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WORLD METEOROLOGICAL ORGANIZATION

GLOBAL ATMOSPHERE WATCH

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WMO AIR QUALITY AND CLIMATE BULLETIN

Introduction

Climate change, caused by the accumulation of greenhouse gases in the atmosphere, occurs at timescales of decades to centuries. The associated environmental changes, from rising temperatures on land and in the ocean to more extreme weather and changes in precipitation, are visible worldwide. In contrast, the air pollution that occurs near the Earth's surface evolves on timescales of hours to weeks, and across spatial scales that range from local (for example, urban centres) to regional.

Despite these differences, air quality and climate change are strongly interconnected. Some pollutants affect climate change. Ground-level ozone and its precursors are common air pollutants and warm the atmosphere. Particulate matter (PM) – tiny particles suspended in the atmosphere, also referred to as aerosols – is detrimental to human health and affects warming. Climate change also affects pollution. It affects the pace of chemical reactions that drive the formation and destruction of pollutants, it changes the rate and distribution of biogenic pollution (such as wildfires) and bioaerosols, and it can lead to increasing emissions from human activities. The sources of air pollution and climate change are intertwined: fossil fuel burning and other human activities that contribute to climate change also emit pollutants.

Each year, the Air Quality and Climate Bulletin seeks to report on the state of air quality and its interconnections with climate change, and to reflect on trends and geographical distribution of pollution. The 2025 edition emphasizes two particular areas: firstly, the impacts of, and anthropogenic influences on, aerosols; and secondly, the atmospheric composition monitoring and modelling infrastructure across the globe. Although such underlying infrastructure remains incomplete, the available information only illustrates the importance of understanding more about this critical determinant of climate, ecosystem and human health.

The 2025 edition of the Bulletin now includes estimates from three rather than two sources in its overview of PM anomalies, highlighting that results are comparable and, for the most part, consistent, despite the use of different models with different inputs.

The Bulletin's first article is a case study on the climate and health impacts from recent international regulations reducing sulfur emissions in shipping fuels. While the reductions of this aerosol led to health gains, the measures also have implications for climate and other forms of pollution.

The next piece sheds light on the effects of aerosol emissions from agricultural biomass burning on the Indian subcontinent. These emissions make fog episodes longer and more persistent, contributing to a host of deleterious effects for health.

The third and final piece on aerosols looks at the consequences on air quality of smoke and PM emissions from wildfires in South America. Wildfire emissions have been a perennial topic for the Bulletin in the context of both a warming planet and increasingly intense wildfire seasons. It is important to note that the monitoring infrastructure for wildfire emissions has many gaps, particularly in lower-income countries, leading to likely underestimation of impacts.

Keeping the focus on South America and on the atmospheric composition monitoring infrastructure, the next piece looks at the factors that influence ozone formation over two cities with different topography, meteorological conditions and availability of precursor substances.

The 2024 Bulletin featured a piece on the nascent pollen monitoring network in Europe enabling quicker and more accurate pollen forecasts. In the present edition, a follow-up piece looks at pollen modelling and forecasting, touching on the opportunities that new technologies provide for early and accurate forecasts of pollen.

Finally, this year's Bulletin features two articles highlighting the importance of the atmospheric composition monitoring infrastructure. With human activities having a rapid and profound effect on atmospheric composition, a global, fit-for-purpose, in situ monitoring network is crucial. Together with computer models, it assists scientists in understanding the complex processes that lead to the formation, transformation and trends in atmospheric pollutants. The first piece is about the EarthCARE satellite mission, which aims to help elucidate the role of clouds and aerosols in regulating the Earth's climate. The piece centres on the crucial – and often overlooked – ground network of Global Atmosphere Watch (GAW) stations necessary to calibrate the satellite's instruments and validate the retrieval algorithms derived from it. The second piece highlights efforts to establish and develop a network for monitoring deposition of atmospheric pollutants in Africa.

Global particulate matter concentrations in 2024 as recorded by three products

Johannes Flemming, Allison Collow, Mikhail Sofiev, Peter Colarco

Particulate matter at the surface that is smaller than 2.5 micrometres in diameter is referred to as $PM_{2.5}$. In ambient air, $PM_{2.5}$ is a severe health hazard (World Health Organization, 2021). Anthropogenic and natural sources contribute to $PM_{2.5}$ pollution in varying proportions at the global scale. Emissions of $PM_{2.5}$ originate from human activities such as transport, industry and agriculture, as well as from natural sources such as wildfires and wind-blown desert dust. The formation of secondary aerosol particles from gases such as sulfur dioxide, nitrogen oxides, ammonium and volatile organic compounds is an important additional source of $PM_{2.5}$. This diversity in emission sources, and uncertainties in formation and other processes, make predicting (forecasting) $PM_{2.5}$ challenging.

The best estimates of global $PM_{2.5}$ concentrations are obtained by optimally combining satellite observations of aerosol optical depth (AOD) with model predictions of $PM_{2.5}$, which also rely on observations. Three such products are illustrated in Figure 1. The Copernicus Atmosphere Monitoring Service (CAMS) and NASA Goddard Earth Observing System for Instrument Teams (GEOS-IT) reanalysis products formally assimilate satellite AOD information, while the System for Integrated Modelling of Atmospheric Composition (SILAM) product does not. Despite their different approaches, the three products show consistency in their 2024 $PM_{2.5}$ anomalies (compared to a 2003–2024 reference period).

All three products show enhanced $PM_{2.5}$ associated with biomass burning in northern Canada, the Amazon, Siberia and central Africa. All three models also show positive $PM_{2.5}$ anomalies over northern India (where a mix of anthropogenic and biomass burning pollution occurred), as well as high $PM_{2.5}$ loading associated with Saharan dust exported from north-west Africa over the North Atlantic Ocean. Likewise, all three models show negative $PM_{2.5}$ anomalies in eastern China, reflective of a decline in anthropogenic emissions across the reference period, and consistent with the decline in $PM_{2.5}$ across north-eastern Africa that is related to dust emissions. The relatively greater positive anomalies in $PM_{2.5}$ over biomass-burning regions evident in CAMS and GEOS-IT compared to SILAM are possibly the result of differing aerosol data assimilation approaches (which can help correct any errors in emissions data used in the models), although it may stem from other model differences (such as assumptions about particle sizes and composition).

