WORLD METEOROLOGICAL ORGANIZATION

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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. The *WMO Air Quality and Climate Bulletin* reports annually on the state of air quality and its connections to climate change, reflecting on the geographical distribution of and changes in the levels of traditional pollutants.

Traditional pollutants include short-lived reactive gases such as ozone – a trace gas that is both a common air pollutant and a greenhouse gas that warms the atmosphere – and particulate matter (PM) – a wide range of tiny particles suspended in the atmosphere (commonly referred to as aerosols), which are detrimental to human health and which, due to their complex characteristics, can either cool or warm the atmosphere.

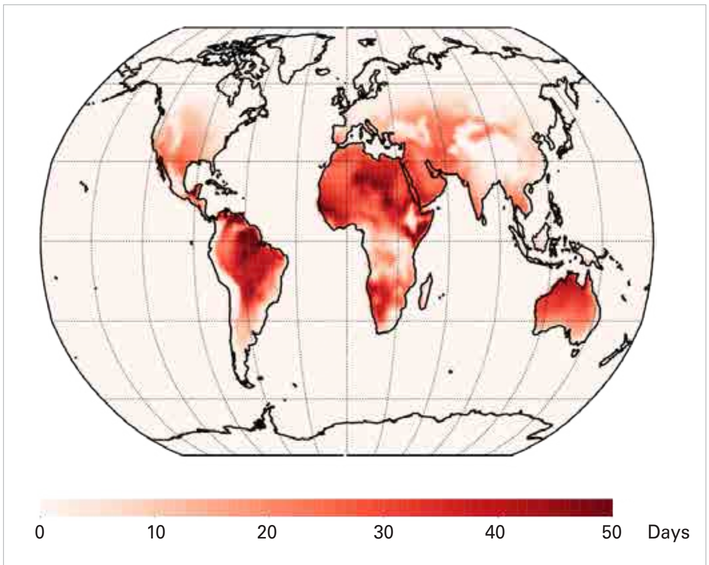

Figure 1. Change in the number of days per year with daily maximum surface temperatures above 35 °C, relative to an 1850–1900 baseline, as predicted by 27 numerical models, in a world that will have experienced 1.5 °C warming (based on the Shared Socioeconomic Pathway SSP5-8.5), globally averaged

Source: Figure produced using data from the IPCC Working Group I Interactive Atlas: https://interactive-atlas.ipcc.ch/

Air quality and climate are interconnected because the chemical species that affect both are linked, and because changes in one inevitably cause changes in the other. Human activities that release long-lived greenhouse gases into the atmosphere also lead to the enhancement of concentrations of shorter-lived ozone and PM in the atmosphere. For example, the combustion of fossil fuels (a major source of carbon dioxide (CO_2)) also emits nitrogen oxide (NO) 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 aerosols. Air quality in turn affects ecosystem health via atmospheric deposition (the process by which air pollutants settle from the atmosphere onto the Earth's surface), which therefore also links air quality to climate. Deposition of nitrogen, sulfur and ozone can negatively affect the services provided by natural ecosystems such as clean water, biodiversity and carbon storage, and can impact crop yields in agricultural systems.

The present edition of the *WMO Air Quality and Climate Bulletin* provides an update on the global distribution of PM for 2022 and explores avenues through which heatwaves affect atmospheric composition. Heatwaves are expected to worsen with climate change (Figure 1), and several notable heatwaves occurred in 2022. Two case studies further examine the interconnections between PM, climate and air quality. Increased severity of wildfires in heatwave-stricken areas can produce more aerosol pollution, such as occurred over western North America in August–September 2022, while the intrusion of a desert air mass over Europe from North Africa brought both heatwave conditions and desert dust in August 2022. Furthermore, the present edition of the Bulletin explores how the persistent heatwave that impacted Europe in June–August 2022 influenced concentrations of ground-level ozone. New findings elucidating the role that wildfires play in driving nitrogen deposition, which can negatively affect ecosystems, are summarized, and the numerous and complex interactions between agriculture and air quality are outlined. Finally, the Bulletin concludes by exploring how elevated temperatures may be exacerbated in cities via the Urban Heat Island effect and how the presence of parks can benefit urban centres by cooling the surrounding air and absorbing CO_2.

Global particulate matter concentrations in 2022 recorded by the Copernicus Atmosphere Monitoring Service

Johannes Flemming, Vincent-Henri Peuch

Inhaling PM smaller than 2.5 micrometres ($PM_{2.5}$) over long periods is a severe health hazard (WHO, 2021). Human and natural sources contribute to $PM_{2.5}$ pollution in varying proportions at the global scale, and include emissions from fossil fuel combustion, wildfires and wind-blown desert dust. Figure 2(b), produced from the $PM_{2.5}$ data from the Copernicus Atmosphere Monitoring Service (CAMS) reanalysis, shows the average $PM_{2.5}$ surface concentrations for 2003–2022 and the anomalies (absolute differences) in 2022 compared with the mean values for 2003–2022 (Figure 2(a)).

