruptions can be detected), and horizontal resolution from 50 km (G) to 500 km (T) in the troposphere and 200 km (G) to 500 km in the stratosphere (where aerosols are fast spread in latitude bands and therefore, higher resolution is required along meridians than within latitude bands).

The chemical composition of aerosol particles forms as a complex mixture of inorganic salts (ammonium sulfates, ammonium nitrate, and sea salt), organic compounds, Elemental Carbon (EC), mineral dust, volcanic ash, biological particles, and others. Aerosol chemical composition can be measured directly as particle mass (μg m^{-3}), or indirectly based on several proxy properties, i.e. aerosol hygroscopicity, refractive index, other optical properties, and thermal volatility. Required temporal and horizontal spatial resolution for climate applications extends from one day and 50 km (G) to 3 months and 500 km (T), the latter being considered as sufficient in describing any seasonal and/or long-term changes over larger areas. Threshold uncertainty in measurements is 60%, while the goal is 20%.

Number of Cloud Condensation Nuclei (CCN) is the number of particles that can activate cloud droplets at a given supersaturation (typically 0.5%) and is defined either as particles per volume of air, or as % of the total particle number (CN). CCN can be directly measured with a CCN counter in situ, by using PNSD and chemical composition as proxies, or roughly approximated based on the fine mode AOD. The required temporal and spatial resolutions are from half a day and 50 km (G) to one month and 500 km (T). Target uncertainty is 60%, and the goal is 20%.

Characterization of bioaerosols assigns the observed number concentration of primary biogenic particles to a specific class (pollen, fungal spores, plant debris, bacteria, …) and determines the origin species. Modern methods allow for recognition of tens of the most abundant types in real time (Maya-Manzano et al, 2023) reaching down to individual events with the recognition uncertainty staying within 20–30%. Detailed calibration and evaluation of these devices is ongoing, with an overall target of 20% of the total uncertainty of the observations.

2.2.1.1 Gaps in measurement capabilities, calibration, and data quality

Aerosol observational systems have varying degrees of maturity in terms of data quality and reporting. Some systems, operated by ESA, NASA, EC / Copernicus, research infrastructures, WMO and meteorological organizations, etc., provide guidelines and assistance that aim at achieving a well defined threshold data quality. Global data repositories also have an important role in controlling the submitted data and metadata quality. These are not, however, globally agreed nor harmonized. In addition, several short-term data series, and smaller observational systems, do not follow an established measurement protocol or data quality standards.

2.2.1.2 Spatial gaps

The spatial gaps in the ground-based aerosol observing system are quite significant (Laj et al., 2020). While on-site measurements are crucial for reducing observations uncertainty, these observations are only performed with sufficient (T) density in North America and in Europe. In the tropics and the southern hemisphere, aerosol variable observations are heavily complemented with remote sensing instruments and proxies, without which there would be insufficient coverage for long-term climate applications. This comes at the expense of many available variables and their uncertainty in the lower and upper troposphere and stratosphere. Concerning columnar measurements AOD is measured by various networks with spatial gaps in the African continent and also over oceans. Absorption properties such as single scattering albedo are also retrieved though these measurements are limited to the areas with sufficiently high levels of AOD and not available for the UV wavelengths.

2.2.1.3 Temporal gaps

Trend studies of several aerosol variables are biased and there is limited spatio-temporal coverage of the data. Multidecadal trend studies have been performed using remote sensing data, in situ data, and various data proxies, on parameters such as aerosol number concentration, AOD or optical properties (Gliss et al., 2021; Schutgens et al., 2021; Schutgens, 2020; Rose et al., 2021).

Only in situ observations comply with the temporal resolution requirements of aerosol dynamical process-level simulations and forecasting e.g. air quality. Only remote sensing observing systems comply with the threshold requirements needed for the spatial resolution and global climate applications.

2.2.2 Long-lived greenhouse gases

2.2.2.1 Gaps in measurement coverage

The global surface monitoring network for greenhouse gases has a strongly heterogeneous global coverage with dense regional monitoring from tall towers in the EU Integrated Carbon Observing System (ICOS) and the US North American Carbon Project (NACP) as well as global urban monitoring in large, populated cities/areas (see more in the forthcoming Urban Applications Statement of Guidance) contrasted with sparse flask sampling elsewhere on the globe. Some regions, notably equatorial Africa, central Asia, polar regions and oceans, remain virtually unsampled by the network. Most of the measurements are collected near the Earth-surface, which may be sufficient at sites representing the well mixed background atmosphere to monitor large-scale source/sink balance but becomes more problematic near important emission regions. Measurements are also conducted using other platforms such as aircraft (e.g. routine vertical profile measurements in North America; trans-continental measurements by Japan Airline (JAL), IAGOS and CARIBIC) and cargo ships as voluntary observing ship programmes (e.g. NIES, Japan.

Greenhouse gas monitoring from recent Earth orbiting satellites (e.g. GOSAT for CO_2 and CH_4, OCO-2 and 3 for CO_2, GOSAT-2 for CO_2, CH_4 and CO, TROPOMI for CH_4) partly addresses the spatial coverage limitations of the surface network, particularly over the tropical areas. In addition, total column measurements from Short Wave InfraRed (SWIR) sensors provide a better representation of the greenhouse gas abundance in the whole atmosphere, supported by other instruments that are sensitive to specific altitude ranges (e.g. Thermal IR sensors, solar occultation, etc.). Most current carbon observing satellites are in a sun-synchronized polar orbit using reflected sunlight, they only measure a specific time of day (early afternoon) with a certain revisit cycle (e.g. 3 days for GOSAT and 16 days for OCO-2). Also due to geophysical difficulties including clouds and aerosols, day-to-day variability of mixing ratios is not well observed. Some regions, such as tropical rainforests, are difficult to measure because of cloud cover.

2.2.2.2 Gaps in measurement accuracy

The accuracy requirements for measurements of most long-lived greenhouse are highly demanding (0.1% or better). Global background in situ surface networks can provide this accuracy, thanks to major efforts to maintain calibration standards by a few laboratories and the distribution of calibrated gas tanks to others (e.g. GAW Report 292). Provided that these efforts will continue to receive the required priority in the future, global monitoring of greenhouse gas abundances and trends is possible at the required accuracy. Measurements of nitrous oxide are particularly challenging and require further attention and development.

For satellite remote sensing of greenhouse gases, while significant advancements made in the retrieval algorithms, the RRR accuracy requirements are difficult to meet. In part, this is because of the intrinsic difficulty of calibrating space borne instruments to the WMO gas standards, which can only be done in an indirect manner using limited profile measurements. The accuracy of satellite measurements relies on the accuracy at which the observed spectral radiances can be translated into greenhouse gas abundances, which is complicated by the limited spectroscopic knowledge in the important wavelength windows and the limited control on the light path due to scattering and aerosols and thin cirrus clouds. The latter causes subtle dependences of the retrieval on surface albedo, aerosol optical thickness, etc. Various options have been proposed to address this issue, including the use of an onboard aerosol sensor (e.g. GOSAT and CO2M mission) and the ranging capability of a space borne lidar (e.g. the Merlin) mission. These improvements planned for future missions still must be demonstrated in orbit.