Overall, there is good agreement among the three models in terms of the signs of the anomalies and their spatial distribution, although at times significant differences remain in the magnitudes. This highlights the challenges in predicting $PM_{2.5}$. Nevertheless, the patterns of positive anomalies for 2024 which are evident in these models is very similar to what was shown for CAMS and GEOS-IT in 2023, as presented in last year's Bulletin. Fire remains a significant and persistent contributor to particulate pollution, a factor which is expected to continue and even increase as the climate warms in coming years. In addition to the destructive impacts of fire on infrastructure and ecosystems, there is also the air quality impacts on human health to contend with, and a rise in adverse health outcomes will likely be seen in coming years.

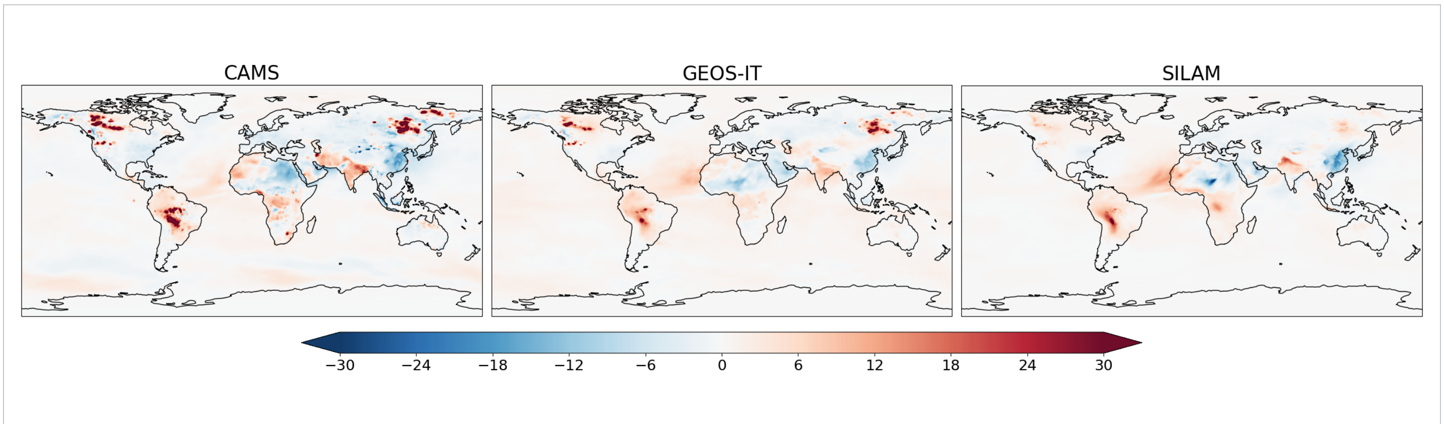

Figure 1. $PM_{2.5}$ anomaly ($\mu g\ m^{-3}$) in 2024 (reference period 2003–2024)

Source: Third-party maps. These maps were provided by CAMS (left), NASA Global Modeling and Assimilation Office (centre) and the Finish Meteorological Institute on 28 July 2025 (right) and may not fully align with United Nations and WMO map guidance.

Shipping emissions, air quality and climate change

Jukka-Pekka Jalkanen, Mikhail Sofiev, Jessica Seddon

Observations suggest that the pace of global mean atmospheric temperature warming is increasing, to about 0.27 °C per decade in 2015–2024, up from 0.18 °C in the previous decade. The change in pace is due to two factors. Firstly, atmospheric concentrations of carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O), the key drivers of climate change, are now higher than ever, with emissions also setting records at 53.6 ± 5.2 gigatonnes of CO_2 equivalent ($GtCO_2e$) per year in 2014–2023 (Forster et al., 2025). Secondly the concentrations of aerosols in the atmosphere – small particles with varying effects on climate and negative effects on human health and ecosystems – have decreased.

Aerosols are complex. Some aerosols are directly emitted into the atmosphere whereas others are created in the atmosphere through chemical reactions. Darker ones, such as black and brown carbon, *absorb* solar radiation. They warm the atmosphere and melt the ice or glaciers that they land on. Research has shown that aerosols that absorb as little as 5% of the incoming solar radiation may have a warming effect (Sofiev et al., 2018). Ship and industry exhausts include such dark particles (soot, minerals). The net direct radiative forcing of dark aerosols (i.e. its net warming or cooling effect on the atmosphere) is likely to be a slight warming, of <0.01 W/m^2. Conversely, brighter aerosols, such as sulfates, reflect solar radiation back to space, providing temporary cooling before depositing as acid rain and snow or landing on (and acidifying) soil or bodies of water. It should be noted that aerosols of all colours can act as cloud nuclei (the "seeds" of cloud droplets), and once coated with water, often (but not always) brighten clouds so that they reflect more energy back into space, with a corresponding cooling effect.

Aerosols harm human health, because they pollute the air. Indeed, aerosols in the lower atmosphere are the particulate matter (PM_{10}, $PM_{2.5}$, PM_1) that constitutes the leading global environmental health risk (see previous section on global PM concentrations in 2024). Concentrations of aerosols in the atmosphere increased globally from the 1950s to 1980s but have come down substantially since then due to concerted efforts to reduce health- and ecosystem-damaging air pollution in North America, Europe and, later, East Asia. They continue to rise in some regions such as South Asia, South America and the northern latitudes due, in part, to increasing wildfires.

Against this backdrop, it is important to take an integrated approach to managing emissions, not only to protect the climate but also ecosystem and human health.

One example of action is the 2020 International Maritime Organization's MARPOL VI regulations for lowering the sulfur content of marine fuels (see Figure 2 for impacts of shipping). These regulations led to air quality improvements that lowered premature mortality (–137 000 cases/year) and childhood asthma (–7.6 million cases/year) globally (Sofiev et al., 2018). Most of these improvements were in Asia and Africa. However, one other consequence of the regulations was that they also contributed to removing the previous cooling effect of the sulfate aerosols in the atmosphere. The estimates of the global mean effective radiative forcing associated with lower-sulfur fuels are likely close to 0.09 W/m^2 (Sofiev et al, 2018) – a slight increase in net global forcing (i.e. a net warming effect). It may be projected to approximately 0.04 °C of additional

