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WMO AIR QUALITY AND CLIMATE BULLETIN

Introduction

Ongoing climate change, caused by the accumulation of greenhouse gases in the atmosphere, is happening on a timescale of decades to centuries and is driving environmental changes worldwide. In contrast, the air pollution that occurs near the Earth's surface happens on a timescale of days to weeks, and across spatial scales that range from local (for example, urban centres) to regional (such as the eastern United States of America, northern India or the Amazon).

Despite these wide-ranging differences, air quality and climate change are strongly interconnected, with some pollutants affecting climate change. For example, short-lived reactive gases such as ozone, along with its precursors, are both common air pollutants and greenhouse gases that warm the atmosphere. Climate change also affects pollution: warmer temperatures, changing winds, increasing wildfires in new places and new precipitation patterns alter the formation, duration and dispersion of air pollution. Air quality also affects climate via ecosystem health. Through atmospheric deposition (the process by which air pollutants settle from the atmosphere onto the Earth's surface), nitrogen, sulfur and ozone can negatively influence the services provided by natural ecosystems, such as clean water, biodiversity and carbon storage, and can impact crop yields in agricultural systems.

Many of the sources of air pollution and climate change are the same. For example, the combustion of fossil fuels (a major source of carbon dioxide (CO_2)) is responsible for organic and inorganic aerosol formation and also emits nitrogen oxides (NOx) into the atmosphere, which can lead to the formation of ozone and nitrate aerosols. Similarly, some agricultural activities (which are major sources of the greenhouse gas methane) emit ammonia, which then forms ammonium inorganic aerosol.

Air quality and climate discussions are also increasingly integrated in governance. The Sixth Assessment Report, released by the Intergovernmental Panel on Climate Change (IPCC) in 2021, systematically assessed the adverse effects of climate change on health. In 2023, health was included in the official agenda for the first time during the 28th Conference of the Parties to the United Nations Framework Convention on Climate Change (COP28). The host country and the World Health Organization (WHO) issued the *Declaration on Climate and Health*, signed by more than 130 countries, prioritizing health in climate action and promoting climate-resilient, sustainable and equitable health systems. At WMO, the Air Pollution – Climate Change – Health Effects Nexus Working Group (ARCH WG) of the WMO Global Atmosphere Watch (GAW) Programme was established in 2023. It supports the WMO–WHO Joint Climate and Health Office and assists groups across the WMO Science and Innovation Department in co-designing products and services to enhance public health.

The fourth annual *WMO Air Quality and Climate Bulletin* reports on the state of air quality and its connections to climate change, reflecting on the trends and geographical distribution of pollution. On the state of the air, the 2024 Bulletin has (i) expanded the summary of the state of air quality in 2023 to include estimates from two sources (Copernicus Atmospheric Monitoring Services (CAMS) and the National Aeronautics and Space Administration's (NASA) Global Modeling and Assimilation Office (GMAO)) and (ii) included an article on bioaerosol concentrations. On connections to climate change, the 2024 Bulletin considers the impacts of Canadian and Chilean wildfires on pollution and includes a piece on formation of nanoparticles, that in turn may affect near-term warming. On impacts, the present Bulletin includes an article on the consequences of particulate matter pollution on agriculture.

The range of topics covered in the 2024 Bulletin illustrates some of the science that GAW, as part of its strategic objectives, seeks to catalyse to inform the development of policies and conventions. Reliable, regular monitoring and reporting support accountability and progress tracking. Information on sources of pollution helps to prioritize climate and air pollution mitigation – and highlights some of the interconnections between climate change and pollution. Evidence on impacts – in this case, the effects of particulate matter pollution on agricultural yields – identifies an area of concern. Analysis of the links between air pollution and climate – as in the pieces on bioaerosols and shifts in nucleation and cloud events – helps to motivate and direct integrated action on pollution and climate change.

Global particulate matter concentrations in 2023 as recorded by two products

Johannes Flemming, Allie Collow

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 activity 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 $PM_{2.5}$. These diversities in emission sources, and uncertainties in formation and other processes, make predicting (forecasting) $PM_{2.5}$ challenging.

Best estimates of global $PM_{2.5}$ concentrations are obtained by optimally combining satellite observations of aerosol optical depth (AOD) with model predictions of $PM_{2.5}$. These fused products are referred to as $PM_{2.5}$ reanalysis. Two global reanalysis products are currently available: the CAMS reanalysis (CAMSRA) and GMAO's Goddard Earth Observing System for Instrument Teams (GEOS-IT) reanalysis.

The 2023 $PM_{2.5}$ anomalies for the reference period 2003–2023 are presented in Figure 1. The 2023 $PM_{2.5}$ anomalies were dominated by the exceptionally strong wildfire emissions over North America in the northern hemisphere summer of 2023. Both the CAMS and GEOS-IT data show a good level of agreement in the location and magnitude of the anomaly. The magnitude of the 2023 $PM_{2.5}$ anomaly over North America was even more pronounced than the 2021 $PM_{2.5}$ anomalies caused by the strong wildfires in Siberia (WMO, 2022).

The positive $PM_{2.5}$ anomaly over India and the negative anomalies over China and Europe were caused by gradually increased or decreased anthropogenic emissions in the respective regions. Both datasets show agreement in terms of the direction of the trends, but the trends appear more pronounced in the CAMSRA dataset, probably caused by the stronger trends in the underlying anthropogenic emission inventories. The CAMSRA data show a decreasing $PM_{2.5}$ trend over the eastern United States, which is not present in the GEOS-IT dataset.

Desert dust emissions are controlled by meteorological factors such as wind speed and soil state. Both datasets show lower than usual dust emissions over the deserts in the Arabian Peninsula and large parts of North Africa, where the negative anomalies were more pronounced in the CAMSRA dataset.