2.2.2.3 Gaps in measured variables

Measurements of greenhouse gas mixing ratios provide crucial information about the size and trend of regional sources and sinks. However, additional information is needed to support the process attribution. Measurements of isotopes (e.g. ^{13}C and ^{14}C) and co-emitted species (e.g. CO, COS, APO, and NO_x) can provide this information. However, the coverage of such measurements is commonly not at the level required for operational monitoring yet. The challenging accuracy requirements of isotopic measurements can often be reached, but the techniques needed to achieve this are too expensive and/or labour intensive to apply to the whole monitoring network.

2.2.3 Stratospheric ozone and vertical ozone profiles

Total ozone column and vertically resolved profiles should be measured at the required spatial and temporal resolutions to provide baseline for stratospheric ozone recovery detection (expected at ~1% per decade) in support of the Montreal Protocol (MP) and its amendments.

Calibrated and quality assured WMO GAW ground-based observations are the cornerstone for providing he fiducial reference measurements (FRM) for satellite ozone product validation.

There is an ongoing reduction of the ozone ground-based observing stations around the world that should be monitored and regularly evaluated to identify regions of the low coverage. The Vienna Convention for the Protection of the Ozone Layer in collaboration with WMO GAW supports the needs of developing countries for monitoring of ozone and ODS changes. This collaboration with other ozone observing networks (e.g. NDACC, SHADOZ and ACTRIS) should continue in the future to ensure collection of valuable records and capacity building.

WMO GAW requirements for the archival of ozone data collected by the GAW stations is described in the OSCAR requirements. The Standard Operating Procedures (SOPs) are developed under the WMO GAW and timely refined (Ozonesonde Measurement Principles and Best Operational Practices, ASOPOS 2.0 (GAW Report No. 268), Dobson observer guidance, Brewer SOP, etc.)

For total column ozone, the T/G values are 100/5 km in horizontal resolution, 24/6 hours in observing cycle and 3/one hours in timeliness. For stratospheric ozone, T/G are: 200/50 km for horizontal resolution, weekly/daily for observing cycle and 30 days/one week for timeliness. For tropospheric ozone, T/G are: 20/5 km for horizontal resolution, one day/3 hours for observing cycle and one year/2 months for timeliness.

Altitude registration uncertainty can be high in nadir (up to several km) and even limb (±1 km) satellite observations and impacts e.g. on the ozone trend detection. Besides classical requirements on stratospheric ozone value uncertainty and on vertical resolution, users may have requirements on vertical registration uncertainty as well.

Interactive chemistry in the NWP forecast is of importance for producing the chemical weather predictions, but also to improve Sudden Stratospheric Warming (SSW) predictions on seasonal to sub-seasonal (S2S) scales, that impact precipitation, temperature and other meteorological anomalies, and for the assessment of radiative forcing variability driven by the atmospheric composition change.

While some users work with volume mixing ratio (VMR) units (nmol/mol) or partial pressure (mPa), other users (i.e. WMO/UNEP Ozone Assessments, SPARC and TOAR Reports) use total and partial columns (i.e. DU) and number density (mol/cm^3). Conversions between these units are well defined but, since they also depend on the auxiliary information (e.g. temperature) which might be not measured by the same system (i.e. conversions from altitude to pressure), they are thus reliant on climatology or reanalysis. Calculations of partial columns in case of highly resolved ozone observations rely on the definition of the tropopause. In the case of remote sensing applications, representation of ozone profile in vertical coordinates depends on the retrieval algorithm.

2.2.4 Reactive gases

2.2.4.1 Tropospheric ozone

It is a short-lived climate forcer and the third most important greenhouse gas after CO_2 and methane (Szopa et al., 2021); at the surface tropospheric ozone is also an air pollutant, detrimental to human health and crop and ecosystem productivity (Fleming and Doherty et al., 2018; Mills et al., 2018). Due to its wide range of impacts, a dual strategy is required to monitor tropospheric ozone focusing on climate impacts and air quality impacts.

(1) Climate impacts: In terms of monitoring tropospheric ozone's impact on climate change, routine vertical profiles are required especially in the mid- and upper troposphere where ozone's long-wave radiative forcing is greatest. As reviewed by the Tropospheric Ozone Assessment Report (Gaudel et al., 2018; Tarasick and Galbally et al., 2019), ozone profiles are routinely measured by commercial aircraft at several major airports, by ozonesondes at about 60 locations worldwide, and by a few lidars. With uneven spatial distribution, the existing network is not globally representative, with many stations clustered in Europe, North America and East Asia. The sampling frequency is often quite low (most ozonesonde stations collect just one profile per week), or in the case of commercial aircraft, highly intermittent as flight routes of instrumented aircraft change often. Several studies have shown that weekly profiling is insufficient to calculate an accurate monthly mean or an accurate long-term trend (Logan, 1999; Saunois et al., 2012; Chang et al., 2020). While three ozonesonde sites in Europe launch three sondes per week (12 per month), the only locations with consistent, high frequency (> 20 profiles per month) ozone profiling are a few airports in the Northern Hemisphere frequented by IAGOS (In-Service Aircraft for a Global Observing System) commercial aircraft, and the JPL TOLNet Table Mountain lidar near Los Angeles.

(2) Air quality impacts: In terms of monitoring surface ozone pollution, extensive networks are located across North America, Europe, and East Asia, with limited monitoring in South Asia and South America, and almost no monitoring in Africa (except for South Africa) and the Middle East. While relatively dense monitoring exists in the USA and EU, only a small fraction of the population lives close to a measurement site that is directly relevant to their daily lives, for example the USA has about four ozone monitors for every million people, and Europe has about three (Fleming and Doherty et al., 2018). Considering the deficiencies of in situ surface ozone monitoring, new developments in satellite ozone products can help to fill the gaps.

The tropospheric ozone column has been retrieved from Low Earth orbiting (LEO) solar backscatter satellites for several decades, the accuracy, stability and latitude range of the data depending on the spectral range of the measurement, the retrieval method and the orbit. Geostationary (GEO) satellite instruments of the same type can now monitor tropospheric column ozone or lower tropospheric ozone across an entire continent at hourly intervals during daylight hours, at the typical resolution of 4–8 km: KARI's GEMS over Southeast Asia since 2020, NASA's TEMPO over North America since 2023, and Sentinel-4 UVN over Europe planned for 2025. This deployment of a LEO+GEO constellation of air quality sounders is an important advance in our ability to monitor ozone, but routine ozone profiling at many locations several times per day will be required to validate the satellite data products, and atmospheric chemistry models will be needed to assimilate the satellite data and estimate the surface ozone concentrations.