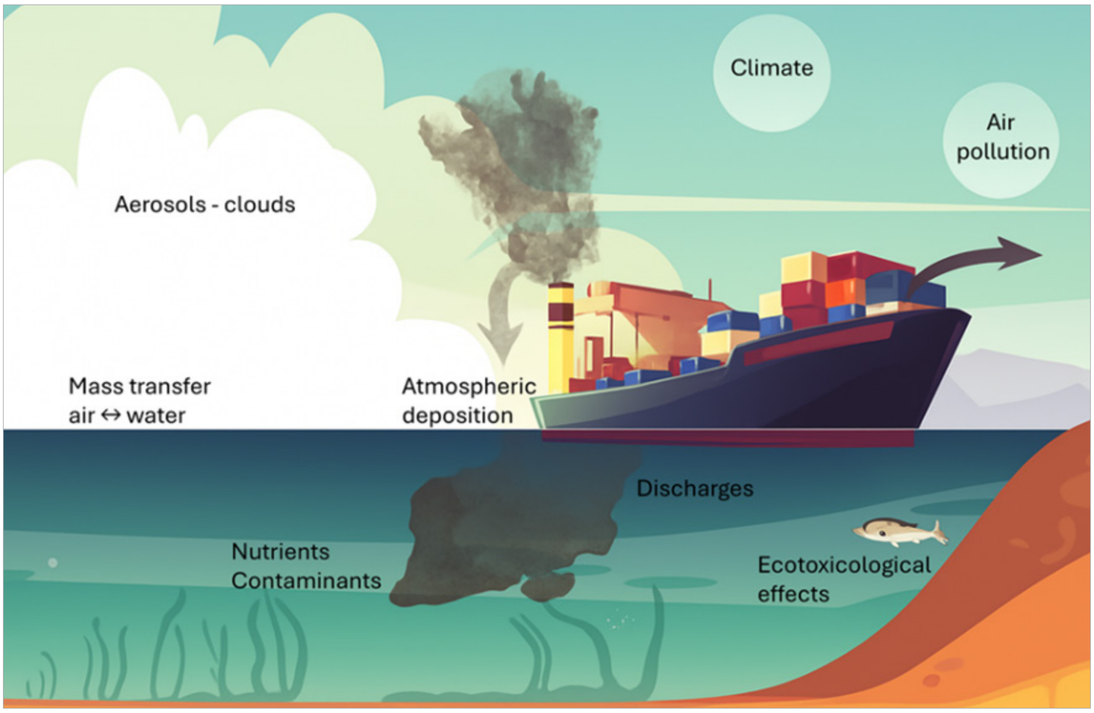

Figure 2. The most important ways in which shipping impacts climate and the environment

Source: Adapted from the European Union Horizon 2020 EMERGE project for the evaluation, control and mitigation of the environmental impacts of shipping emissions, https://emerge-h2020.eu/

warming by 2025 (Gettelman et al., 2024; Skeie et al., 2024; Yoshioka et al., 2024). Therefore, the lower sulfate aerosol content in the atmosphere means that clouds are less bright, and consequently less solar radiation is reflected back into space (hence the reduced cooling effect). Overall, however, the average effective radiative forcing from 1750–2024 was the same as the average from 1750–2019 (Forster et al, 2025). This is because the average period is relatively long and the warming effect from the reduction of sulfate aerosols is relatively small.

Aside from the health benefits and the (albeit small) warming effect of the MARPOL regulations, the methods for complying with them have also had side effects. For example, one method has been the use of shipboard emission abatement systems such as sulfur oxide (SOx) scrubbers, now installed in over 6 000 ships. The scrubber-related effluent discharge into the sea is the biggest water contamination source from ships (by volume), with detrimental effects on marine life (Chen et al., 2024). In future, the use of low- or zero-carbon fuels and propulsion systems would eliminate the need for scrubbers and have benefits for both climate change and air quality.

While the precise impacts of a particular policy are hard to disentangle, this case highlights the need for more research on aerosol impacts and more holistic thinking about how to achieve climate, health and ecosystem goals.

Persistence of winter fog in the Indo-Gangetic Plain: A consequence of enhanced anthropogenic activity and population growth

Tarun Gupta, Pradhi Rajeev

The Indo-Gangetic Plain (IGP), home to over 900 million residents, is among the most densely populated and agriculturally active regions in the world. This region has experienced a marked rise in air pollution as well as winter fog episodes. Although fog is a seasonal occurrence, its growing frequency and duration are increasingly linked to ever increasing human activities and regional environmental changes (Kutty et al., 2020).

Fog forms when air near the ground cools to dew point, allowing moisture to condense on certain airborne particles (known as "fog condensation nuclei" (FCN)) and form tiny droplets. This process is heavily influenced by fine particles ($PM_{2.5}$) in the atmosphere, released from sources such as tail-pipe emission, industrial flue gas, and combustion of crop residue, fossil fuel and domestic biomass. These FCN cause more persistent and dense fog formation (Gupta et al., 2022). During winter, temperature inversions, where cold air becomes trapped beneath a layer of warmer air, lock pollutants near the ground, thereby extending the duration of fog events (Deshpande et al., 2023).

Mushrooming of urban areas within the IGP has led to enhanced emissions and to development of urban heat islands, altering local weather dynamics. Sources of emissions include vehicles and construction. Another source is ammonium emitted from large cattle populations and poor sanitation facilities. When this ammonium interacts with other chemicals in the atmosphere, stable FCNs are formed. This, in turn, results in persistent fog. Many brick kilns, using inferior coal and obsolete technology, further increase organic aerosol emissions. One dominant seasonal contributor to emissions is burning of post-monsoon agricultural residue, particularly in Punjab and Haryana (upper IGP). Satellite data confirm sharp increases in aerosol optical depth during these months, correlating with spikes in fog intensity all along the IGP (Bharali et al., 2024).

Interaction of fog droplets with aerosols also alters aerosol chemistry, with consequences for both climate and pollution (Mandariya et al., 2019). Biomass combustion is a key source of oxygenated organic aerosols (OA); these are formed through aqueous chemical reactions whereby volatile organic compounds in the atmosphere are oxidized, leading to the formation of less volatile compounds that can condense to form new particles. The smaller fog droplets normally found in fog, with a higher surface-to-volume area and more efficient chemical processes (see Figure 3), contain more of these oxidized, less volatile OA, thus