Overall, there is very good agreement between the 2023 $PM_{2.5}$ anomalies derived from CAMSRA and GEOS-IT in terms of spatial distribution and, to a lesser extent, magnitude. This is an indication of the robustness of the monitoring by the two centres. Despite the good agreement in the variability and trends, there are still considerable differences in the mean $PM_{2.5}$ concentration, varying from 20% to 30% depending

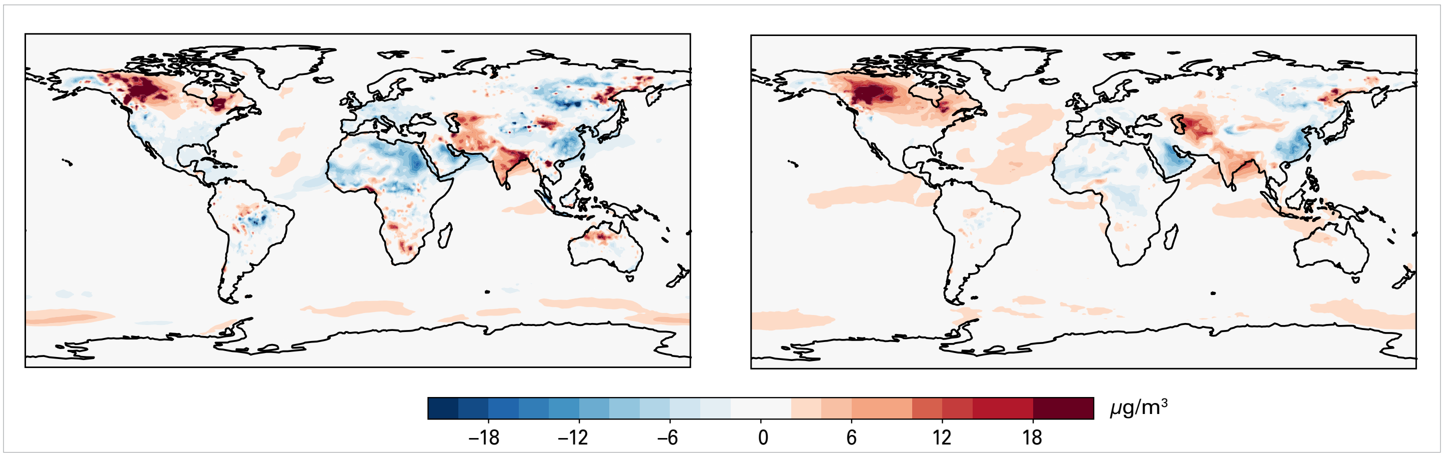

Figure 1. $PM_{2.5}$ anomaly ($\mu g\ m^{-3}$) in 2023 (reference period 2003–2022)

Source: Generated from the CAMS reanalysis (left) and the NASA GMAO GEOS-IT reanalysis (right) (https://gmao.gsfc.nasa.gov/GMAO_products/GEOS-IT/)

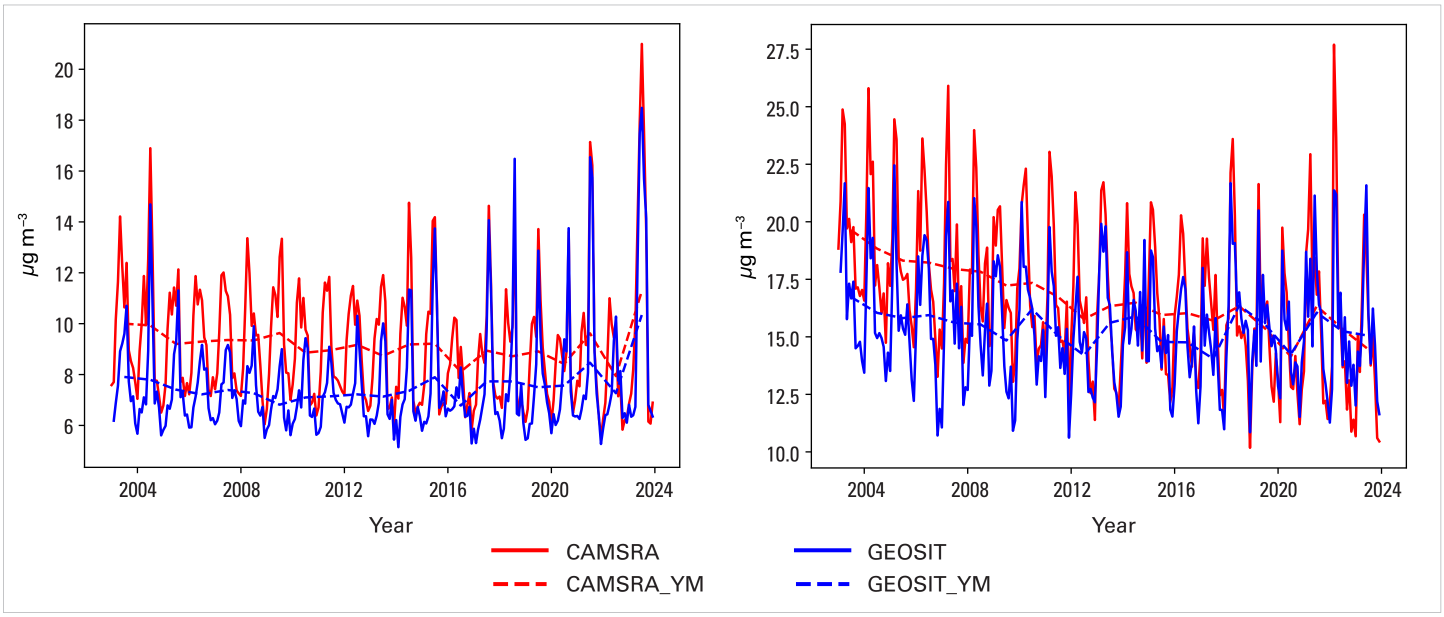

Figure 2. Time series of monthly (solid line) and annual (dotted line) area-averaged $PM_{2.5}$ concentrations over North America (left) and Europe (right)
Source: Generated from CAMSRA data (red) and GEOS-IT data (blue)

on the location (Figure 2). The differences in the mean $PM_{2.5}$ values between CAMSRA and GEOS-IT decrease over time with smaller differences in more recent years.