2.2.4.2 Nitrogen oxides (NO_x)

In the troposphere NO_x (NO + NO_2) are primary pollutants emitted mainly from fossil fuel combustion activities, and as such are common contributors to air quality problems in urban areas. NO_x also participates in atmospheric chemistry that leads to the formation of ground-level O_3 and secondary inorganic and organic aerosol, with implications for both air quality and climate forcing. As a regulated primary pollutant in many countries, surface NO_2 is routinely monitored by national and regional networks for the purpose of establishing compliance. Common in such routine monitoring is a technique where NO_2 is measured by chemiluminescence following an initial conversion to NO, offering mole fraction detection limits of around 0.5 ppb, with precision in ambient monitoring applications usually on the order of 0.5 ppb. This does not account for potential interferences during the conversion step that could result in species other than NO_2 being included in the NO_2 measurement, and thus introducing unknown accuracy issues. These interferences are generally assumed to become more important in less-urban environments where the contribution of true NO_2 to the total fraction of oxidized nitrogen decreases (possibly approaching >50% of the overall signal (e.g. Dunlea, 2007). NOx also controls ozone production and destruction in the free troposphere, originating from lightning, aircraft emissions or transport from the boundary layer. Four complementary networks measure the tropospheric, stratospheric, and total column of NO_2 worldwide. The vertical column and low-resolution profile of tropospheric NO_2 is measured by MAX-DOAS UV-visible instruments at about 60 stations around the world, although without a coordinated strategy and network-wide common settings. The stratospheric NO_2 column is monitored at all latitudes by about 20 zenith-scattered-light (ZSL) UV-visible DOAS spectrometers and about 20 FTIR spectrometers, all performing network operation in the framework of the Network for the Detection of Atmospheric Composition Change (NDACC). Continuation of operation of the ZSL-DOAS instruments has become uncertain at several stations and several of them have already stopped operation, endangering in several latitude zones the continuity of the time series started in the 1980s. The total column of NO_2 is measured worldwide by an increasing number of Pandora UV-visible DOAS spectrometers performing network operation in the framework of the Pandonia Global Network (PGN). Altogether, these four networks provide the necessary set of fiducial reference measurements for the validation of the LEO+GEO satellite constellation for air quality already mentioned for the tropospheric ozone theme. Their mutual coherence deserves some more quality assurance. Monitoring of NO_x in the free troposphere is extremely limited. NO_x, NO_y and/or NO_2 concentrations at flight altitude and their vertical profiles during ascent and descent at a few airports are measured intermittently by chemiluminescence-

based and visible-absorption systems onboard commercial aircraft participating in the IAGOS programme.

Declining NO_x emissions in some countries are challenging the ability of routine monitoring efforts to further quantify continued reductions. Therefore, such routine measurements often do not meet the scientific requirements for NO_2 mole fraction in applications related to emission constraints and trends, where recommended threshold uncertainties should be below 0.2 ppb and within 10%.

2.2.4.3 Tropospheric column (NO_2)

NO_2 can also be retrieved from satellite-based solar backscatter measurements, offering long-term global observations of tropospheric NO_2 vertical column density (VCD). Such tropospheric retrievals are relevant to air quality applications and surface emission constraints but require methods of inferring the contributions from stratospheric NO_2 to the total column measured primarily by satellite, which can introduce some uncertainties (Boersma, 2004, Geddes, 2018, Verhoelst, 2021). The current generation of instruments offer individual retrievals with a spatial resolution on the order of ~5 x 5 km² (e.g. TROPOMI with a current spatial footprint of 5.5 km x 3.5 km). The uncertainty of individual tropospheric NO_2 VCD retrievals is sensitive to observing conditions, pollutant concentration profile, and the quality of a priori geophysical inputs to the retrieval. Error analyses of satellite derived tropospheric NO_2 VCD generally suggest that tropospheric NO_2 can be retrieved with an uncertainty of about 20% in clean to slightly polluted conditions but reaching values as high as 50% over highly polluted areas. Uncertainties can be reduced when high-resolution inputs (e.g. surface reflectance, elevation, and NO_2 vertical profile shapes) are introduced to the retrieval (Laughner, 2016, van Geffen et al., 2022; Douros et al., 2023), pointing to the crucial role of high-quality modelling and supporting datasets in satellite remote sensing of air quality. Along with the tropospheric NO_2 data, the stratospheric NO_2 column is also retrieved from the same satellite measurements, with an uncertainty usually better than 5% in summer up to 15% in winter.

Current satellite-based methods for retrieving tropospheric NO_2 may satisfy the T observational requirements for many science applications (uncertainty of ~2 x 10^{15} molec/cm^2 or 50%), but do not meet breakthrough requirements of uncertainty on the order of 0.5 x 10^{14} molec/cm^2, or 10%.

2.2.4.4 Ammonia (NH_3)

NH_3 is a primary pollutant associated predominantly with agricultural activities (e.g. animal husbandry and crop fertilization), and causes secondary pollution by contributing to inorganic aerosol mass, with implications for both air quality and climate. When deposited to terrestrial and aquatic ecosystems, this reduced nitrogen also has consequences for ecosystem productivity and health. Although often recognized as a hazardous pollutant, few countries have enacted regulations to restrict NH_3 emissions, which contributes to a lack of routine monitoring.
For monitoring and forecasting, observation requirements for NH_3 include near surface and/or boundary layer mole fraction with a G of 20 ppt or 10% uncertainty, T of 200 ppt or 30–50% uncertainty.

A defined observing cycle requirement has not been identified, but atmospheric processes relevant to air quality impact of NH_3 can occur on the timescale of hours. However, where available, ground-based observation networks of NH_3 have tended to use diffusive passive sampling or active denuder sampling techniques with integration times of around two weeks or greater that require subsequent chemical analysis. Detection limits and uncertainty vary by integration time and analytical protocol. Improved temporal sampling (~24-hr) in routine monitoring of total inorganic ammonium (NH_3 and NH_4+) has been implemented using filter pack methods, but these lack the speciation between gas-phase NH_3 and particle-phase NH_4+.

NH_3 can also be inferred from satellite-based measurements, generally retrieved in the thermal infrared region of the electromagnetic spectrum. Examples include AIRS (on board the AQUA satellite), IASI (on board the MetOp-A/B/C satellites), CrIS (on board Suomi NPP, NOAA-20, NOAA-21, and will be on JPSS-3/4 satellites), and the upcoming IASI-NG (on board the MetOp-SG-A1/2/3 satellites) all of which have circular spatial footprints on the order of 15 km. These low Earth orbiting instruments provide global coverage with up to two measurements per day (daytime and nighttime). Due to the nature of the retrieval, vertical profiles can be collected, and near surface concentrations (e.g. ~900 hPa) can be retrieved under ideal conditions. As for any satellite data ground-based validation is important and requires fiducial reference measurements, e.g. acquired by NDACC FTIR spectrometers.

2.2.4.5 Volatile organic compounds (VOCs)

VOCs are a complex mix of hundreds of carbon-containing gases. It should be noted that VOCs are reactive gases, and some VOCs are also greenhouse gases.

Individual VOCs may impact stratospheric ozone depletion, climate change, and/or air quality. Lifetimes of individual VOCs cover the range from hours to decades. Shorter-lived VOCs become depleted as they travel from their source region and may have significant regional variability, while longer-lived VOCs can accumulate and mix throughout the troposphere. Because of this, the observational requirements may vary by compound or compound class.