The 2022 $PM_{2.5}$ anomalies were much less impacted by large fire events compared to 2021 (*WMO Air Quality and Climate Bulletin, No. 2*). Rather, the trends of anthropogenic emissions and annual variability of the desert dust emissions played a larger role in controlling surface $PM_{2.5}$. Fire-driven positive $PM_{2.5}$ anomalies occurred in parts of the Amazon basin and Alaska because of an active fire season in July and August 2022, and over South Africa because of fire activity in July to September. Dust storm activity was, in general, lower than usual over most of the Sahara Desert except over its north-west fringe, while the Taklimakan Desert and most of the Arabian Peninsula experienced a higher than usual amount of dust which contributed to the increased $PM_{2.5}$ levels. As was the case in 2021, the positive $PM_{2.5}$ anomaly over India and the negative anomalies over China, Europe and the eastern United States in 2022 were mainly manifestations of increased or decreased anthropogenic emissions in the respective regions (Figure 2(a)). Overall, the 2022 $PM_{2.5}$ anomalies were consistent with the long-term trends, with decreases across East Asia and Europe, and increases across South Asia (Figure 3).

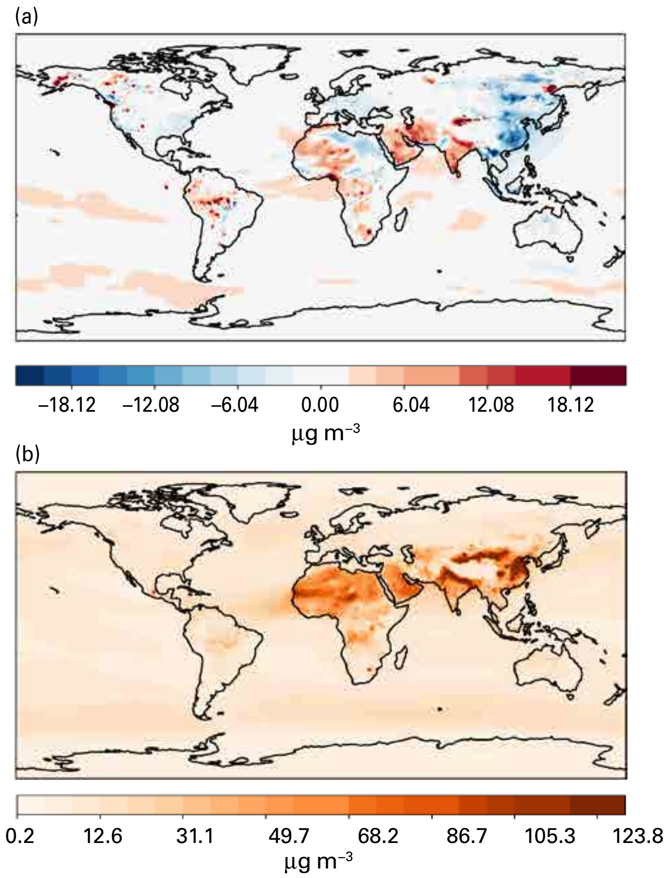

Figure 2. (a) Anomaly (absolute difference) of the mean $PM_{2.5}$ surface concentrations ($\mu g\ m^{-3}$) in 2022 compared to (b) the average for the period 2003–2022, as produced by the CAMS reanalysis. Low concentrations across the oceans are largely due to naturally occurring sea salt particles. The CAMS reanalysis system assimilated satellite-detected aerosol optical depth (AOD) retrievals from the Moderate Resolution Imaging Spectroradiometer (MODIS) and Advanced Along-Track Scanning Radiometer (AATSR) instruments. The Global Fire Assimilation System (GFAS) wildfire emissions data set was also used.

Source: European Centre for Medium-Range Weather Forecasts (ECMWF)/CAMS

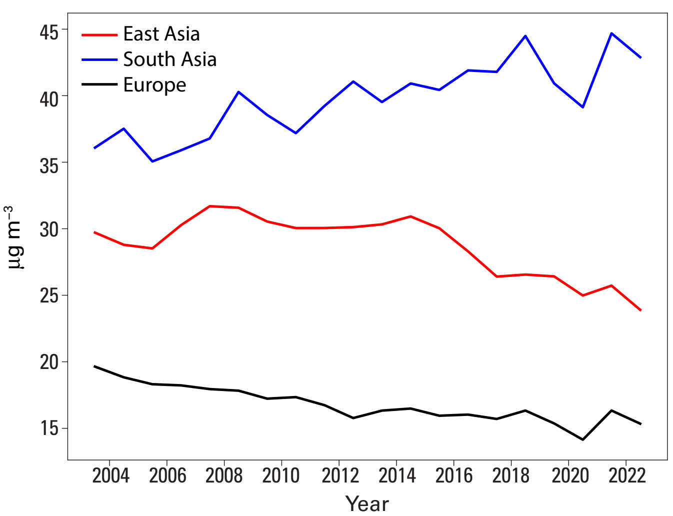

Figure 3. 2003–2022 time series of annual mean $PM_{2.5}$ surface concentrations ($\mu g\ m^{-3}$) for different regions: East Asia (red), South Asia (blue) and Europe (black)