Impacts of atmospheric particulate matter on crops

Frank Dentener, Gina Mills, Ward Smith, John Walker

With eight million people estimated to die prematurely from atmospheric particulate matter (or "aerosol") pollution every year (Yin et al., 2021), the global impacts of PM on health are understandably a major focus. A recent report from WMO (2023) highlights how PM can also reduce crop productivity in areas where maximizing yield is of crucial importance for feeding the population. Global PM hotspots include agricultural areas in Central Africa, Pakistan, India, China and South-East Asia (Figure 3). The report also shows that agriculture is itself a major contributor to PM through release of particles and their precursors by stubble burning, fertilizer and pesticide applications, tillage, harvesting, and manure storage and use. Whether present in their original form or chemically transformed in the air, these particles

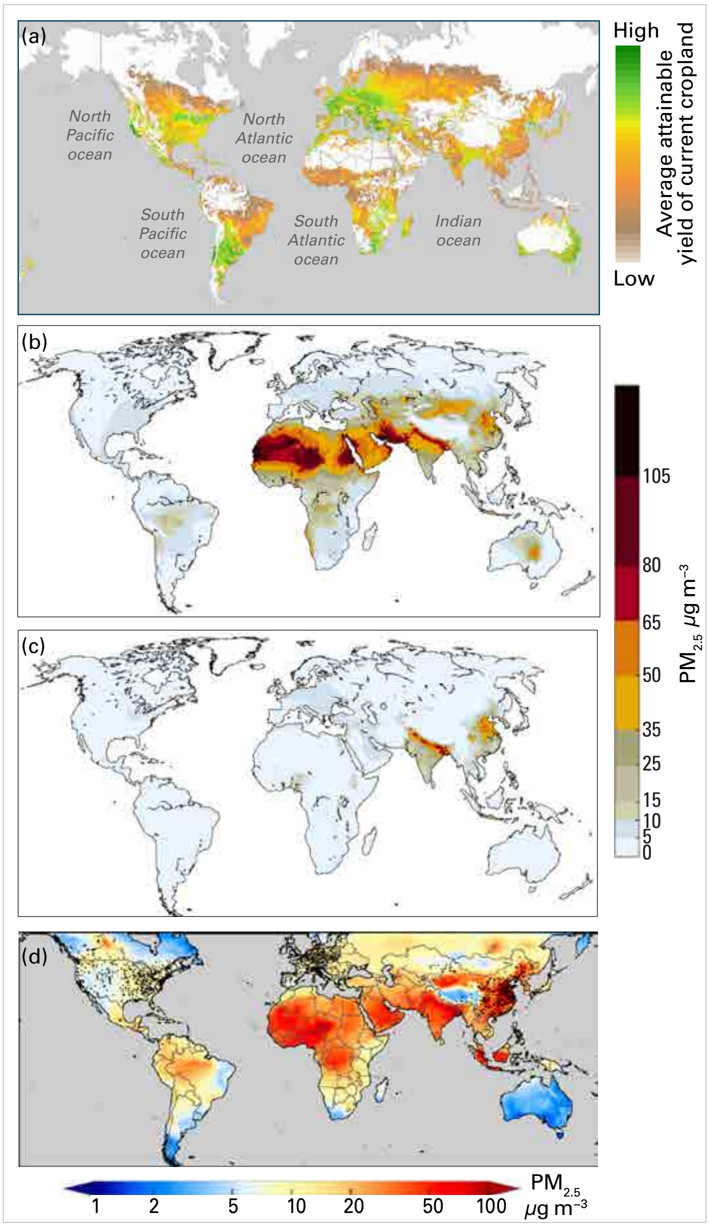

Figure 3. Global crop-growing areas and hotspots for $PM_{2.5}$ in 2015.
(a) Crop-growing areas shown as the average attainable crop yield (Food and Agriculture Organization of the United Nations (FAO) Global Agro-Ecological Zones (GAEZ) data portal);
(b) combined natural and anthropogenic $PM_{2.5}$ concentrations, modelled using the Greenhouse Gas and Air Pollution Interactions and Synergies (GAINS) model (Amann et al., 2020);
(c) concentrations of $PM_{2.5}$ from anthropogenic sources only, modelled using GAINS (Amann et al., 2020);
(d) geophysical $PM_{2.5}$ concentrations determined using a combination of aerosol optical depth and ground-based measurements, where black dots represent monitor locations (Hammer et al., 2020).

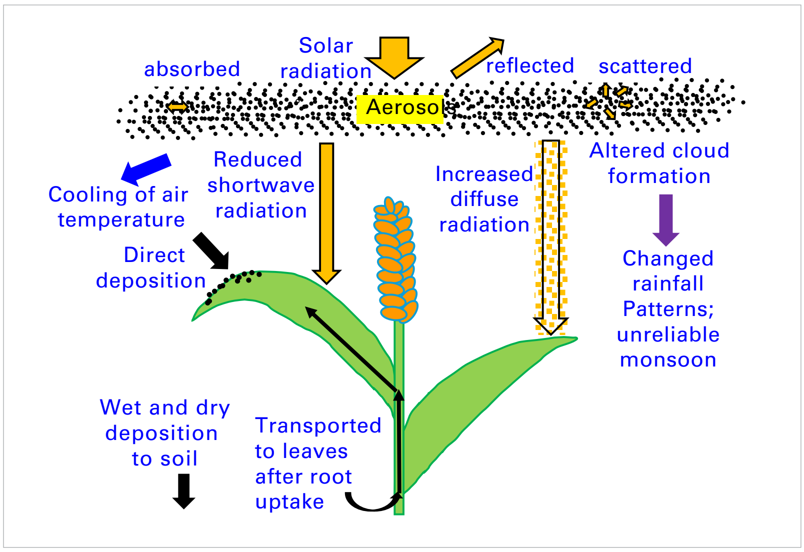

Figure 4. The multiple routes by which PM affects crops, including direct deposition to crop leaves and soil (black arrows), and indirect impacts via effects on sunlight (solar, short-wave and diffuse radiation: orange arrows), temperature (blue arrow) and rainfall (purple arrow)

Sources: *The Impacts of Particulate Matter on Crop Yield: Mechanisms, Quantification and Options for Mitigation* (WMO-No. 1340)

can affect crops growing nearby or may be transported tens to thousands of kilometres in the atmosphere, affecting distant crops.