For this discussion, VOCs are roughly sub-divided into shorter-lived (lifetime < 1 yr) and longer-lived (lifetime > 1 yr) groups. Shorter-lived compounds include non-methane hydrocarbons (e.g. ethane, toluene), organic nitrates (e.g. methyl nitrate), selected halocarbons (e.g. dichloromethane or CH_2Cl_2), dimethyl sulfide (DMS), and oxygenated VOCs (OVOCs, e.g. methanol). Longer-lived compounds include selected halocarbons (e.g. CFC-11, HFC-134a) and carbonyl sulfide (COS).

Table 1 summarizes the recommended VOC measurement requirements for monitoring and forecasting applications. For shorter-lived VOCs, the recommended measurement uncertainty for goal (G), breakthrough (B) and threshold (T) applications are five ppt or 5%, 10 ppt or 10%, and 30 ppt or 20%, respectively. For longer-lived VOCs, the recommended measurement uncertainty for G, B and T applications are one ppt or 1%, 3 ppt or 3%, and 10 ppt or 10%, respectively. In each case, the recommendation is X ppt or X%, whichever is larger. For example, for a global background CFC-11 mixing ratio of 226 ppt (Gulev et al., 2021), the goal uncertainty is one ppt or 1% (2.3 ppt), so in this case 2.3 ppt is the larger value. Note that actual measurement capabilities may exceed the goal uncertainty.

Table 1. Recommendations for VOC observational requirements for monitoring and forecasting applications, for goal (G), breakthrough (B) and threshold (T) applications.

NMHC = non-methane hydrocarbon, OVOC = oxygenated VOC, DMS = dimethyl sulfide, COS or OCS = carbonyl sulfide. 5 ppt/5% means "5 ppt or 5%, whichever is larger".

VOC compound class	Uncertainty G	Uncertainty B	Uncertainty T
Short-lived VOCs			
NMHCs	5 ppt / 5%	10 ppt / 10%	30 ppt / 20%
OVOCs	5 ppt / 5%	10 ppt / 10%	30 ppt / 20%
Organic nitrates	5 ppt / 5%	10 ppt / 10%	30 ppt / 20%
Halocarbons (short)	5 ppt / 5%	10 ppt / 10%	30 ppt / 20%
DMS	5 ppt / 5%	10 ppt / 10%	30 ppt / 20%
Long-lived VOCs			
Halocarbons (long)	1 ppt / 1%	3 ppt / 3%	10 ppt / 10%
COS	1 ppt / 1%	3 ppt / 3%	10 ppt / 10%

2.2.4.5.1 Gaps in measurement variables

VOCs have a complex mix of natural and anthropogenic sources, including biogenic emissions (e.g. isoprene), fossil fuel combustion (e.g. ethene), fossil fuel evaporation (e.g. *i*-pentane), solvents (e.g. toluene), biomass burning (e.g. acetonitrile), oceanic (e.g. DMS) and so forth. Many VOCs are emitted from multiple sources. The existing priority VOCs within the GAW reactive gases programme have been published in Schultz et al. (2015), Carpenter et al. (2022) and Apel et al. (2023) and are summarized in Table 2. The priority VOCs have been selected over the years to emphasize a range of commonly emitted VOCs from the various major sources. While the list is not exhaustive, it is maintained here, and no additional gaps are identified for VOC measurement variables in the context of monitoring and forecasting applications.

Table 2. Priority VOCs within the GAW reactive gases programme.

GC = gas chromatography, FID = flame ionization detection, MS = mass spectrometry, PTR = proton transfer reaction, BB = biomass burning. Reproduced from Carpenter et al. (2022).

Molecule	Formula	Lifetime	Analysis Method	Major Sources
Ethane	C_2H_6	2 mo	GC-FID	Anthropogenic, BB
Ethyne	C_2H_2	15 d	GC-FID	Anthropogenic, BB
Propane	C_3H_8	11 d	GC-FID	Anthropogenic, BB
i-Butane	C_4H_{10}	5 d	GC-FID	Anthropogenic
n-Butane	C_4H_{10}	5 d	GC-FID	Anthropogenic
i-Pentane	C_5H_{12}	3 d	GC-FID	Anthropogenic
n-Pentane	C_5H_{12}	3 d	GC-FID	Anthropogenic
Isoprene	C_5H_8	3 hr	GC-FID, PTR-MS	Biogenic

Molecule	Formula	Lifetime	Analysis Method	Major Sources
Monoterpenes	$C_{10}H_{16}$	4–5 hr	GC-FID, PTR-MS	Biogenic
Benzene	C_6H_6	10 d	GC-FID, GC-MS	Anthropogenic, BB
Toluene	C_7H_8	2 d	GC-FID, GC-MS	Anthropogenic, BB
Formaldehyde	CH_2O	1 d	DOAS	VOC oxidation, BB
Methanol	CH_3OH	12 d	GC-FID, PTR-MS	Biogenic, VOC oxidation
Ethanol	C_2H_5OH	4 d	GC-FID, PTR-MS	Biogenic, anthropogenic
Acetone	C_3H_6O	2 mo	GC-FID, PTR-MS	Biogenic, anthro, VOC ox.
Acetonitrile	CH_3CN	6–12 mo	GC-MS, PTR-MS	BB
DMS	C_2H_6S	2 d	GC-FID, PTR-MS	Oceanic

2.2.4.5.2 Spatial gaps

Ground-based VOC measurements and metadata collected as part of the GAW network are archived with the World Data Center for Reactive Gases (WDCRG), which is hosted by the Norwegian Institute for Air Research (NILU; http://ebas.nilu.no). The VOC instrument types include online gas chromatography (GC) and Proton Transfer Reaction – Mass Spectrometry (PTR-MS). The current state of VOC measurements within the GAW network is summarized in Carpenter et al. (2022). Currently only a few stations, mostly within Europe, report continuous in situ VOCs within the GAW framework (Carpenter et al., 2022). For example, a search of online GC measurements of ethane within the GAW-WDCRG framework yields 13 sites, with no data from Asia and only one site in the Southern Hemisphere. Note that only data that are submitted to the data repository are included, which means that spatial gaps may represent a gap in terms of data submission rather than an actual gap in the measurements.

The LEO+GEO constellation of UV-visible-NIR solar backscatter satellites being deployed by CEOS agencies procure observations of some VOCs like formaldehyde and glyoxal. Satellite observations can in principle fill in spatial gaps between stations. However, the limited accuracy of these VOC retrievals and limited number of measured compounds, requires averaging of the data over significant areas to reach mission requirements, to the detriment of geographical resolution. Their poor sensitivity to the low troposphere prevents their use for this spatial gap filling. The network of NDACC FTIR spectrometers provides observations of the formaldehyde column at about 20 sites in the world and is used for the validation of the aforementioned satellite constellation for air quality. A network of MAX-DOAS UV-visible instruments with formaldehyde and glyoxal column observation capabilities is also being deployed and used for satellite validation, although without a coordinated strategy and network-wide common settings at the time being.