Source: ECMWF/CAMS

Mechanisms linking heatwaves and particulate matter: Wildfires and desert dust intrusions

Peter Colarco, Lucia Mona

While large fires and dust storm activity were generally less frequent in 2022, as mentioned in the previous section, notable events of this kind still occurred. Their linkages to heatwaves, high levels of aerosols and poor air quality are explored in the following paragraphs in relation to two examples from 2022: wildfires in the north-western United States and desert dust intrusions in Europe.

The extreme anomaly in air temperature lasting many days during a heatwave can foster a favourable environment for fires to propagate. The resulting dry environment and the high temperatures of the heatwave enhance the probability of fires igniting and, once started, growing rapidly as they encounter dry, easily combustible vegetation. Such situations can result in an overall higher quantity of aerosol emissions than occurs in the absence of heatwaves. An example of this is shown in Figure 4, where results from the National Aeronautics and Space Administration (NASA) Modern-Era Retrospective Analysis for Research and Applications, version 2 (MERRA-2) reanalysis show that a lengthy heatwave in September 2022 (Figure 4(a)) correlated with anomalously high levels of biomass burning across the north-western United States (Figure 4(b)), leading to unhealthy air quality across much of the region, as reported by the United States Environmental Protection Agency (EPA) (Figure 4(c)).

Turning to the example from Europe, two types of heatwaves typically occur over Europe: the heat dome and the southerly flow. In the latter case, heatwaves often occur in the presence of intrusions of desert dust particles coming from North African deserts. Here, the cause/effect role is mostly the opposite of the forest fire case: when the circulation pattern fosters the intrusion of desert dust over Europe, the temperature increases because of hot air intruding from the desert regions. A positive feedback mechanism could be envisaged too: the dry and hot atmosphere contributes to the desertification processes over Europe, potentially increasing the presence of crustal aerosols over European countries.