Existing PM standards aim to protect people from consuming crops that may be damaging to their health. For example, edible parts of crops may become contaminated with PM containing heavy metals such as lead and mercury (Hou et al., 2020). However, these standards do not address direct and indirect impacts on food production. Where PM concentrations are high (Figure 3), dry deposition[1] of PM onto crops directly affects them by reducing the amount of sunlight reaching leaf surfaces and physically blocking leaf stomata which regulate exchange of water vapour and carbon dioxide with the atmosphere (Figure 4). Experimental evidence from India and China indicates that dry deposition of PM in highly polluted areas reduces crop yields by up to 15% (Mina et al., 2018). PM also affects crop growth indirectly by changing the amount and characteristics of solar radiation reaching the Earth's surface (Figure 4). For example, modelling studies suggest that combined radiative effects reduced yields of rice and wheat in China during the 2010s by 4.6% and 4.7%, respectively (Zhang et al., 2021). Aerosols also indirectly affect the reliability of crop yields by, for example, altering precipitation patterns.

The recent WMO PM report *The Impacts of Particulate Matter on Crop Yield: Mechanisms, Quantification and Options for Mitigation* (WMO-No. 1340) outlines several actions to better understand and mitigate the effects of PM on crops. The most practical mitigation option at the farm scale is to plant trees or shrubs to physically shelter crops from local sources of PM, with added carbon sequestration and biodiversity benefits. More broadly, reducing PM emissions and atmospheric concentrations is key. The agricultural sector could reduce PM by reducing soil erosion and ammonia volatilization and improving tillage and grain handling practices. While air pollution control policies have reduced concentrations of PM in some regions (Europe, North America, China), concentrations remain high in some important agricultural regions such as the Indo-Gangetic Plain of Pakistan, India and Bangladesh, and across north-east China (Figure 3). Targeted mitigation in crop-growing areas at risk of PM impacts would benefit from an expansion of ground- and satellite-based PM monitoring (see *Global particulate matter concentrations in 2023 as recorded by two products* section). New research is also needed to improve models used to predict future crop yields by including the interactive effects of changing air quality and climate.

The 2023 wildfire season in Canada

Mark Parrington, Radenko Pavlovic

Several studies have shown that climate change can be a driving factor behind warmer weather conditions, prolonged drought and a dry atmosphere in some parts of the world. These conditions increase the risk and likelihood of forest fires spreading, which in turn has a major impact on air quality. North America, particularly its western regions, is one of the areas prone to intense and extreme wildfires.

The 2023 wildfire season set a multi-decade record in Canada in terms of total area burned, with seven times more hectares burned than the 1990–2013 average (Canadian National Fire Database: http://nfdp.ccfm.org/en/index.php). Many large and persistent fires burned from the first week of May and throughout the summer until the last week of September. The first May fires started in western Canada, where conditions were warmer and drier than usual for the time of year. Later in the month, the first fires broke out in Quebec, east of Hudson Bay. These were noted in the international media due to the worsening air quality in eastern Canada and the north-eastern United States, particularly in New York City, which experienced several days of heavy smoke in early June. Smoke from Canadian forest fires was

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[1] Dry deposition is the transfer of particles and gases from the atmosphere to the Earth's surface by turbulent motion, diffusion and gravitational settling.

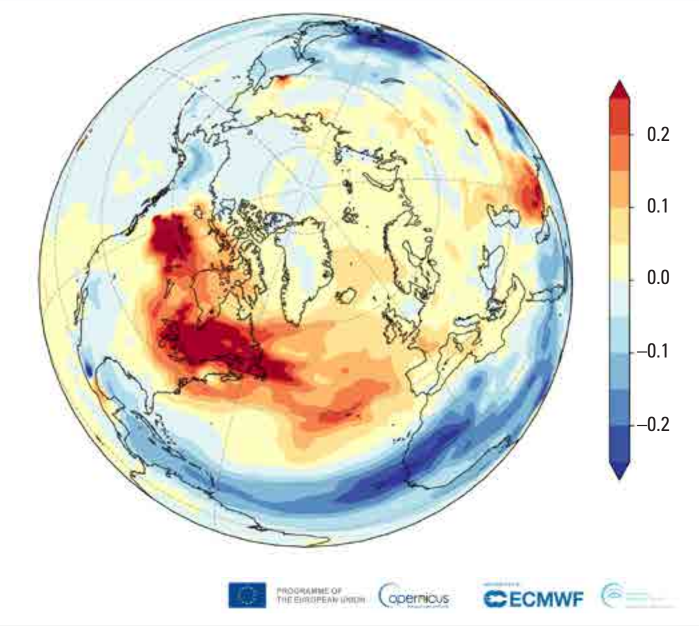

Figure 5. Monthly mean anomaly in total aerosol optical depth at 550 nm for June 2023 relative to June 2003–2022

Source: CAMS reanalysis of global atmospheric composition (2003–2023): https://ads.atmosphere.copernicus.eu/cdsapp#!/dataset/cams-global-reanalysis-eac4-monthly?tab=overview

also transported across the North Atlantic Ocean and was detected in measurements taken by instruments in NASA's Aerosol Robotic Network (AERONET) and by aircraft within In-service Aircraft for a Global Observing System (IAGOS) in southern Greenland, the Azores and Western Europe.

The persistence of forest fires in the Northwest Territories of Canada throughout the rest of the northern hemisphere summer resulted in cumulative total estimated emissions well above the annual total from forest fires in Canada since at least 2003. The accumulation and persistence of smoke pollution, and especially aerosols, from the fires was reflected in the total aerosol optical depth data from the CAMS global atmospheric composition reanalysis, which showed positive anomalies relative to the 2003–2022 average for all months between May and September, underscoring the unusual nature of the 2023 forest fires (see, for example, Figure 5).

Aerobiology in transition: new challenges and opportunities

Mikhail Sofiev, Bernard Clot, Jeroen Buters, Evgeny Kadantsev, Mika Komppula, Lucia Mona, Julia Palamarchuk, Xiaoxia Shang, Svetlana Sofieva-Rios, Olga Sozinova, Fiona Tummon, Ingrida Šaulienė

Information about primary biological aerosols of different origin (for example, plant pollen, fungal spores, bacteria, and so forth) in the atmosphere is in high demand from medical practitioners, allergy sufferers, agriculture and forestry industries, and climate change, biodiversity and air quality researchers, to name a few. However, until recently, aerobiological monitoring was based on a manual method, using the volumetric Hirst-type pollen and spore trap. Although a breakthrough at the time, this type of device has received substantial criticism for its limited accuracy and the limited reproducibility of its results, as well as its associated expensive manual analysis (Adamov et al., 2021).