2.2.4.5.3 Temporal gaps

The temporal gaps within the GAW-WDCRG data repository vary with instrument type, and some VOC measurements within the GAW network have shut down in recent years. Again, using ethane as an example, weekly or near-weekly glass flask measurements are available at about 45 global sites from start-times ranging from 2000–2014, and most have end-times in 2016 (http://ebas.nilu.no). Steel flask data are available from about 20 sites, mostly in Europe, with start-times ranging from 1989–2016 and end-times ranging from 1999–2018. Like the spatial gaps, the end-times for the flask data may represent a pause or cessation of monitoring, as in the case of the glass flasks, or they may represent a case where the monitoring is ongoing but recent data have not yet been uploaded. Online ethane data from the 13 stations listed above have start-times ranging from 1991–2020 and end-times ranging from 1993–2021.

Overall, there are significant spatial and temporal gaps in the GAW-WDCRG data repository in the context of global monitoring of VOCs. While some of the gaps are due to a lack of measurements, others are because existing datasets are not archived within the GAW-WDCRG data repository.

2.2.5 Total atmospheric deposition

Quantifying total atmospheric deposition requires estimates of wet and dry fluxes. Wet deposition fluxes can be estimated as the product of species concentration in precipitation samples and the precipitation depth (thus, both precipitation composition and precipitation volume must be coincidently measured). In addition to acidity (pH), precipitation chemistry that is routinely measured by regional networks such as EMEP, EANET, CAPMoN, and NADP include sulfate, nitrate, ammonium, chloride, and cations of sodium, potassium, calcium, magnesium. Important but under-observed contributors to total nitrogen, sulfur, and acid deposition include organic nitrates and organic sulfates, and organic acids respectively. Total phosphorous is also an important nutrient that has been excluded from many precipitation chemistry networks. A defined observing cycle for total atmospheric deposition has not been identified, but the GAW Precipitation Chemistry Programme (WMO, 2004) recommends 24-hour (highly recommended) or weekly (recommended) sampling for wet deposition. Sampling periods beyond seven days are not recommended (WMO, 2004). The GAW Programme has established data quality objectives for individual analytes and measurement of precipitation depth (WMO, 2004). Detection limits and uncertainties vary by collection and laboratory analysis protocol.

The fraction of a species deposited by dry deposition must generally be estimated indirectly by combining atmospheric concentrations with inferential modelling of dry deposition velocities. Therefore, the same observational deficits that are present for monitoring and forecasting of reactive gases in general would exist for inferential estimates of dry deposition. For example, in the case of total nitrogen, dry deposition of NH_3, NO_2, HNO_3, and organic nitrates must be considered in addition to deposition of ammonium and nitrate ions and aqueous organic nitrogen compounds in precipitation. Depending on climate and chemical constituent, dry deposition can potentially dominate the total deposition budget, so that these indirect methods introduce large uncertainties in regional deposition estimates. This fraction is particularly notable in the case of O_3 deposition. Deleterious toxicological effects of O_3 uptake into plant stomata represent a threat to ecosystem productivity with consequences for carbon storage and crop yields.

Observations of deposition are generally sparse over much of the globe, hindering efforts to derive spatially continuous estimates of total deposition without relying very heavily on chemical transport models. Routine monitoring capabilities and major gaps in precipitation and deposition monitoring have been assessed previously (Vet et al., 2014), and many of these gaps persist. In terms of precipitation chemistry, the speciation and quantification of organic compounds (e.g. nitrogen containing species, and organic acids that contribute to acidity) are lacking. Our understanding of phosphorous deposition also continues to be limited, due to limited measurements. Finally, many major regions of the globe remain poorly sampled for atmospheric deposition estimates (particularly South America, Africa, Oceania, large parts of Asia, and polar regions). Relative to wet deposition, observations of dry deposition are much more limited, and few long-term observations exist. As noted above, determination of broad spatial and temporal patterns of dry deposition will rely on inferential modelling until low-cost methodologies for dry deposition suitable for routine monitoring are further developed and deployed.

2.2.6 UV radiation

2.2.6.1 Spectral UV irradiance

In this context, UV radiation stands for the UV wavelengths of the total solar spectrum which reaches the surface of the Earth, UVB (280–315/320 nm) and UVA (315/320–400 nm) radiation. Changes in surface UV radiation depend on changes in ozone, cloudiness, surface albedo, and atmospheric aerosols. As the effects of UV radiation and interaction of the radiation with atmospheric components depend on its wavelength, spectral UV measurements are the state-of-art measurements for trend detection and UV climate monitoring. The challenge is to maintain the sensitivity of the instrument at all wavelengths, as the dynamic range of the UV radiation is of several orders of magnitude. The GAW Scientific Advisory Group for Ozone and UV Radiation has developed SOPs for different categories of UV instruments and guidelines for instrument characterization and calibration (e.g. WMO 1998, 2001, 2003, 2008, 2010).

User requirements can be found in OSCAR. Following WMO 2011b, the ambitious goal is to detect a change in spectral UV irradiance resulting from a 1% change in total ozone column. The effect of a 1% change in total ozone column on spectral UV irradiance depends on the measured wavelength, solar zenith angle (SZA), and total ozone amount. For the erythemally weighted UV irradiance, the effect is typically between 1 and 2%, depending on SZA and the total ozone amount. Thus, the uncertainty G is ambitiously set to 1% (1 sigma) for the monitoring application area, and to 2.5% (1 sigma) for the forecasting application area. The corresponding T value is set to 5% for M and kept at 2.5% for F application areas. Regarding horizontal resolution, the challenge is the effect of rapidly moving clouds, and changes due to topography, in e.g. mountainous areas. The G requirements are for forecasting 1 km and for monitoring 100 km, and T requirements are 10 km and 500 km, respectively. For the monitoring application area, the G for observing cycle is set to one minute to catch the effect of changing cloudiness on e.g. daily doses, while T is 30 minutes.

2.2.6.1.1 Gaps in measurement accuracy

The requirements for the instrumentation can be found in WMO (2001). The World reference spectroradiometer QASUME represents the state-of-art in spectral UV monitoring instruments. The expanded uncertainty of the spectral solar UV irradiance measurements (k=2) of the QASUME is 1.7 % for overcast situations (diffuse sky) and 2.0 % for clear sky situations (Hülsen et al., 2016). Thus, the quality of existing spectral measurements is good, but that can be achieved only by following carefully quality assurance/quality control (QA/QC) guidelines (WMO, 2003, WMO, 1998).

To achieve accurate measurements, a regular calibration schedule with an irradiance scale traceable to National Standards should be followed, or regular comparison with reference instruments should be performed. The World reference spectroradiometer is in PMOD-WRC in Davos (Gröbner et al., 2005). It performs regular site audits around the World. However, most of the sites are in Europe. Results from the site audits can be found in https://www.pmodwrc.ch/en/world-radiation-center-2/wcc-uv/qasume-site-audits/ (last visit 23 Feb 2023). The last intercomparison for spectral UV irradiance scale provided by the National Metrological Institutes was published in 2008 (https://iopscience.iop.org/article/10.1088/0026-1394/45/1A/02002, last visited 24 Feb 2023).