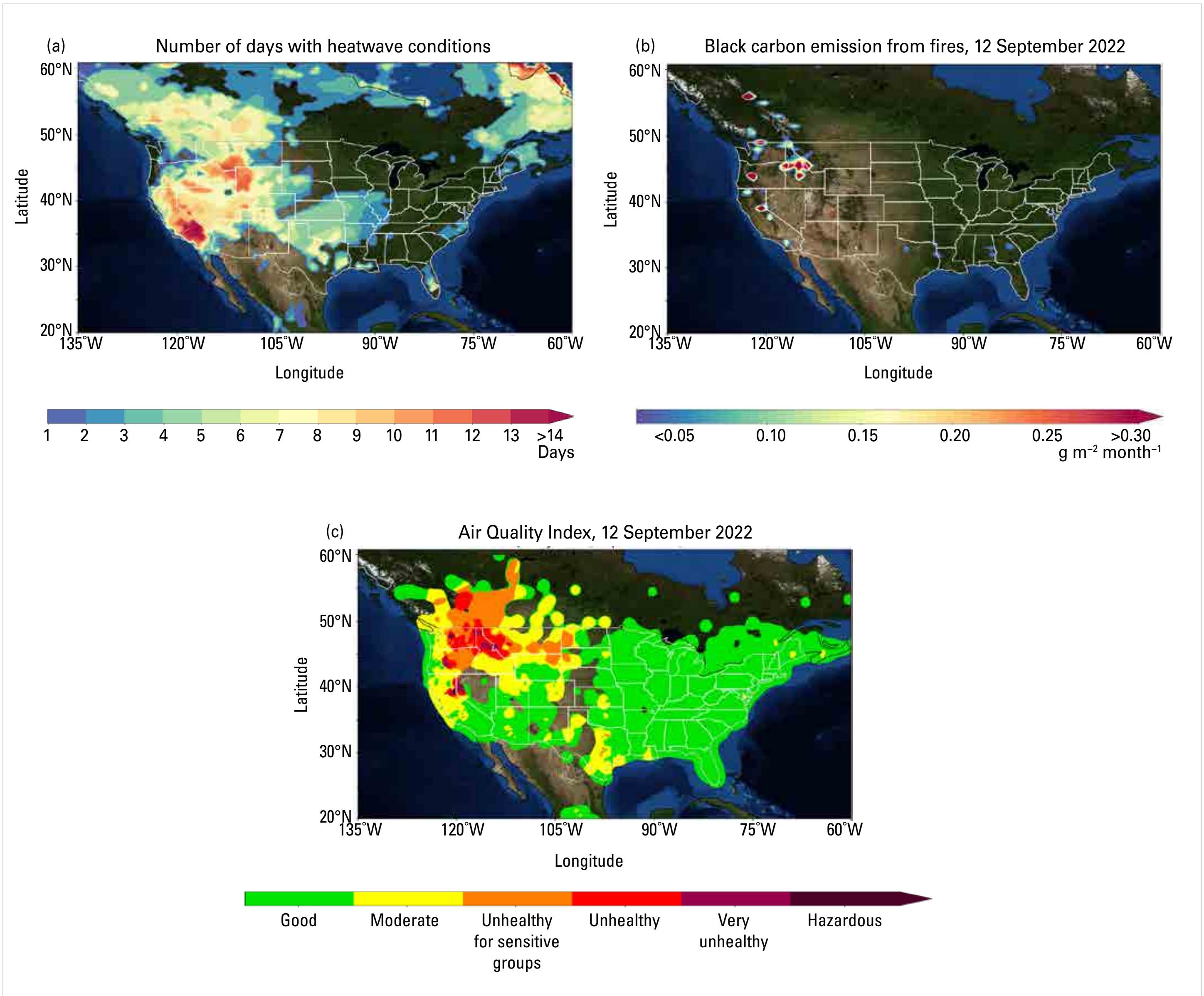

Figure 4. (a) The NASA MERRA-2 atmospheric reanalysis shows a high frequency of heatwave conditions across the western USA for September 2022. The heatwave occurrence across the north-western USA corresponds with high emissions from wildfires (b). These conditions resulted in unhealthy air quality conditions across much of the region, as shown in data from the United States EPA (c).
Source: NASA Goddard Space Flight Center (GSFC), Global Modeling and Assimilation Office (GMAO); United States EPA

Figure 5 shows a heatwave affecting Europe during the second half of August 2022, perfectly showcasing the link with desert dust intrusions. The long-lasting anomaly in temperature reported by Copernicus Climate Change Service (Figure 5(a)) is associated with a corresponding anomaly in the amount of dust (quantified by a metric known as Dust Optical Depth), compared to the dust climatological mean provided by the Barcelona Supercomputing Center (Figure 5(b)) (Di Tomaso et al., 2022). (It is worth noting that this dust anomaly was forecasted using the Sand and Dust Storm Warning Advisory and Assessment System multi-model ensemble.) Even though desert dust intrusions over the Mediterranean and Europe are common in August, this event was anomalously higher in terms of overall dust amount. Aerosol observations were collected for the period and for the region through several platforms such as the ground-based Aerosol Robotic Network (AERONET), and the space-based MODIS and Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO). Figure 5(c) shows the anomalous aerosol loading observed in aerosol profiles retrieved at the ACTRIS-EARLINET station in Potenza, Italy, where anomalous high aerosol content was observed in the 3–6 km above sea level altitude range.

The coincidence of high temperature and high aerosol amounts, and therefore PM content, could affect human health and well-being. It is known that high temperature is a risk factor for elderly populations as it can cause, for example, heatstroke and can also worsen chronic conditions such as cardiovascular disease and respiratory disease (NIEHS, 2022). Therefore, the coincidence of high temperature and high levels of PM (such as from forest fires or desert dust) poses dangerous health risks for a large part of the population.