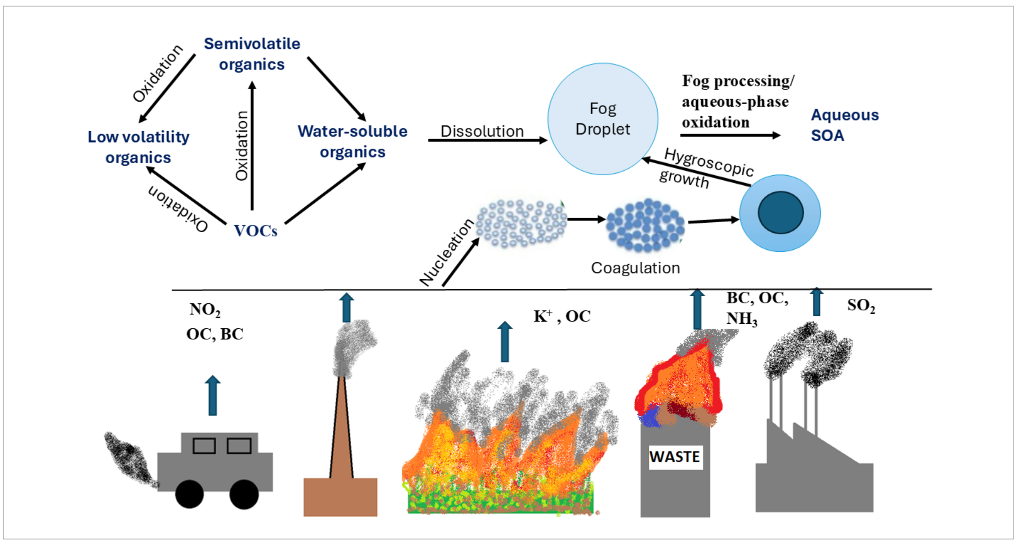

Figure 3. Aqueous processing of chemical species originating from different combustion sources inside the fog droplets

Note: OCs = volatile organic compounds; SOA = secondary organic aerosols; OC = organic carbon; BC = black carbon; NO_2 = nitrogen dioxide; K+ = potassium ion; NH_3 = ammonia; SO_2 = sulfur dioxide making these fogs episodes potentially more harmful, for example, by contributing to additional PM pollution and negative health impacts.

Poor visibility during fog episodes impacts transportation, causing delays and accidents. Fog also causes severe health conditions such as asthma, bronchitis and other respiratory ailments. Elevated levels of toxic metals and organic compounds in fog water are a potential public health concern (Gupta et al., 2022). Therefore, persistence of fog in the IGP is no longer a simple, seasonal weather event – it is a symptom of escalating human impact on the environment. Addressing this requires comprehensive strategies, such as enforcing regulations on agricultural residue burning, and promoting cleaner energy for cooking, heating, lighting and public transport systems.

Hotspots of wildfire-induced $PM_{2.5}$ across the globe: Insights from South America

Admir Créso Targino, Mikhail Sofiev

Significant wildfires impacted numerous regions across the globe in 2024. Canada and Australia, among the most affected in 2023, again experienced significant wildfires in 2024. Parts of central Africa and western North America were also affected. The highest anomaly, however, was in the Amazon basin, as part of a record wildfire season and record wildfire smoke concentrations in Latin America. The extensive wildfires in the western Amazon region and in northern South America were facilitated by drought conditions. Devastating and deadly wildfires also affected Chile.

These events not only impacted ecosystems and society, but also resulted in widespread negative impacts on air quality, including in densely populated urban areas.

In August, the Amazonian city of Porto Velho, Brazil, exhibited mean daily $PM_{2.5}$ concentrations exceeding the National Air Quality Standards (NAQS) and World Health Organization (WHO) guidelines (Krecl et al., 2025). Furthermore, the impact of the fires can also be seen in increases of aerosol optical depth (AOD), a measure of the extinction of solar radiation by atmospheric particulates, over the region. The mean AOD (at 550 nm) obtained from the MODIS satellite-based spectroradiometer was 0.67 during the period 16–21 August, when less $PM_{2.5}$ was observed, and reached 1.62 in the period 24–29 August. The increase correlates with a surge in fire hotspots in South America from 625 800 in the period 16–21 August, to 911 470 in the period 24–29 August. The majority of hotspots were in Brazil (60.2% in the 16–21 August period and 61.8% in the 24–29 August period) and in the Plurinational State of Bolivia (26.8% and 31.9% in the respective periods).

The global $PM_{2.5}$ anomalies depicted in Figure 4 (top), coupled with the sharp increases in $PM_{2.5}$ concentrations in specific cities (bottom), underscore the far-reaching and significant consequences of the widespread wildfire activities across the globe in 2024.