Over the past few years, new technologies have made it possible to obtain information on bioaerosol concentrations in real time (Buters et al., 2022; Tummon et al., 2024), to analyse vertical concentration profiles via lidar observations (Shang et al., 2022) and to perform metagenomic analysis of bioaerosols (an approach exploring all genetic material extracted directly from the sample) with third generation DNA sequencing techniques (Sofiev et al., 2022). These new techniques, all of which are still being further developed, open entirely new possibilities for the wide range of stakeholders interested in bioaerosols. The new instruments are expensive but, despite the high initial investments, automatic bioaerosol monitors are being deployed across Europe (see Figure 6), making data available to all, as the new networks strive to follow open data and open science principles.

The new observational techniques rely heavily on sophisticated technologies, such as high-resolution image analysis, holography, multi-band scatterometry, fluorescence spectrometry and nanotechnology for DNA sequencing. The task of particle recognition is then

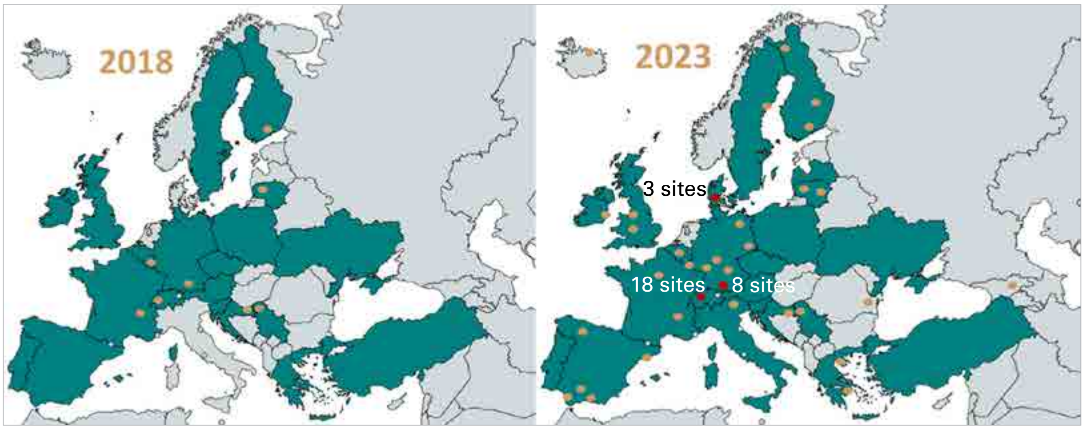

Figure 6. Distribution of automatic bioaerosol monitors in 2018 and 2023. The dark green colour denotes participants of the EUMETNET AutoPollen programme (https://autopollen.net/).

Source: Adapted from Tummon et al. (2024)

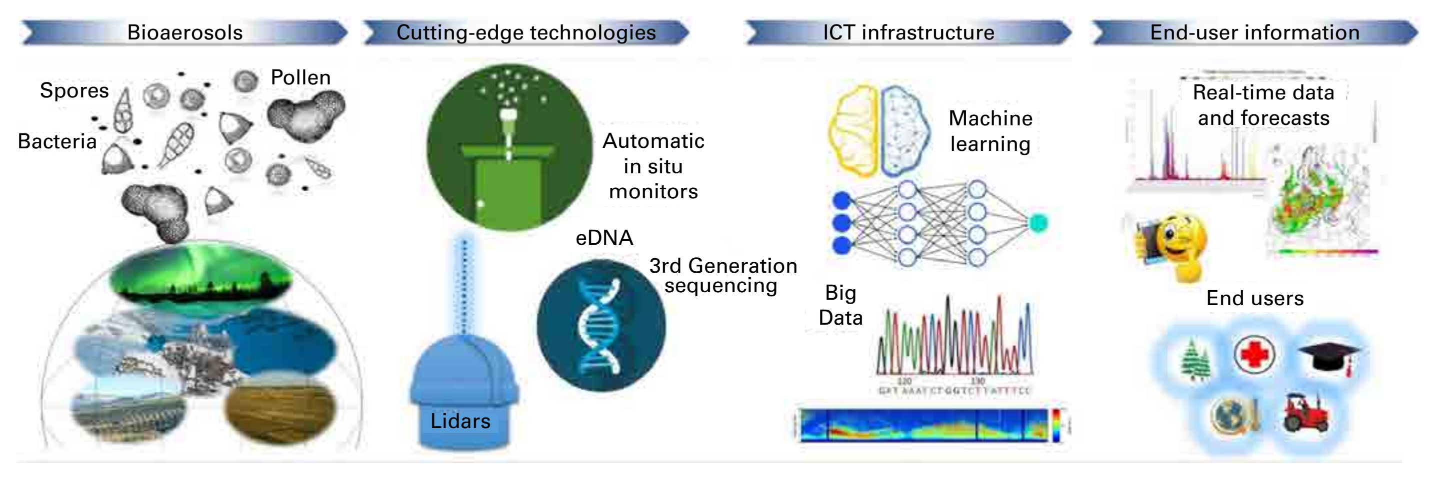

Figure 7. Components of the new bioaerosol observation paradigm
Source: https://sylva.bioaerosol.eu

typically carried out using machine learning approaches, that is, identification algorithms independently developed for each device type. This changes the existing paradigm of bioaerosol observations, as monitoring networks now require large-scale data infrastructure, which also includes numerical models as an interface between the different technologies and an open bridge to information users (see Figure 7). The particle identification algorithms are quickly evolving, and the most advanced versions are already used in operational networks and real-life applications (Maya-Manzano et al., 2023).

New bioaerosol monitoring networks have enabled the first real-time integration of these data into modelling applications at the regional and national scales (for example, see Figure 8 for European and national pollen forecasts). As often occurs in the field of air quality, classical model-state assimilation does not lead to any lasting improvement (Sofiev, 2019) but extended assimilation techniques and real-time preprocessing of model parameters improve the skills of short-term forecasts. Operational European-wide applications require a denser network than currently exists (Sofiev et al., 2023), but the real-time technology has shown robust performance in a new European pollen reanalysis. These developments open new possibilities for continental-scale forecasting, whether supervised, that is, involving an expert to generate the final prediction, or unsupervised, upon demonstrating robustness of predictions for some applications.