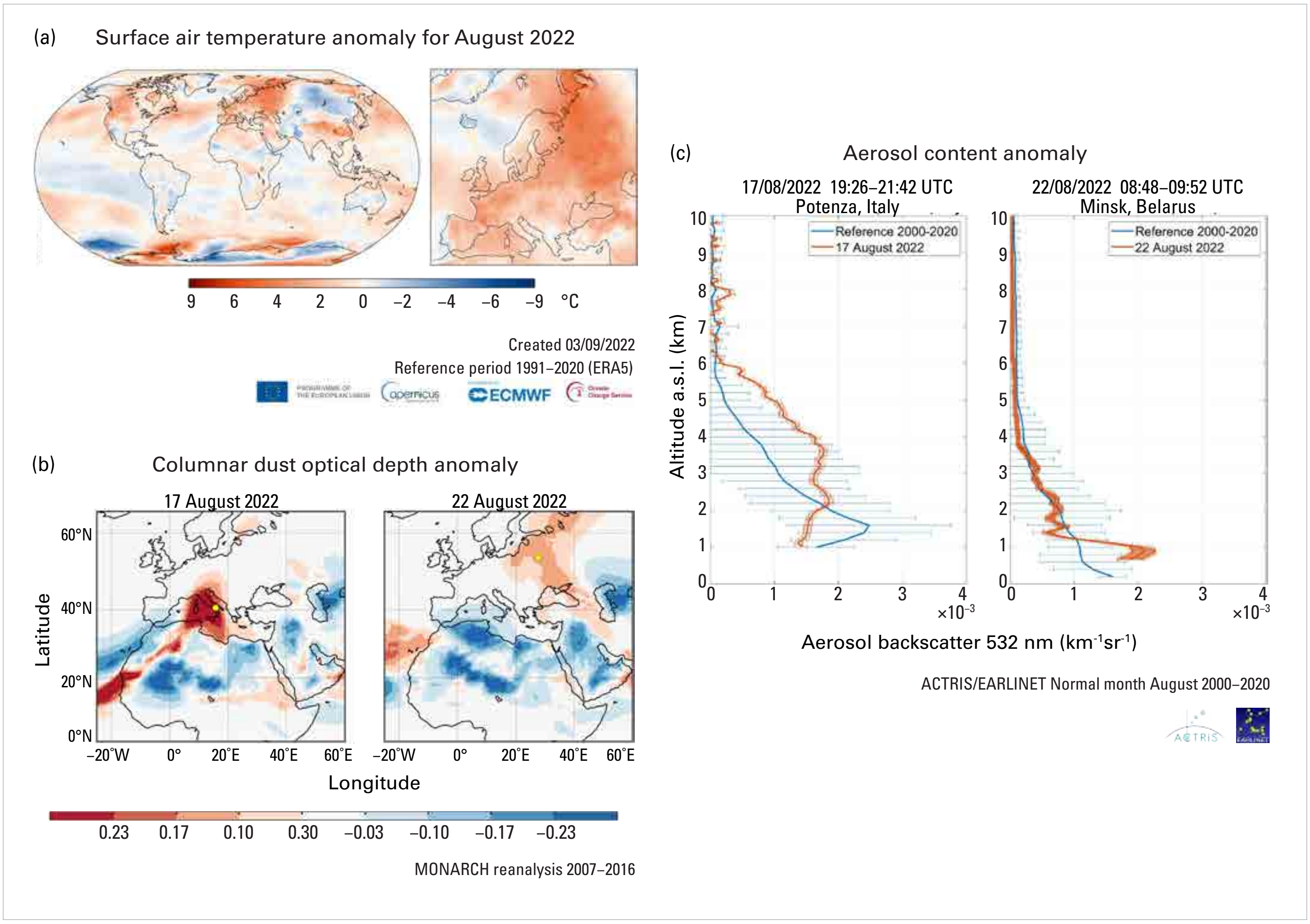

Figure 5. (a) Climatological analysis shows anomalies in surface air temperature for August 2022 over all of Europe, associated with an anomalous intrusion of desert dust in the second half of the month (b) from northern Africa, crossing the Mediterranean Sea and reaching eastern Europe. This desert dust intrusion produced observed aerosol content well above climatological averages over the central Mediterranean Sea and eastern Europe (c). The aerosol backscatter profiles in (c) correspond to the yellow points in (b). Aerosol backscatter indicates the extent to which aerosol particles present in the atmosphere scatter solar radiation, and depends on aerosol characteristics (such as composition and dimension) and abundance.

Sources:

(a) Copernicus Climate Change Service/ECMWF

(b) Barcelona Supercomputing Center

(c) Consiglio Nazionale delle Ricerche, Istituto di Metodologie per l'Analisi Ambientale (CNR, IMAA)/Aerosol, Clouds and Trace Gases Research Infrastructure-European Aerosol Research Lidar Network (ACTRIS-EARLINET)

The effect of heatwaves on ground-level ozone across Europe

James Lee, Beth Nelson, Will Drysdale, Sam Wilson

Although ozone is beneficial at very high altitudes, where it protects the planet from harmful ultraviolet radiation, it is damaging at ground level where exposure to high concentrations of ozone is hazardous to vegetation and human health. There is a strong link between the occurrence of heatwave events and high levels of ground-level ozone. During the July 2022 heatwave observed across Europe, hundreds of air quality monitoring sites exceeded the World Health Organization's ozone air quality guideline level of 100 μg m^{-3} for an 8-hour exposure (WHO, 2021). These exceedances first occurred in the south-west of Europe, later spreading to central Europe and finally reaching the north-east (Figure 6), following the spread of the heatwave across the continent.