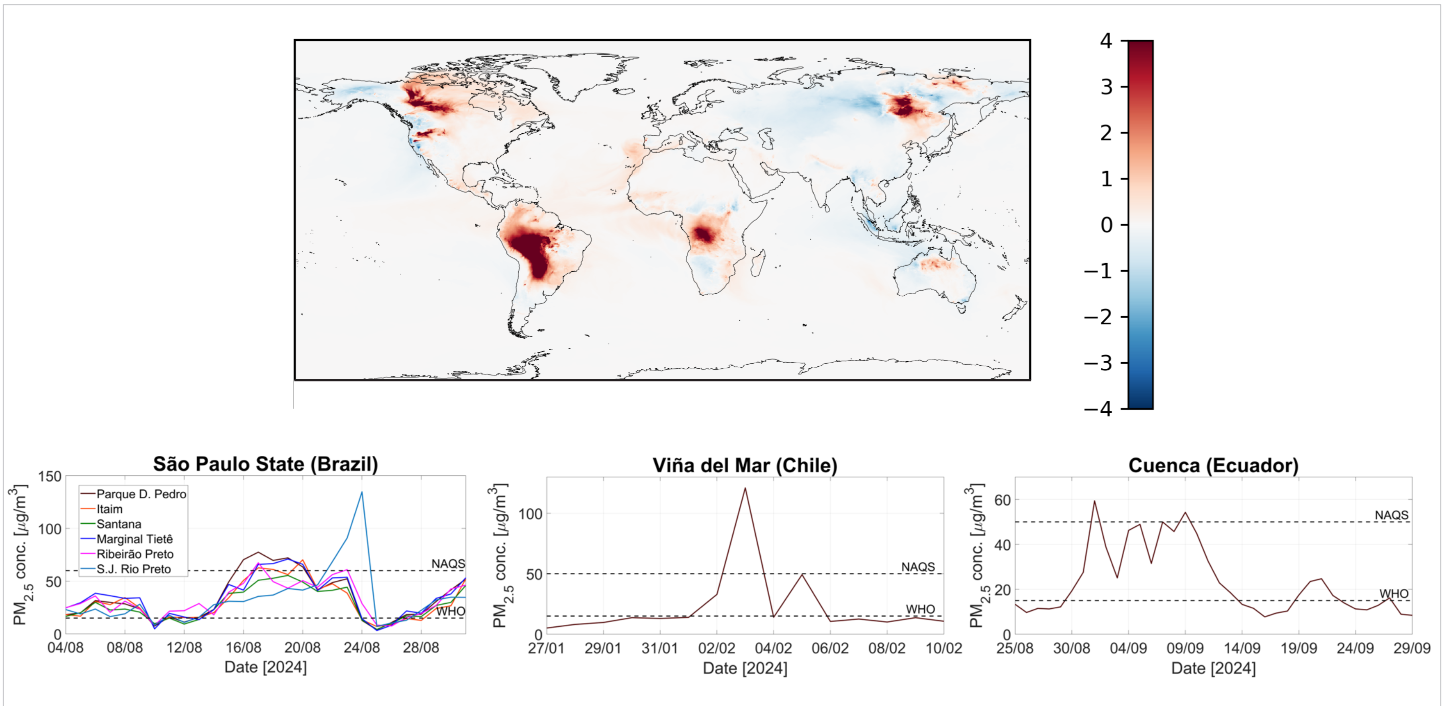

Figure 4. (Top) Fire-related $PM_{2.5}$ anomalies for 2024 (in $\mu g\ m^{-3}$), compared with the multi-annual mean in 2003–2024. (Bottom) Time series of $PM_{2.5}$ concentration (in $\mu g\ m^{-3}$) in three locations in South America.

Source: Third-party map. This map was provided on 7 July 2025 by the Finnish Meteorological Institute (based on the dataset in Hänninen et al., 2025; see also Romanello et al., 2024) and may not fully align with United Nations and WMO map guidance. The sources of the $PM_{2.5}$ data are: São Paulo State Environmental Company (CETESB) (for São Paulo state, Brazil), National Air Quality Information System (SINCA) (for Viña del Mar, Chile) and Prof. Chester A. Sellers at the Universidad del Azuay, Instituto de Estudios de Regimen Seccional del Ecuador (for Cuenca, Ecuador).

Factors that influence ozone production: Contrast across cities

Maria Cazorla, Laura Gallardo, Isobel J. Simpson

Ground-level ozone is a regulated air pollutant, due to its harmful effects on human health. Additionally, tropospheric ozone is the third most significant climate forcer after carbon dioxide and methane. Ozone forms due to complex chemical reactions involving sunlight and gas precursors, namely nitrogen oxides (NO_x) and volatile organic compounds (VOCs) (see the box below entitled Ozone anomalies 2024). In South America (SA), ozone is monitored by air quality networks in some cities and countries, but few studies have investigated factors that influence its formation. In contrast, the chemistry of ozone production has been well-characterized in many cities and regions in the United States of America (USA).

A recent model study in SA compared the ozone production chemistry in Santiago (Chile) (where VOCs were measured) and Quito (Ecuador) (where VOCs were modelled). Both cities are located within the complex Andes topography (Cazorla et al., 2025). In Santiago, during the ozone season (December–March), unhealthy ozone levels (60–100 parts per billion by volume (ppbv), 1-h data) were linked to rates of ozone production of 23–50 ppbv/h (the latter are shown in Figure 5). Based on available VOC measurements, traffic emissions (alkenes and aromatics) contribute 50% to ozone formation, aldehydes and ketones from chemical reactions (that is, secondary origin) contribute 30% and isoprene (biogenic and anthropogenic) contributes 20%. In equatorial Quito, simulations with modelled VOCs point to similar rates of ozone production, but with ozone usually staying below 60 ppbv. This difference is likely due to unconstrained vertical mixing in Quito (meaning that ozone readily mixes in the atmosphere) while Santiago is permanently impacted by a temperature inversion caused by the Pacific Subtropical High (meaning that ozone remains trapped beneath the inversion).

Alkenes and aromatics from traffic were found to contribute up to 70%–90% to ozone formation in Quito. However, the impact of non-traffic VOCs needs to be fully evaluated. A VOC survey of Santiago in the 1990s found a strong impact from the leakage of liquefied petroleum gas (LPG) on local ozone formation (Chen et al., 2001). LPG is regularly used in Santiago for domestic cooking and heating. Other countries in SA, such as Ecuador and Peru, also use LPG for cooking and water heating, but the contribution of light alkanes from this source to ozone production has yet to be characterized there. Meanwhile in the USA, by way of comparison, strict motor emission controls have considerably reduced the abundance of traffic VOCs in urban air (Warneke et al., 2012). As a result, other chemical products, especially those from personal care and cleaning agents, currently account for half of the total emissions of petrochemical VOCs in major urban areas in the USA (McDonald et al., 2018; Coggon et al., 2021; Gkatzelis et al., 2021).

As the current global environmental crisis progressively intensifies, city authorities need to adapt their control strategies to protect public health and mitigate climate change. In SA, this work requires implementing programmes to measure VOCs, identify sources and