Bioaerosols play an important role in climate studies: vegetation is one of the most sensitive indicators of climate change. Biodiversity changes and plant flowering

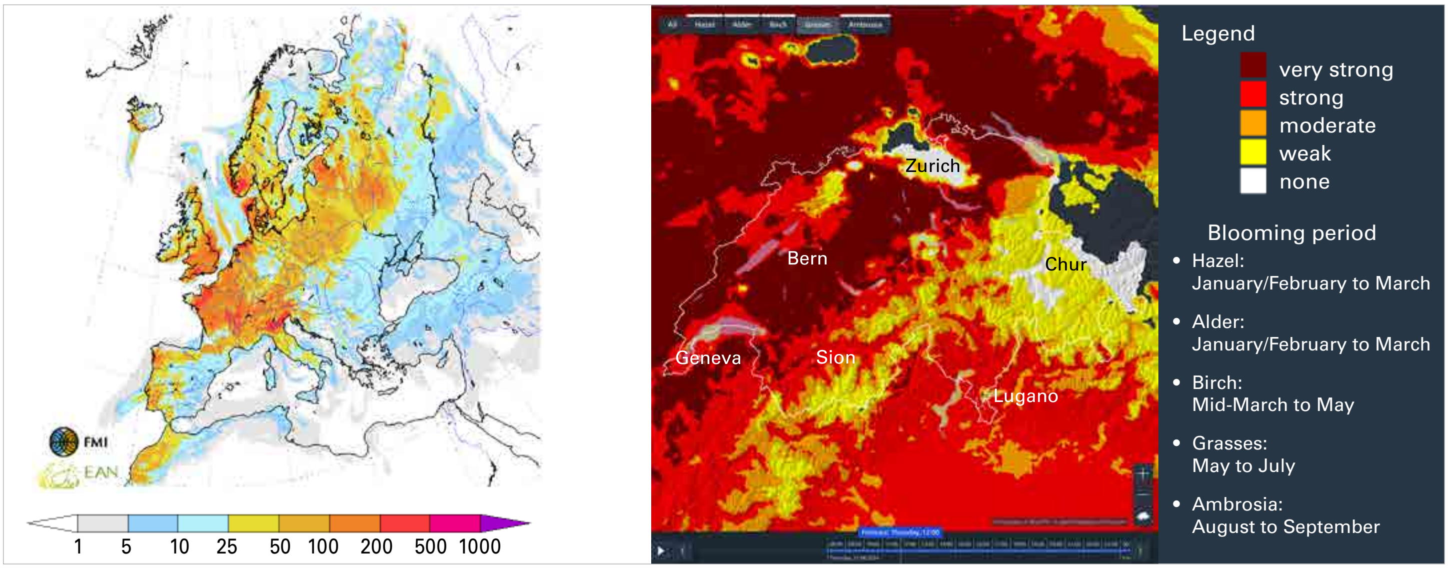

Figure 8. Example forecasts of grass pollen concentrations for 27 June 2024 for Europe (left, generated by the SILAM model, in pollen/m^3: http://silam.fmi.fi) and for Switzerland (right, generated by the COSMO-ART model, in categories from "none" to "very strong": http://www.meteoswiss.ch). Pollen forecasts are also available from Copernicus: https://atmosphere.copernicus.eu/european-air-quality-forecast-plots.

time, intensity and distribution patterns are all sensitive to meteorological conditions. Long time series of phenological and aerobiological data allow for detailed studies of variability and trend assessment (Ziska et al., 2019). A question of vital importance is whether the observed tendencies represent the plant reaction to specific conditions of a particular year, that is, reversible changes, or an adaptation to new climate conditions and therefore essentially irreversible changes (Fu et al, 2015).

Decreasing formation of atmospheric nanoparticles across Global Atmosphere Watch stations

Sang-Woo Kim, Do-Hyeon Park

The cooling and warming effects of aerosol particles on the Earth's climate depend on the particles' size, their chemical composition and their concentration in the atmosphere. These effects also vary across different locations and times, due to the diverse sources of aerosols and their relatively short lifespan in the atmosphere. Recent global analyses of climate-relevant aerosol properties from the long-term records at near-surface observatories of the WMO GAW Programme have shown an unequivocal decrease in the scattering and absorption of light by particles in Europe and North America. These analyses have also provided the most up-to-date picture of the spatial distribution of particle number concentration and particle number size distribution (PNSD) (Collaud Coen et al., 2020; Laj et al., 2020; Rose et al., 2021).

As an extension of these efforts, quality-controlled PNSD data from 27 GAW stations across urban, rural and remote environments were analysed to assess trends in (i) new particle formation (NPF) events and (ii) nucleation-mode particles. NPF involves formation of larger particles which can act as seeds for cloud droplet formation. Nucleation-mode particles are particles between 10 nm and 25 nm in diameter. Both NPF and nucleation-mode particles are of particular interest because they are closely linked to air quality (human health), cloud formation and climate impacts.

Urban sites exhibited the highest total particle number concentrations, peaking at around 20 nm in diameter, indicative of frequent NPF events. Nucleation-mode particles were a dominant contributor to total particles in urban areas (see Figure 9(a)). On days with NPF events compared to non-event days, total particle number concentrations were 100%–200% higher, showing that NPF significantly increases particle levels. The highest NPF frequency of approximately 40% was found in urban areas, compared to about 30% at remote sites with minimal local emissions.