Ground-level ozone is created through complex chemical reactions involving nitrogen oxides (NO and NO_2, collectively known as NO_x) and reactive volatile organic

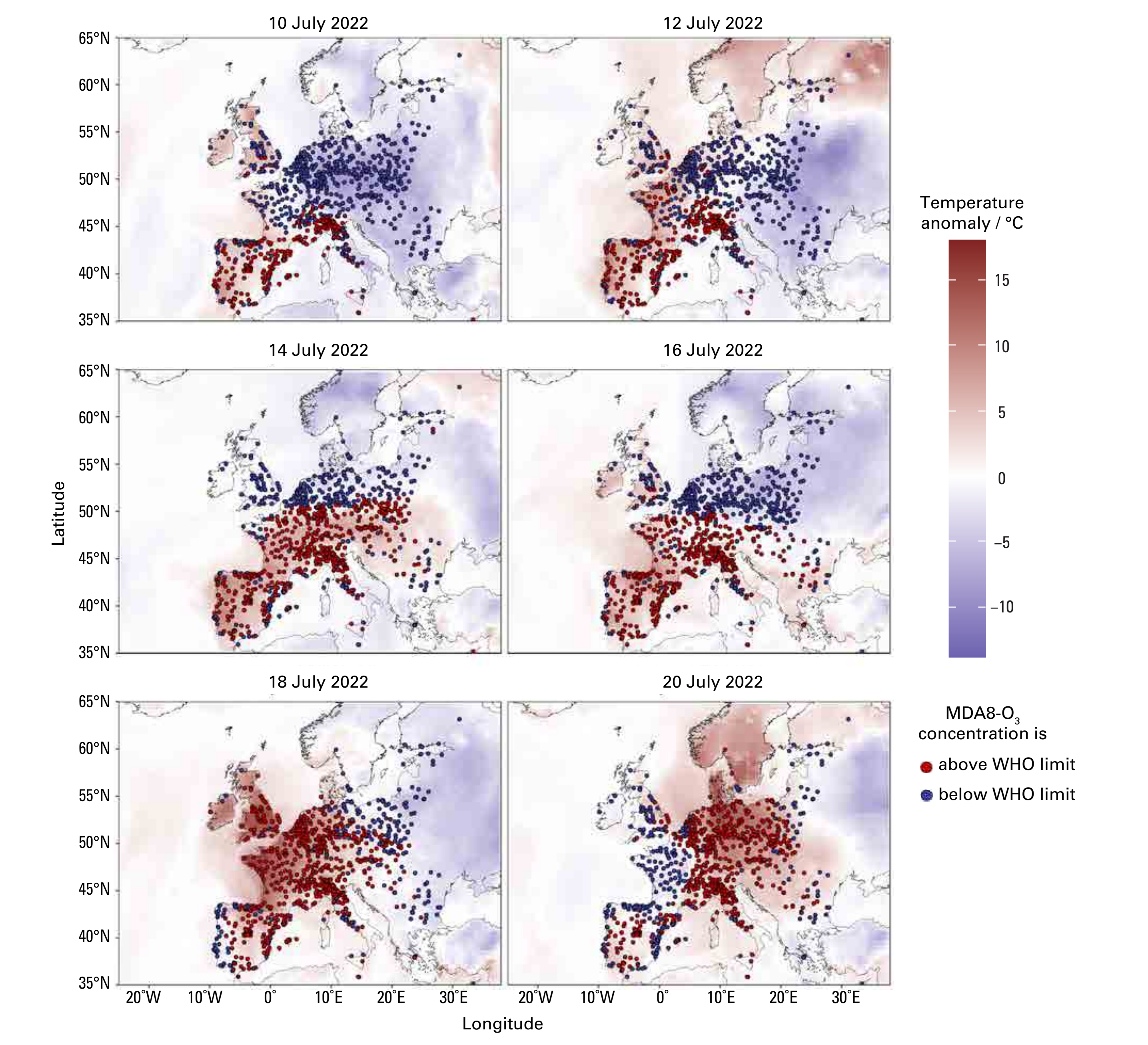

Figure 6. Ozone (O_3) exceedances and temperature anomalies across urban sites in Europe between 10 and 21 July 2022. The WHO O_3 guidelines are exceeded when the maximum daily 8-hour ozone concentration (MDA8-O3) is greater than 100 μg m^{-3}. Temperature anomaly has been calculated as the difference in daily maximum temperature from the median of the daily maximum temperature during the 2022 northern hemisphere summer (June–August) at a given location.

Source: Surface ozone observational data are available from the UK Department for Environment Food and Rural Affairs (DEFRA) (https://uk-air.defra.gov.uk/) and the European Environment Agency (EEA) (https://www.eea.europa.eu/themes/air/explore-air-pollution-data). Modelled temperature surface data was downloaded from the Copernicus Climate Change Service (2023) (https://doi.org/10.24381/cds.adbb2d47) compounds (VOCs), the latter being emitted by plants or by burning fossil fuels or being associated with industrial activity (Figure 7). Ozone is invisible but it typically forms in a polluted environment containing visible PM. The brownish haze observed in such environments is known as photochemical smog due to the role of sunlight in initiating the chemical reactions that create it. As ozone formation is heavily dependent on sunlight and high concentrations of its precursor chemical species, the hot and stagnant conditions created during heatwave events exacerbate ozone production by facilitating the build-up of highly reactive chemical species over several days. Hotter ambient temperatures also lend themselves to increased rates of atmospheric chemical reactivity that lead to increased ozone formation (Gouldsbrough et al., 2022). In addition, high temperatures lead to increased emissions of VOCs from plants, which are highly reactive and participate heavily in ozone formation (Pusede et al., 2015). These biogenic VOCs are often the key drivers of ozone formation during heatwave events.