2.2.6.1.2 Spatial gaps

The state-of-the-art spectroradiometers are expensive scanning instruments. They have also the disadvantage that the scanning time is long, every 10 minutes. This makes it difficult to assess the effects of fast changes in intensity, for example, due to moving clouds (EEAP, 2019). During the last decade, array spectroradiometers have been introduced for measuring the entire UV spectrum within seconds. However, there exists still challenges in the suppression of unwanted stray light at wavelengths shorter than 305 nm. For SZAs larger than 50 degrees, the problem can occur up to 310 nm (EEAP, 2019).

The WOUDC includes 64 stations measuring spectral irradiances. Of those, only 18 reported data until 2020. The number of active stations should be encouraged to stay as it is or even increase, as more spectral UV measurements representing different climate zones would be an improvement for evaluating global spectral UV trends (EEAP, 2019). The spatial coverage of spectral UV is marginal. There may be stations that do not report to WOUDC. These stations should be encouraged to report in the future.

2.2.6.2 Erythemally weighted UV irradiance

Information on UV levels is very important, as excessive UV exposure increases the risk of skin cancer and cataract in addition to short-term skin burns. The UV index (UVI) is globally used as an information tool (WHO, 2002). It is calculated by multiplying the erythemally weighted UV irradiance by 40. The related variable is thus the erythemally weighted UV irradiance. It can be either calculated from spectral measurements and multichannel radiometer measurements or measured directly using broadband radiometers whose spectral response follows that of skin erythema.

The UVI should be presented as a single value rounded to the nearest whole number, and the UVI values are grouped into exposure categories (WHO, 2002). Thus, the uncertainty G and T are set to 0.5 UVI (1 sigma) (F application area). The G for monitoring e.g. long-term trends is 5% (1 sigma) (M application area), but T is 10% which is sufficient for general information on UV levels. UVI reports should present at least the daily maximum value. When forecasting or reporting daily maxima, a 30 minute time average value should be used (WHO, 2002). The values of the index vary throughout the day and local clouds may affect them a lot. These affect the requirements of the horizontal resolution and observing cycle. The G is set to be for F 0.5 h and 1 km and for M 1 h and 100 km for observing cycle and horizontal resolution, respectively. The corresponding Ts for F are 1 h and 10 km and for M 1 month (e.g. monthly average or dose) and 500 km.

2.2.6.2.1 Gaps in measurement accuracy

It is essential that broadband and multiband radiometers are regularly calibrated, characteristics (like spectral and angular response) are determined, and proper QA tools are used (WMO, 2008). In the past, challenges have been recognized in the long-term stability of the instruments and in the homogeneity of calibrations, but significant efforts have been made in recent years. The PMOD-WRC has organized three international comparison campaigns, in 2006, 2017 and 2022. Results clearly show the need for such campaigns and that there has been an improvement in the overall situation between the campaigns (WMO, 2018). 74 instruments from 29 countries participated in the campaign 2022. Results showed that when using the standard calibration methodology, the expanded uncertainty (k=2) was around 6% for most well characterized broadband radiometers (WMO, 2023). However, almost half of the instruments used in routine operation a single calibration factor instead of the suggested calibration matrix. Thus, the uncertainty requirements are met at an acceptable level for most of the instruments and good for those following adequate QA/QC protocols (M application area). Challenges exist in recording the

stability of broadband instruments. The instruments are known to be sensitive at least to humidity, but most instruments do not include online humidity monitoring.

Many countries have set up their own monitoring network to monitor the erythemally weighted UV irradiance, either using broadband or multiband radiometers. In 2020, 25 stations reported data to the WOUDC. In addition, some countries have either their own databases or upload their data to regional databases. Erythemally weighted UV irradiance can also be calculated from spectral measurements.

Mostly of the countries having UV measurements met the horizontal resolution required for the M application area, and some of them, even exceed it. However, there exist many large areas on the Earth which do not have at all UV measurements, e.g. in some tropical and arctic areas, and oceans in general. The spatial resolution of UV index forecasts is typically 0.25–0.5 by 0.25–0.5 degrees. Thus, horizontal resolution of the F application area is mostly not met. The tight requirements for erythemal UV radiations are driven by locally changing cloudiness conditions and topography. However, the actual forecasts give a good estimate for clear sky conditions.

2.2.6.2.2 Spatial gaps

In addition to ground-based measurements, satellite measurements are used to provide erythemally weighted surface UV irradiance, and irradiances at selected wavelengths. The satellite retrieval algorithms use as input total ozone measurements and cloudiness information from satellites. In many of the retrievals, surface albedo and aerosol information are taken from a precalculated climatology. Satellite UV products can be used to fill gaps in spatial coverage of ground-based measurements. However there exist challenges to fulfil the temporal requirements and uncertainty requirements, as global satellite products are so far retrieved from polar orbit satellites, and there are only a few overpasses per day. Non-homogenous surface (non-homogenous albedo or topography) increases the uncertainty of the satellite retrievals, and discrepancies of 50% can be found over snow cover at high latitudes (Bernhard et al., 2015). Over a homogeneous surface the accuracy of satellite retrievals can be within ±5% (EEAP, 2019, Lakkala et al., 2020), which brings the uncertainty requirement to be met at an acceptable or good level under those conditions.

3. RECOMMENDATIONS ON HOW TO ADDRESS THE GAPS

3.1 Aerosols

Global data repositories are not globally agreed nor harmonized. Coordinated efforts are needed based on the activities and efforts of WMO – defined central facilities and expert teams for calibration, data quality and control procedures and measurement recommendations. In addition, several short-term data series can be incorporated in the global efforts, and smaller observation systems, that do not follow any established measurement protocol or data quality standards, could be integrated into global activities.

To address the spatial gaps, sporadic, campaign-based in situ observations play an important role in improving the local proxies even if they do not directly improve the spatial data coverage. In some regions the gap might be reduced simply by improving the data availability and access.

Long-term sustainability and consistency between partial time records from different instruments of all essential aerosol variable measurements is important for future regional and global trend studies. Long time series are available for some bioaerosols, but they are yet to be opened to the community. Operationalization of new methods and work towards opening the historical records are among the key priorities in this area.

3.2 Long-lived greenhouse gases

The current level of greenhouse monitoring is sufficient to keep track of global trends and interannual variations in background mixing ratios. However, to develop a reliable understanding of the underlying causes of observed mixing ratio changes requires significant extensions in network density in many parts of the world. An important and more ambitious challenge of greenhouse gas monitoring is to support national emission mitigation efforts in the framework of the Paris agreement which requires robust sub-continental scale source/sink estimates. To do this will require much more significant extensions in measurement spatial coverage, especially in the data space areas in the current surface network, bringing the sampling density at least to the level of the ICOS regional network over all land areas. These observations should not be limited to surface measurements but resolve gradients within the planetary boundary layer and above using diverse observational platforms, such as aircraft, drones, aircores, balloons, etc. For example, the use of commercial aircraft is a cost-effective solution towards that goal that could be exploited on a larger scale than is currently done (for example by IAGOS and CONTRAIL).