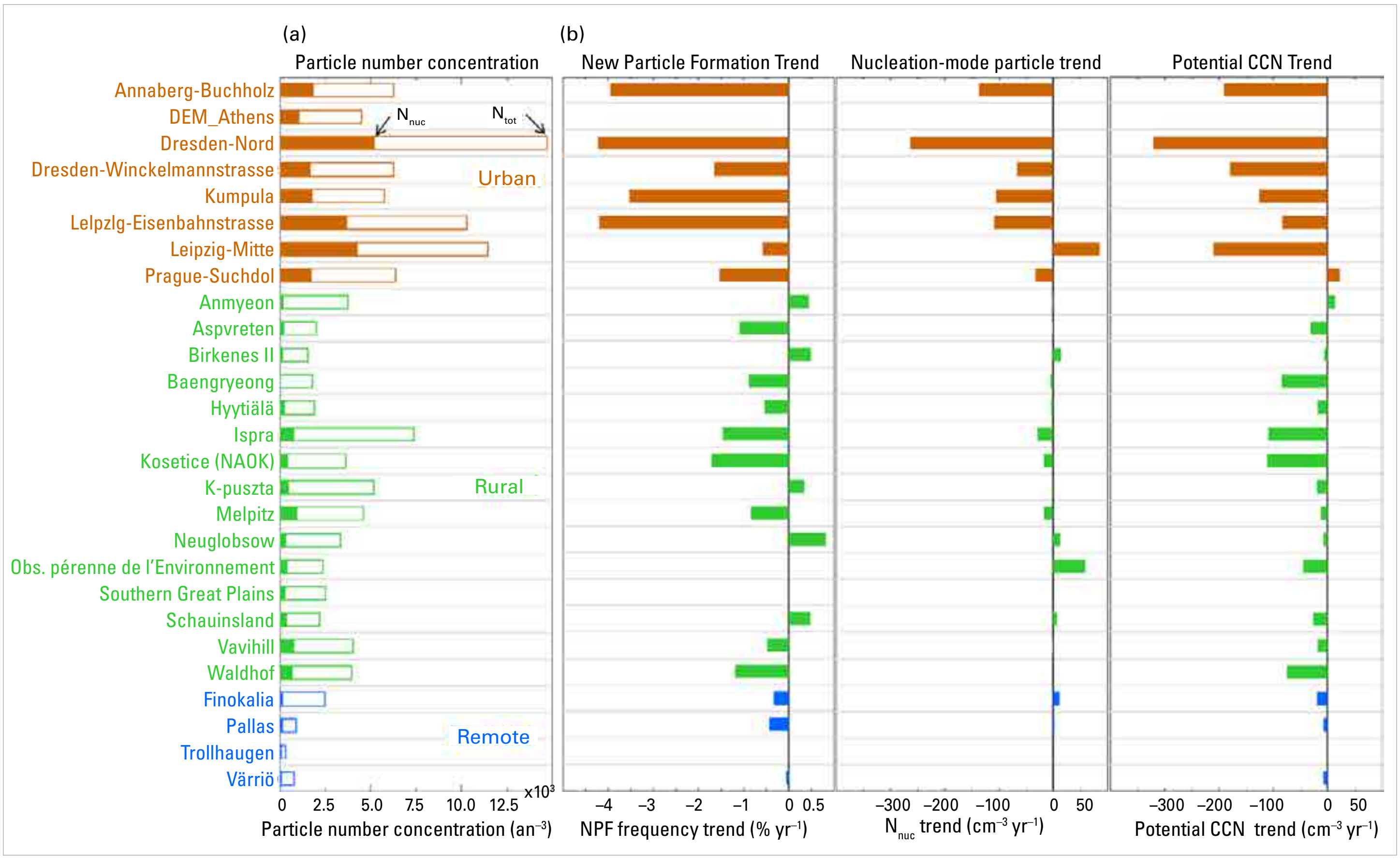

Figure 9. (a) Overall mean of the total (N_{tot}) and nucleation-mode (N_{nuc}) particle number concentration at three environmental conditions (urban–brown, rural-green and remote-blue), and (b) annual trends for NPF frequency (left), nucleation-mode particle number concentration (middle) and potential cloud condensation nuclei (CCN) (N_{50}) particles (right)

Source: Park, D.-H. and Kim, S.-W.

Decreasing decadal trends were overwhelmingly found for both NPF frequency and nucleation-mode particle concentrations across all site types, especially in urban areas (see Figure 9(b)). For example, the NPF frequency declined by up to 4% per year in urban sites.

The reduction in nucleation-mode particles was closely linked to decreasing concentrations of potential cloud condensation nuclei (CCN) (N_{50}, that is, particles larger than 50 nm in diameter: see Figure 9(b)). Potential CCN concentrations (N_{50}) were 70%–170% higher on NPF days, suggesting that decreasing NPF occurrences are reducing available CCN across diverse regions globally. This alteration in the CCN budget due to decreased nucleated particles may impact cloud microphysical properties and cloud effects on radiation through changes in how cloud droplets form.

Trends in NPF, and therefore particle number and CCN concentrations, are due to declining trends in emissions of precursor pollutants. While reducing air pollution is undoubtedly beneficial for human health and the environment, there are unintended side effects of this that call for careful monitoring, especially around highly polluted megacities. Reducing particle concentrations brings down the level of harmful $PM_{2.5}$ (see above), however, depending on the reflectivity of the type of particles, can lead to different impacts on radiation reaching Earth's surface. When reducing light-coloured, more reflective particles, more sunlight can reach – and therefore warm – the surface as the "shading" effect of aerosols is reduced. This "aerosol demasking" effect caused by pollution control measures was briefly observed during the COVID-19 pandemic when emissions declined due to lockdowns (Nair et al., 2023). Such trends could result in overshooting climate targets and enhanced risk of severe heat stress for large populations. However, the opposite can be true for dark-coloured, light-absorbing particles, pointing to the need for continuous observation and attempts to model and understand these complex, sometimes competing effects.

Extreme wildfires in central Chile impacted air quality in early 2023

Rodrigo Seguel, María Cazorla, Lucas Castillo, Tomás Carrasco-Escaff, Laura Gallardo

In January and February 2023, central and southern Chile were struck by devastating wildfires that developed south of the Santiago Metropolitan Region. Over 400 fires, most of them intentional, burned vast regions of plantations and woods. Extreme ambient air temperatures fuelled the fires in an area already affected by a pervasive drought that has lasted more than a decade. The National Air Quality Information System recorded the impact of these disastrous events that led to increased levels of all air pollutants in all stations, as shown in Figure 10.