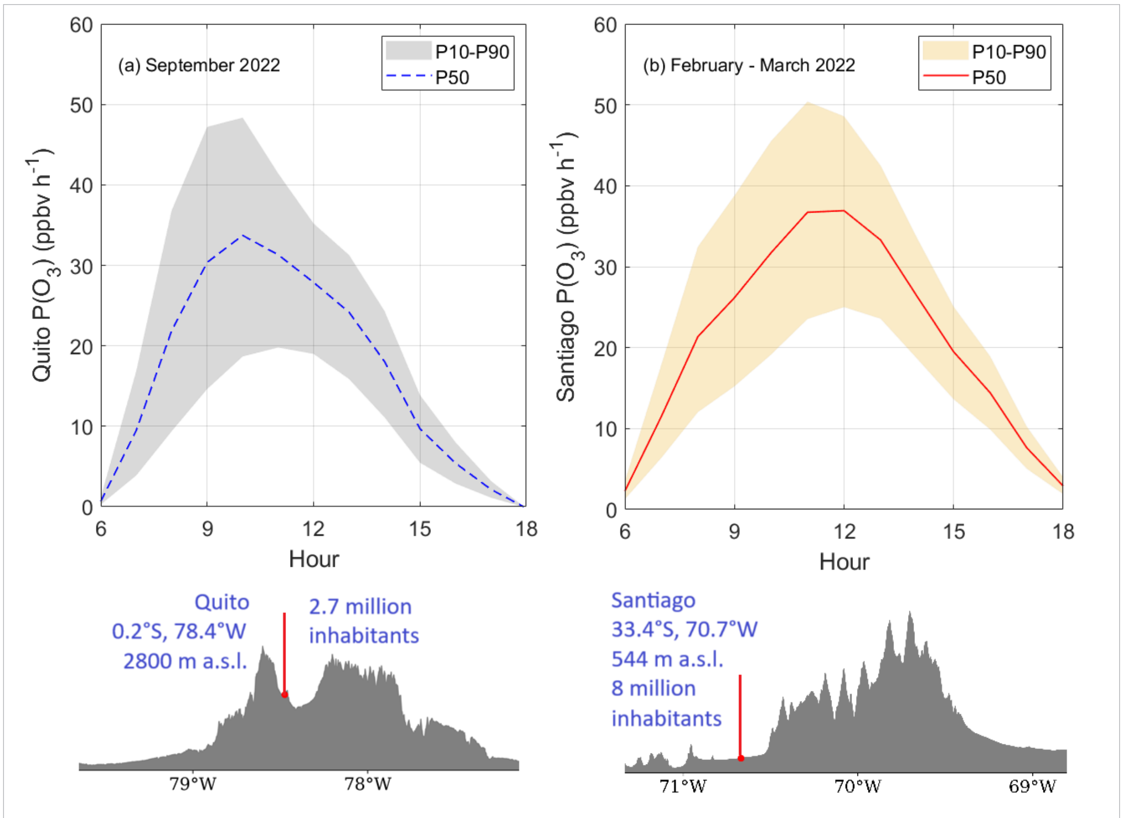

Figure 5. (Top) Ozone production rates $P(O_3)$ (ppbv h^{-1}) in Quito (left) and Santiago (right) during peak ozone months from model simulations with the Framework for 0-D Atmospheric Modeling (F0AM). Shaded areas indicate model output at the 10th and 90th percentiles.

Source: Adapted (with permission) from Cazorla et al. (2025)

Ozone anomalies 2024

Mikhail Sofiev

Tropospheric ozone, O_3, is an air pollutant affecting both people and vegetation, including agricultural crop yields. Global losses of staple crops from ozone in 2010–2012 are estimated at 227 teragrams (Tg) annually. Ozone is also a powerful greenhouse gas. Tropospheric ozone is formed by sun-dependent reactions between nitrogen oxides, carbon monoxide and a host of volatile organic compounds from a variety of anthropogenic sources (such as transport, industry and agriculture) and natural sources (such as vegetation, soil processes and wildfires).

Levels of ozone varied substantially over space and time in 2024, as in any year. Ozone is absorbed by vegetation, is produced and destroyed in chemical reactions, and is heavily affected by the intensity of solar radiation. Local concentrations at any given time are also affected by meteorological and geophysical processes, especially in regions with high anthropogenic pollution. In 2024, wildfire emissions in the lower latitudes contributed to positive anomalies, although the combination of smoke with lower background levels of solar radiation offset this increase in the northern hemisphere. The long-term average levels of ozone have been comparatively stable over time, though there has been an upward trend in East and South Asia. The highest concentrations over land were in the subtropical latitudes of the northern hemisphere.

conduct modelling studies. In the USA, non-traditional policies addressing new types of emissions (other than from motor vehicles) need to be implemented to respond to the current shift in sources of VOC precursors.

This study highlights the importance of in situ infrastructure for monitoring trace gases, as well as the use of computer models for untangling the interplay of trace gases, meteorology and geography, in order to understand how tropospheric ozone forms under different circumstances and regimes. Expanding the infrastructure to deliver these kinds of insights is important for developing and implementing mitigation measures to reduce ozone impact on health and ecosystems.

Pollen modelling and forecasting for public awareness

Mikhail Sofiev, Julia Palamarchuk, Rostislav Kouznetsov

Wind-transported pollen plays a vital role in plant reproduction cycles, supporting gene distribution and biodiversity. Some pollen species, however, cause allergic reactions and exacerbate respiratory symptoms. Currently, about 20% of the world's population is affected, with prevalence of allergies increasing over the past decades. Therefore, there is a great demand for pollen monitoring, assessment and forecasting. Breakthroughs in automatic pollen measurements and public availability of real-time observations were described in the 2024 Bulletin. The present article describes pollen modelling and the new opportunities provided by these data.

The principles of pollen dispersion modelling were laid down over 20 years ago, and highlighted the primary challenges of predicting the start/end of pollen release (season timing), the total amount released by an average plant over the season (season strength) and the distribution of plants. Since then, season timing models have been developed at regional to continental scales, based on the heat accumulation through the year (Linkosalo et al., 2010), the astronomical calendar and day's length (Prank et al., 2017) or an empirical climatological calendar of the season (Sofiev, 2016). The season strength was more challenging to model accurately, and there are no continental-scale models currently available. The best regional approach was achieved using a machine learning-based model for northern Europe (Ritenberga et al., 2017). Finally, although plant distribution maps remain a challenge, progress has been achieved in several regions (see, for example, maps for Europe: https://efi.int/knowledge/maps). There are several numerical pollen forecasts around the world based on the above approaches.

Assimilation of pollen observations for improving the pollen forecasts and reanalyses had been hampered by data availability – until real-time measurements started to become openly available. The density of real-time networks is still insufficient for European-scale forecasting, but the SwissPollen network in Switzerland and the ePIN network in Bavaria (Germany) have made regional data assimilation possible. Unlike in numerical weather prediction, pollen observations are not used to set the initial conditions of the forecast, due to the very short sensitivity to such correction. Instead, models assimilate the season start/end dates and/or season severity (Adamov and Pauling, 2023; Sofiev et al., 2024). In both cases, significant improvements in the forecasts were demonstrated.

Pollen information published on the Internet and mobile telephone applications is an important tool for (often under-diagnosed) allergy awareness and education, as well as symptom self-management and patient well-being. Accurate and timely data and forecasts pave the way for personalized care and for early warning systems (EWS) for allergic diseases (Sousa-Pinto et al., 2024, Figure 6).

Most operational pollen transport and dispersion forecast systems are currently concentrated in the northern hemisphere, whereas South America and Africa still lack the technical/financial capacity and institutional infrastructure to implement them. Expanding forecasting to the global scale is a challenge to be addressed.