Part of the required increase in measurement coverage in support of large-scale monitoring could be achieved with the help of satellites. However, the focus of new generation satellites that are prepared/planned for launch has shifted away from global monitoring to single city- or facility scale emission monitoring (e.g. CO2M, GOSAT-GW, New Space missions). Regional monitoring using satellites relies on improvements in measurement accuracy, which can be realized theoretically in observing system experiments, but still must be demonstrated on orbit. Supporting this demonstration will require important coordinated extensions of other relevant networks, such as the TCCON, COCCON and NDACC FTIR that support evaluation/validation for the wide range of conditions (differences in surface reflection, atmospheric conditions, viewing geometries, etc.) that are encountered worldwide. The recent experience acquired with the validation of the OCO-2/3, GOSAT, GOSAT-2, TROPOMI and TanSat satellite missions has also identified several weaknesses for each of these GHG column monitoring networks that should be addressed in order to meet the more and more stringent validation needs of the satellite constellation and the emission services being deployed. . Given the variety of mission objectives, instruments, and observation patterns, the ongoing international coordination, and conversations among satellite missions (e.g. CEOS AC-VC, Crisp et al., 2018) remains critical to effectively address gaps in the current observation networks. Collaboration with the emerging WMO Global Greenhouse Gas Watch (GGGW) initiative is also envisaged.

Improved attribution of emissions to processes will require extended monitoring of co-emitted species, which could be achieved cost effectively by extending/coordinating with existing air quality networks with greenhouse gas sensors. Measurements of process specific tracers (e.g. VOCs, isotopes, O_2/N_2, COS, etc.) at existing greenhouse gas monitoring sites would also support emission reduction measures with important process/sector specific information on emissions.

A greenhouse gas sensor deployed in a geostationary orbit would strongly improve spatial and temporal coverage – at least in low to mid latitudes – but is not planned for launch yet. Satellite remote sensing is strongly limited at high latitudes, because of the unfavorable solar illumination conditions. Alternative options are under investigation (TIR sensors, lidar, highly elliptical orbits), but still require further development to address the challenges at high latitudes.

3.3 Stratospheric ozone and vertical ozone profiles

Collaboration between GAW and contributing networks, including NDACC is important to assure the stability and quality of ozone records, including the use of the same reference standards (i.e. WMO world and regional standards) and protocols for data processing (i.e. the SOPs and WMO published guidance).

The redundancy of observations is required to assure stability, continuity and mutual quality control of individual observing systems (i.e. satellite, ground-based and aircraft platforms) for global and temporal coverages (satellite validation documents, CAMS validation reports, reports from the multi-platform intercomparison campaigns and calibration of ground-based instruments campaign reports (e.g. GAW Report 299, GAW Report 302). Ongoing and future observations need to be evaluated for vertically, spatially, and temporally resolved records to assess the sampling biases when records are used for tracking ozone recovery and for attribution of ozone changes to impacts from the ozone depleting substances (ODS) and climate change.

Determination of long-term trends in ozone requires stable operation of instruments, in particular satellites as transition between the satellite instruments can be associated with introduction of biases between observational datasets leasing to substantial trend uncertainties. Assessment of instrument drifts requires a certain redundancy in observation systems to avoid gaps in observations.

Limb profiling instruments that will likely cease operations by the end of 2025 (e.g. Microwave Limb Sounder (Aura-MLS), Optical Spectrograph and Infrared Imager System (OSIRIS)) have provided vertically resolved, global spaceborne measurements of ozone and ozone-related atmospheric constituents (e.g. reactive chlorine, ODSs and substitutes, water vapour, and long-lived transport tracers) over the last decades. This discontinuation will hamper the ability to reduce key uncertainties that remain in understanding of stratospheric ozone depletion, including the lack of emergence of a clear signature of recovery in the Arctic, the potential influence of volcanic and wildfire emissions, and the role of very short-lived substances, among others. Limb profiling measurements of ozone and ozone-related constituents and tracers are also essential for quantification of the "Brewer-Dobson" circulation (BDC) changes and its impacts. The response of the BDC to climate change is highly uncertain. Further, the BDC controls the distribution of greenhouse gases in the stratosphere, leading to potential climate feedback mechanisms. Changes in the BDC also influence the amount of ozone transported from the stratosphere down to the troposphere, where ozone is the main gas-phase contributor to poor air quality.

To continue and expand, where necessary, variables for qualifying important connections between changes in ozone, climate and atmospheric transport, and large-scale circulation. In particular, the expected changes in the global meridional BDC and events like the breakup of the Quasi-Biennial Oscillation (QBO), require appropriate temperature, winds and trace-gas profiles, especially of dynamical tracers like N2O and SF6, as well as ozone, aerosols and water vapour.

Observations are particularly needed for the analysis and improvement of the BDC derived from data assimilation systems. This should include cost-effective instrumentation, such as air-core.

Differences between stratospheric and tropospheric ozone changes observed by different techniques and platforms (i.e. microwave radiometers, ozonesondes, lidar, satellite, FTIR, DOAS techniques and combinations) need to be reconciled (as demonstrated in the recent SPARC LOTUS assessment). This intercomparison work needs to continue to understand the limitations of each observing system and to characterize uncertainties of observations when assessing trends (WMO/UNEP Ozone Assessments, SPARC TUNER, IGAC TOAR-II etc.)

The 2022 eruptions of the Hunga Tonga–Hunga Ha'apai volcano injecting large amounts of water and sulfur into the stratosphere and its transport to the polar regions needs to be monitored to understand the combined water vapour and aerosol impacts on stratospheric ozone, potentially though increases in polar stratospheric clouds and changes in chemical reactions regime.

Rapidly increasing rates of rocket launches, and their resultant fuel emission and re-entry impacts on stratospheric ozone are not well characterized. At present, several modelling groups are studying these impacts, but further evaluations and studies are needed.

The Ozone Research Manager 11th meeting (ORM-11) in 2021 outlined the need for measurements of ozone, ODS and their replacements. It was emphasized that atmospheric monitoring "remain(s) the cornerstone of stratospheric ozone research" and to assure the success of the Montreal Protocol. To study and quantify new influences on ozone health the ORM-11 recommended to continue develop process-based studies of ozone evolution in a changing climate. ORM-11 emphasized that "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".

The 2022 Ozone Assessment (WMO/UNEP, 2022) emphasized the need to track unexpected ODS emissions and evaluate their impacts on ozone recovery. The agreement between models and observations outside of polar regions is very good, but there is a need to reconcile differences in the observed/modelled recovery of the lower stratospheric ozone. Impacts of increasing GHG concentrations on ozone recovery in tropics is of concern. The geoengineering efforts and wildfire and supersonic/rocket emission increases in the lower stratosphere all represent risks for ozone layer.

3.4 Reactive gases

3.4.1 Tropospheric Ozone

Improving the monitoring of tropospheric ozone in terms of gap filling requires two steps:

spatial gap analysis should be conducted to quantify the regional representativeness of the current profiling sites (Weatherhead et al., 2017), followed by a cost-benefit analysis to determine the regions of the globe where new sites can fill the largest gaps for the lowest cost.