Over the past few decades, pollution reduction strategies targeting vehicle and power plant emissions have successfully led to reductions in NO_x across the northern hemisphere. However, the processes leading to ozone formation are non-linear, meaning that simply reducing NO_x without sufficiently reducing VOCs does not necessarily lead to a reduction in ozone. In fact, in many cases the reverse is true, and reductions in NO_x without sufficient VOC reductions can lead to increased ozone formation, a phenomenon observed in many urban centres globally during the COVID-19 lockdowns (Sokhi et al., 2021). When heatwave events are also added to the mix, even very large reductions in NO_x may not offset the impact of heatwaves on the rates of ozone formation. In regions where levels of anthropogenic VOCs dominate, only large reductions in the emissions of anthropogenic VOCs alongside reductions in NO_x emissions may be enough to offset the impact of increased biogenic VOC emissions and the pollutant build-up created by hot and stagnant heatwave events. Over time, the frequency of extreme weather events, including heatwaves, is likely to increase due to climate change. This may lead to increased ozone health limit exceedances if pollution abatement strategies are not implemented and managed effectively (*WMO Air Quality and Climate Bulletin, No. 2*).

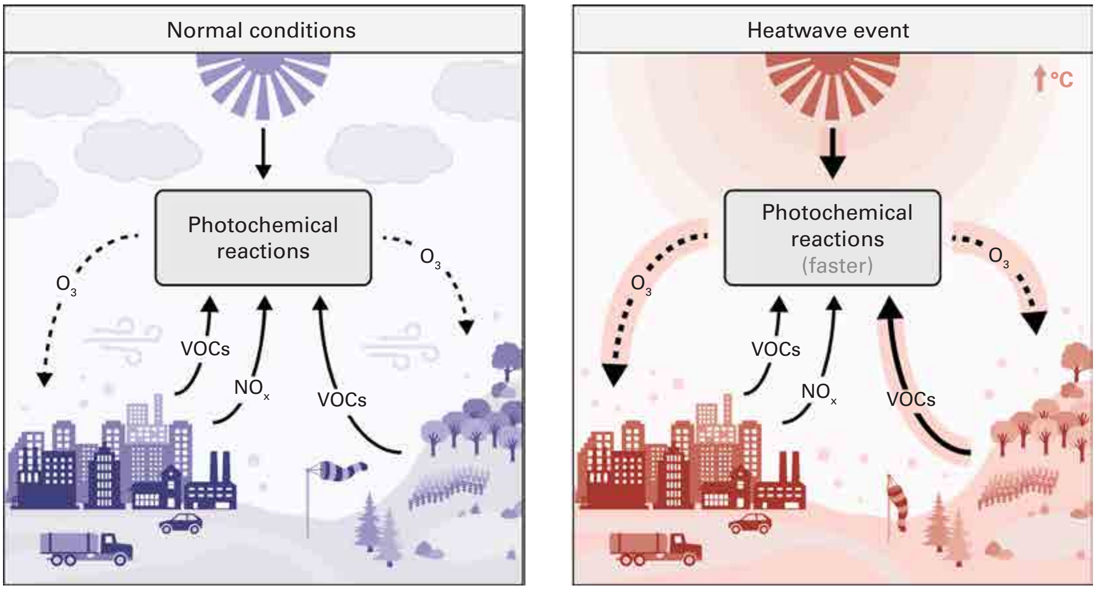

Figure 7. Ground-level ozone (O_3) is formed from the photochemical reactions (chemical reactions in sunlight) of NO_x and VOCs. Hot, stagnant conditions (right) lead to pollutant build-up, faster photochemistry and increased ozone production.

Source: University of York and National Centre for Atmospheric Science (Department of Chemistry), United Kingdom of Great Britain and Northern Ireland

Fire emissions are an important source of atmospheric nitrogen deposition to downwind ecosystems

John Walker, Jeremy Schroeder, Patrick Campbell, Rick Saylor

Fire, also referred to as biomass burning, emits large quantities of nitrogen (N) compounds (along with carbon, mercury, and many other chemical species) to the atmosphere (Andreae, 2019; Bray et al., 2021). These N-containing particles and gases, which include nitrogen oxides (NO_x), ammonia (NH_3) and organic N compounds, travel downwind where a portion returns to the Earth's surface in the form of wet and dry deposition. While N deposition can have a beneficial fertilizing effect, many areas around the world receive N deposition at rates that negatively impact ecosystem health and, subsequently, the quality of services that ecosystems provide to humans (such as biodiversity, clean drinking water, food and forest products, and carbon storage). Fires and associated deposition can also alter the N cycle in soils (Goodridge et al., 2018) which can increase soil emissions of nitrogen oxide (NO), a precursor to air pollutants including ozone and PM, as well as nitrous oxide (N_2O), a potent greenhouse gas. Fires, which are largely human-caused (WWF and BCG, 2020), occur in all major biomes around the globe (van Wees et al., 2022) (Figure 8).