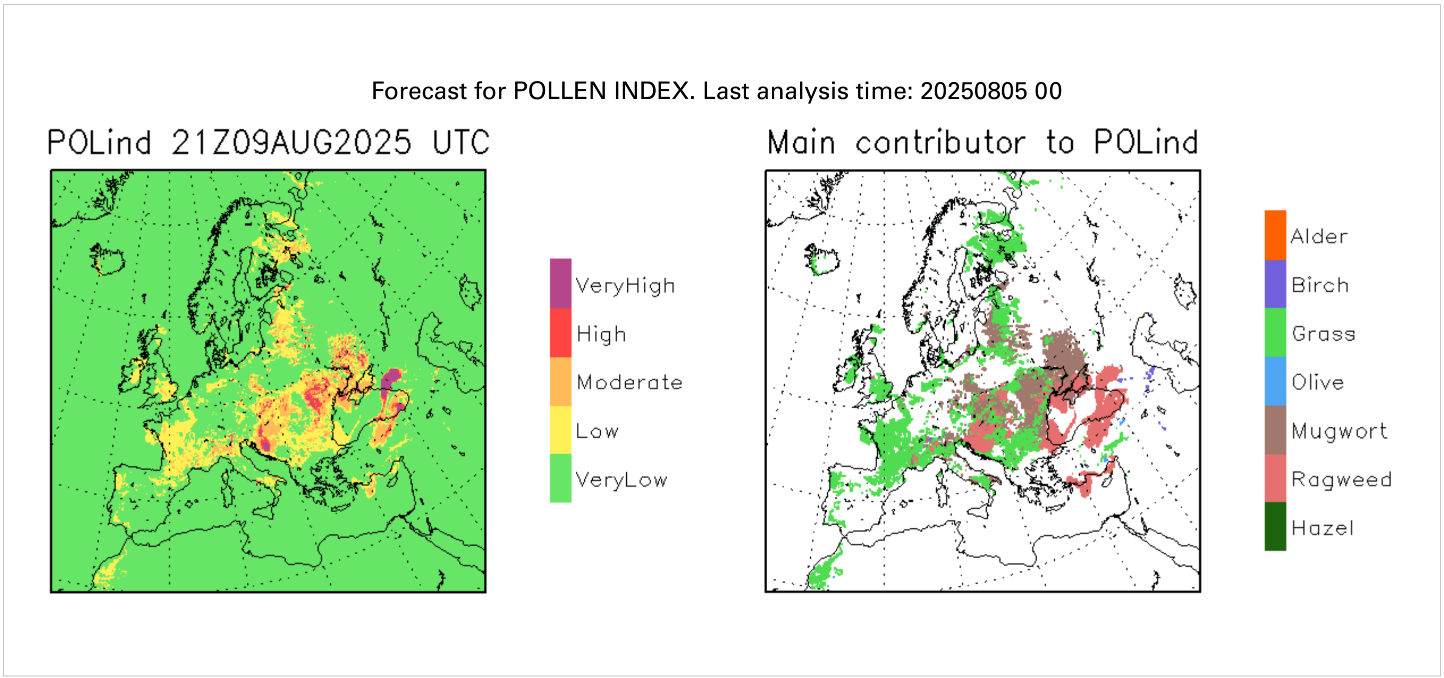

Figure 6. (Left) Forecast of Pollen Index, with indication of the main contributor to it (right)

Source: Third-party map. This map was provided by the Finnish Meteorological Institute (https://silam.fmi.fi) on 8 July 2025 and may not fully align with United Nations and WMO map guidance.

The availability of automatic pollen monitors, in combination with atmospheric composition models capable of pollen predictions and data assimilation, opens new avenues for public health care and a variety of research and industrial activities. It also sets the ground for regulatory and policy developments aiming at better informing society about the challenges and opportunities in this field.

The importance of infrastructure for monitoring atmospheric composition

The EarthCARE mission

Angela Benedetti, Lucia Mona

Launched on 29 May 2024, the Earth Cloud Aerosol and Radiation Explorer (EarthCARE) satellite mission was designed to shed new light on the role that clouds and aerosols play in regulating the Earth's climate. Aerosol-cloud interactions and their feedbacks are still one of the largest uncertainties in future climate scenarios.

EarthCARE is a joint venture between the European Space Agency (ESA) and the Japanese Space Agency (JAXA). The satellite carries four instruments providing a holistic view: a doppler cloud profiling radar and a high spectral resolution lidar, delivering vertical profiles; a multispectral imager; and a broadband radiometer measuring reflected solar radiation and the Earth's outgoing infrared radiation.

The WMO Global Atmosphere Watch (GAW) Programme provides a globally coordinated network of high-quality ground-based observations, located in key regions of climatic interest, offering continuous, traceable, homogeneous and quality-controlled data to validate and complement EarthCARE's remote-sensing observations. The GAW lidar stations (which are part of the GAW Aerosol Lidar Observation Network (GALION)) have been heavily involved, in close collaboration with ESA, in calibration and validation activities. Among those, an extensive and coordinated calibration and validation activity for both aerosol and clouds profiles was organized by the Aerosol, Clouds and Trace Gases Research Infrastructure (ACTRIS) at several stations.

Two international validation workshops have been held since the launch: https://www.earthcare-validation-2025-1.org/. The ground-based validation, including the GAW lidar activities, has contributed to algorithm improvement and data quality assurance. As a result, Level 1 data were released in January 2025, and Level 2 data were released in March 2025. These data are publicly available from the ESA online data dissemination site or JAXA Global Portal site.

The International Network to Study Deposition and Atmospheric Chemistry in Africa for long-term monitoring

Corinne Galy-Lacaux

The International Network to Study Deposition and Atmospheric Chemistry in Africa (INDAAF) programme, launched in 1994, represents an original initiative to fill gaps in long-term observation networks to monitor atmospheric chemistry and deposition in Africa. Conceived and run by a consortium of French research institutions (the National Centre for Scientific Research (CNRS) and Research Institute for Development (IRD)), INDAAF is also a contributing network to the WMO GAW Programme and to the ACTRIS-FR research infrastructure. It consists of 10 stations across Africa, covering major ecosystem types in Niger, Mali, Senegal, Benin, Côte d'Ivoire, Cameroon, Democratic Republic of Congo, South Africa and Tunisia (see Figure 7). Using protocols based on international standards, it collects in situ measurements of key atmospheric variables (trace gas concentrations, aerosol composition and precipitation chemistry) and provides unique open-access, high-quality atmospheric physico-chemical data.