The sampling frequency at each monitoring site needs to meet a minimum threshold, so that accurate monthly mean values can be calculated, which will permit accurate trend quantification. According to a study by Chang et al. (2020), 18 ozone profiles per month are required to minimize bias of the trend to less than 5% using standard linear regression methods, however, an improved statistical methodology allows for accurate trend quantification based on just 14 profiles per month. Another strategy for improving trend characterization of a time series with limited sampling is to apply multiple linear regression to observed ozone and meteorological parameters to account for the influence of meteorological variability on the trend (Chang et al., 2021; 2024). In terms of surface ozone monitoring, the most promising gap filling strategy is to deploy the

constellation of polar orbiting (LEO) and geostationary (GEO) satellite instruments, in partnership with frequent in situ ozone profiling at key locations for evaluation purposes, followed by ingestion of the satellite retrievals into an atmospheric chemistry model that will estimate the surface ozone concentrations (Colombi et al., 2021).

3.4.2 Tropospheric NO_2

The emerging constellation of new generation satellite instruments measuring from LEO and GEO orbits offers new perspectives on the monitoring of tropospheric NO_2 and its variability. New geostationary observations introduce regional intra-daily sampling opportunities complementing global daily coverage available by LEO orbiting instruments.

Expanding ground-based remote sensing coverage would support science applications in addition to satellite validation. For example, the Pandora spectrometer system (a global network of which comprise the "Pandonia Global Network" (PGN), https://www.pandonia-global-network.org/) report nominal accuracy in vertical column direct-sun retrievals under ideal observing conditions on the order of 2 x 10^{15} molec/cm^2 (Herman, 2009). Current efforts to establish state-of-the-art practices and operational settings for the network of MAX-DOAS instruments are encouraged. Operation of the NDACC network of ZSL-DOAS UV-visible spectrometers should be pursued with sufficient coverage of all major latitude zones and stratospheric regimes. Satellite-based retrievals require other a priori chemical and geophysical variables, pointing to the crucial role of high-quality modelling and supporting datasets in remote sensing of air quality.

3.4.3 Ammonia NH_3

Continuous measurements of NH_3 at sub-daily timescales (e.g. hourly or better) continues to be challenging and expensive as NH_3 interacts with instrument inlet and sampling lines. As a result of the limited regulation of NH_3, and instrumental sampling challenges, both the temporal and spatial coverage of ground-based NH_3 networks remains are insufficient and should be expanded. Open-path measurement technology for NH_3, which avoids some of the sampling difficulties mentioned above, is advancing but not yet in widespread use for routine monitoring. As high time resolution methodologies continue to advance, expansion of passive sampling can continue to address geographical gaps and provide data for limited model evaluation, ground validation of satellites and inferential modelling of dry deposition for total atmospheric deposition.

Unlike more mature satellite-based retrievals (e.g. of NO_2 or O_3), many NH_3 retrievals from these instruments remain largely research-grade and few are produced by operational centers. Their ground-based validation by FTIR spectrometers needs further developments.

3.4.4 Volatile organic Compounds VOCs

VOCs include shorter-lived compounds with strong regional variability, and longer-lived compounds that can mix well in each hemisphere away from source influences (Section 2.2.4). Therefore, spatio-temporal monitoring gaps are in general more acute for shorter-lived compounds. Gaps in VOC monitoring may be a real gap due to a lack of measurements, or an apparent gap because existing measurements are not incorporated into the GAW framework. Funding and maintaining robust global and regional VOC monitoring programmes is essential for addressing current gaps and minimizing future gaps. Incorporating existing quality assured VOC measurements into the GAW data repository, with a focus on priority VOCs (Table 2) would increase data accessibility, especially for measurements collected outside of Europe.

Regarding vertical column data, the recent upgrade of the PGN capabilities to formaldehyde column retrievals, as well as current efforts to deploy more MAX-DOAS instruments with formaldehyde and glyoxal column/profile observation capabilities, and to establish state-of-the-art practices and settings for this latter network, are all encouraged.

3.5 Total atmospheric deposition

Expanding the spatial coverage of routine precipitation chemistry into the most data-poor regions is necessary to advance our understanding of total atmospheric deposition and decrease our reliance on chemical transport models, especially in regions of rapid population growth and intensification of agriculture, but also in regions with potentially sensitive ecosystems that require protection. Any opportunities to increase the speciation in routine monitoring should also be pursued. In particular, the lack of routine quantification of phosphorous-containing species, organic nitrogen, and organic acids need to be addressed.

Standardized methods for precipitation chemistry monitoring have been established (WMO, 2004), but there is no such guidance for dry deposition monitoring. Dry deposition of certain chemical species can be inferred more directly by eddy covariance or atmospheric gradient methods. However, except for CO_2 and energy fluxes which have well-established protocol and some regional networks for eddy covariance measurements, these more direct approaches are so instrumentally intensive as to be generally unfeasible for routine monitoring of dry deposition. Community-supported protocol and measurement requirements for networks that will support inferential dry deposition calculations need to be identified. Like with wet deposition, expansion of dry deposition variables to the traditionally data-poor regions of the world is necessary, at least for the major sulfur and nitrogen containing species, and of O_3.

Because of the deleterious toxicological effects of O_3 uptake into plant stomata mentioned in the gap analysis section, observations that help better constrain the stomatal and non-stomatal components of dry deposition by plant functional type would be particularly valuable (e.g. as might be achieved by co-located measurements of ecosystem scale CO_2 and H_2O fluxes).

3.6 UV radiation

Accurate measurements can only be achieved by following the guidelines and recommendations of the SOPs and by performing proper characterization of the instruments and regular calibration. The international scientific community should keep going (low-cost) calibration and QA/QC activities including international measurement comparison campaigns and training on instruments' operation. The QA activities should include comparison of the spectral irradiance scale provided by different National Metrological Institutes.

In general, there is a lack of measurements in some climate areas, especially in the tropics and arctic areas, and new high-quality measurement sites at those areas would be very valuable for trend analysis, climatological studies and validation of satellite retrievals. In addition, operators of the existing sites should be encouraged to submit their data to WOUDC in addition to other existing databases.

Satellite retrievals should be improved to better address spatial gaps in ground-based measurements, for example, by including the use of actual aerosol and albedo measurements in the place of climatologies, and cloud information from various satellites. More validation sites for satellite data, representing different climate zones, are needed.

Long-term monitoring should be supported and continued to enable trend analysis and satellite and model data validation also in the future referring to the concern brought by the UNEP Environmental Effects Assessment Panel (EEAP) Assessment Report of 2022 (EEAP, 2023): "The number of stations with high-quality spectral UV measurements has been declining during the last decade and the funding for many of the remaining stations is uncertain. If this trend continues, the scientific community may lose the ability to assess changes of UV radiation at the Earth's surface and associated impacts, in order to verify new satellite UV data products with ground-based observations and to validate model projections."

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