During the most intense period of active fires, the daily short-term exposure to ozone (based on the maximum daily 8-hour average (MDA8)) increased drastically at several monitoring stations, reaching mixing ratios of

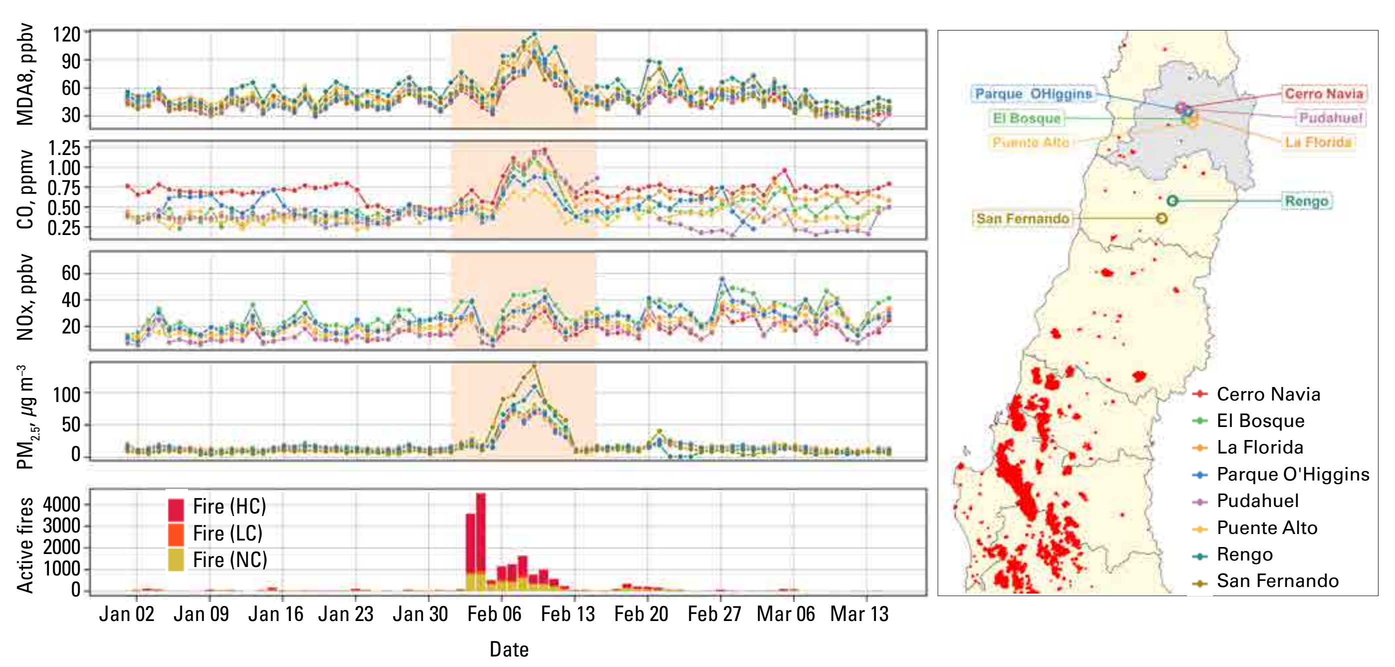

Figure 10. Time series of the maximum daily 8-hour average (MDA8) ozone, carbon monoxide (CO) (in parts per million (ppmv)), nitrogen oxides (NOx) and fine particulate matter ($PM_{2.5}$) from selected air quality monitoring stations (MDA8>50 ppbv) for the period January to March 2023. The lower panel shows the daily (24 h) active fires obtained from MODIS satellite products (https://modis-fire.umd.edu) at 1 km resolution (MOD13A1), with coloured bars indicating confidence (high (HC), nominal (NC) and low (LC)) based on infrared radiation emission. The map (right panel) shows the active fires during February in central Chile. The Santiago Metropolitan Region, where most of the monitoring stations are located, is shaded grey.

Source: Adapted from Seguel et al. (2024) (addition of $PM_{2.5}$), under a *Creative Commons License* up to 117 parts per billion (ppbv) (at Rengo station). Such levels of exposure contrast with typical MDA8 values for summer months in central Chile, which are usually high, although close to the WHO guideline for ozone (51 ppbv). Furthermore, high levels of carbon monoxide were indicative of increased ozone precursors in the ambient air, while fine particulate matter concentrations spiked up to 141 μg m^{-3} (at San Fernando station). These events caused a positive anomaly to be detected in the long-term ozone trends (Seguel et. al., 2024). Atmospheric conditions of strong winds, persistent high pressure, and temperatures of about 40 °C were key factors in propagating the fires. Large plumes were visible from space during the two months of fire activity.

Due to the damage and deaths caused by the fires and the high levels of atmospheric pollutants, Chilean authorities declared a state of environmental emergency in various regions of central Chile. These catastrophic events took the lives of 25 people and caused severe damage to the homes and economies of thousands of citizens. Despite Chile having made significant efforts to enhance the country's preparedness to face extended fire seasons, inadequate territorial planning within cities and their peripheries still has dire consequences. These events are becoming more frequent under the influence of climate change. Therefore, major work based on actionable interdisciplinary science is fundamental to properly address urban resilience in years to come.

Conclusion

This fourth edition of the *WMO Air Quality and Climate Bulletin* surveys the state of the science and highlights some notable events that took place in 2023. An evaluation of $PM_{2.5}$ anomalies for the year includes results from two global modelling centres (CAMS and NASA's GMAO) and a discussion of their similarities and differences. A closer examination of ways in which PM adversely impacts agriculture is presented in the following section, summarizing findings from the recent WMO report *The Impacts of Particulate Matter on Crop Yield: Mechanisms, Quantification and Options for Mitigation* (WMO-No. 1340).

The unprecedented North American wildfires of 2023 and their air quality impacts on downwind areas in the region and abroad are described in the subsequent section. The advent of new monitoring and forecasting capabilities for biological aerosols, which include pollen, fungal spores and bacteria is then presented, along with a discussion of the important connections between these bioaerosols and climate.

The next section examines long-term records of aerosol measurements collected at WMO GAW stations worldwide and concludes that new particle formation events are decreasing in frequency, with implications for cloud formation and radiative effects of both clouds and aerosols. Finally, the last section details an extreme ozone pollution event in Chile resulting from wildfires in early 2023. Concurrent observations of ozone, carbon monoxide, nitrogen oxides and $PM_{2.5}$ in central Chile exhibit the extreme detriment to air quality caused by intense and persistent wildfire events made more common in a warming climate.

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