In addition, INDAAF's successful history of capacity-building and knowledge-sharing has strengthened research partnerships in Africa. INDAAF's work has also led to more than 200 publications. In particular, it has enabled the synthesis and characterizations of wet deposition fluxes at the scale of large African ecosystems, as well as the study of trends for in situ trace gas concentrations and aerosol composition at the seasonal and interannual scale. INDAAF is strongly committed to initiatives that bring together scientists and policymakers to bridge the gap between science and action on nitrogen pollution and other deposited pollutants. This includes participation in the International Nitrogen Network iN-Net project launched in 2025 and the WMO Atmospheric Deposition Initiative (WADI).

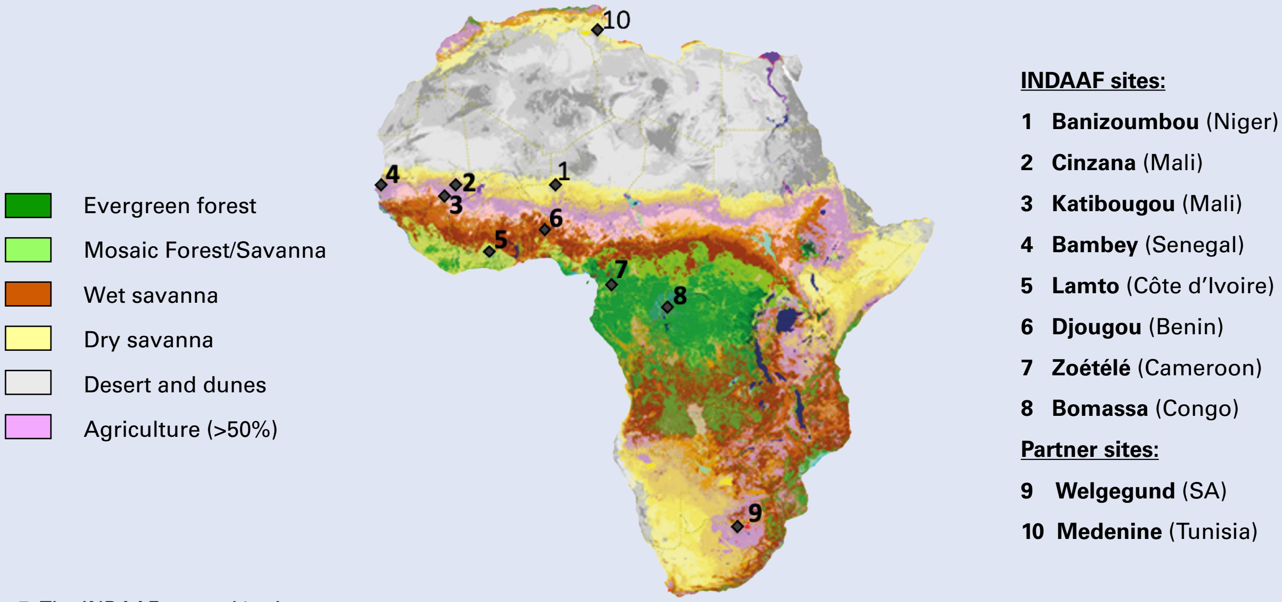

Figure 7. The INDAAF network's sites

Source: Third-party map. This map was provided by INDAAF on 4 August 2025 (https://indaaf.obs-mip.fr) and may not fully align with United Nations and WMO map guidance.

Conclusion

This fifth edition of the WMO Air Quality and Climate Bulletin provides a brief overview of some notable aspects of air quality and climate change in 2024. The articles highlight the relevance of existing data and the importance of addressing data gaps in atmospheric composition monitoring.

Atmospheric composition affects human health, ecosystem health, agricultural productivity, climate and more. It is also dynamic and varied across regions. The present Bulletin provides a few examples of the consequential and complex interplay between aerosols, reactive gases and long-lived greenhouse gases. One such case study looks at aerosols from agricultural practices that alter weather at a local level, by extending the duration of fog episodes. Another examines measures aimed at reducing pollution, with consequences on the Earth's radiative balance and therefore on climate, and another, explores the impact of emissions from wildfires in remote forested areas on air quality in faraway cities.

Monitoring the concentrations of human-made atmospheric pollutants is critical for advancing science, understanding the consequences of emissions, and developing policies and mitigation measures. Such measures aim to manage climate change and protect populations from negative health impacts, protect crops from reduced yields and protect ecosystems from degradation.

Observations are foundational. While satellites are becoming an important tool for atmospheric composition monitoring, their instruments cannot be calibrated and their retrieval algorithms and derived products cannot be validated without a functional and fit-for-purpose ground-based monitoring network. The need for additional observational infrastructure is particularly acute in the developing world.

The WMO GAW Programme continuously strives to promote and develop observational capabilities for atmospheric composition in the developing world by providing advice on monitoring network design, by promoting instrument intercomparison campaigns to ensure that measurements are of good quality and comparable across regions, and by promoting capacity development through the GAW Training and Education Centre.

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All authors in alphabetical order

Angela Benedetti, ECMWF, UK;

Maria Cazorla, USFQ, Colegio de Ciencias e Ingenierías, Instituto de Investigaciones Atmosféricas, Ecuador;

Peter Colarco, Atmospheric Chemistry and Dynamics Laboratory, NASA Goddard Space Flight Center, Greenbelt, USA;

Allison Collow, University of Maryland-Baltimore County, Baltimore, USA, and NASA Global Modeling and Assimilation Office, NASA Goddard Space Flight Center, Greenbelt, USA;

Johannes Flemming, ECMWF, Bonn, Germany;

Laura Gallardo, Department of Geophysics, University of Chile and Center for Climate and Resilience Research, Chile;

Corinne Galy-Lacaux, Laboratoire d'Aérologie, Université de Toulouse, National Centre for Scientific Research (CNRS), Research Institute for Development (IRD), Toulouse, France;

Tarun Gupta, Department of Civil Engineering, Indian Institute of Technology (IIT) Kanpur, India;

Jukka-Pekka Jalkanen, FMI, Finland;

Rostislav Kouznetsov, FMI, Finland;

Lucia Mona, Institute of Methodologies for Environmental Analysis, National Research Council (CNR), Potenza, Italy;

Julia Palamarchuk, FMI, Finland;

Pradhi Rajeev, Department of Civil Engineering, IIT Patna, India;

Isobel J. Simpson, Department of Chemistry, University of California, Irvine, USA;

Mikhail Sofiev, FMI, Finland;

Admir Créso Targino, UTFPR, Brazil.

NOTE

Contacts

World Meteorological Organization

Atmospheric Environment Research Division
Science and Innovation Department
Geneva, Switzerland
Email: gaw@wmo.int
Website: https://community.wmo.int/activity-areas/gaw

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