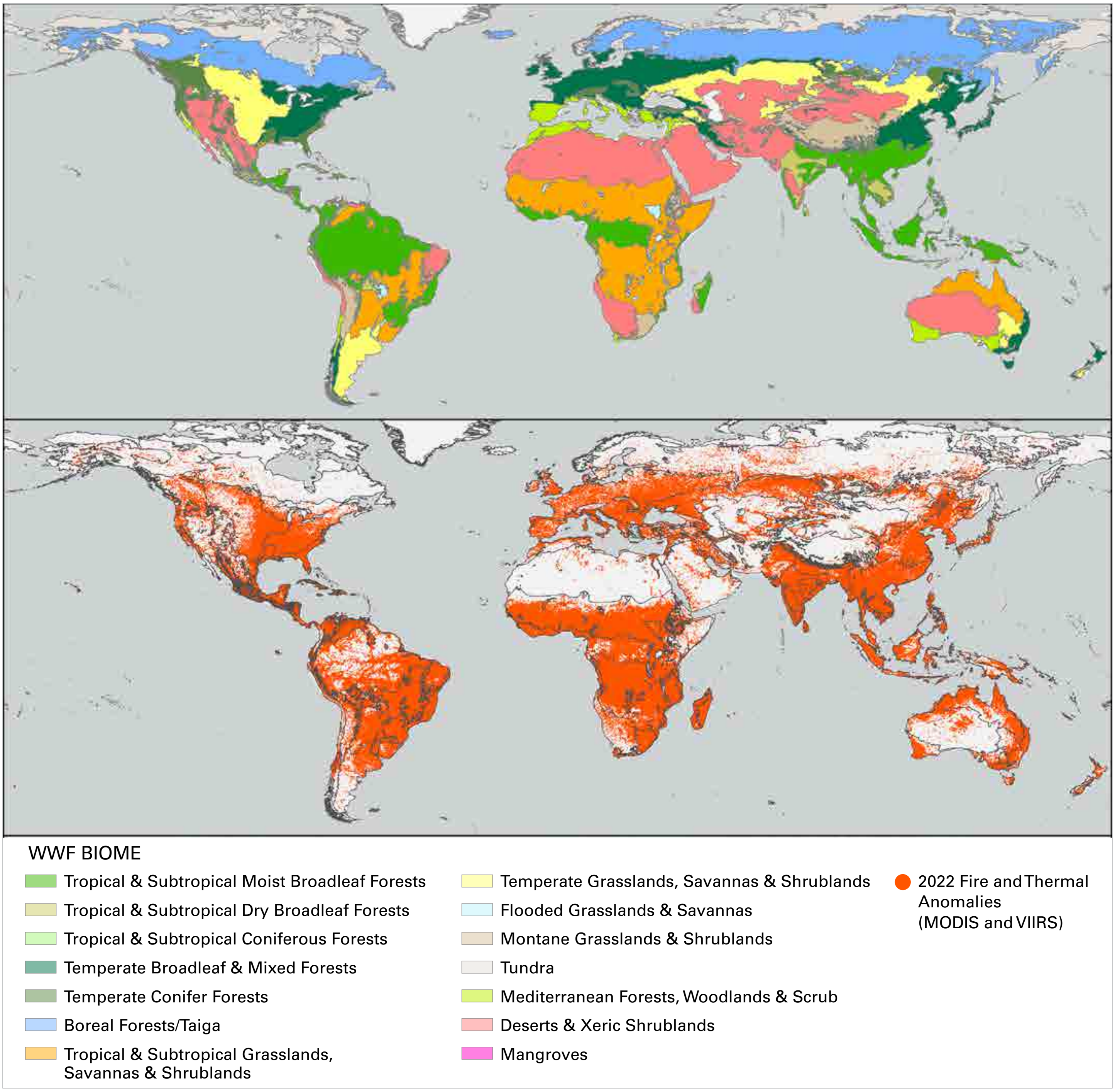

Figure 8. Global map of major biomes (upper panel) (*Source*: Olson et al, 2001), along with 2022 fire occurrence as detected from space by the MODIS and the Visible Infrared Imaging Radiometer Suite (VIIRS) instruments (lower panel) (*Source*: United States EPA/Office of Research and Development)

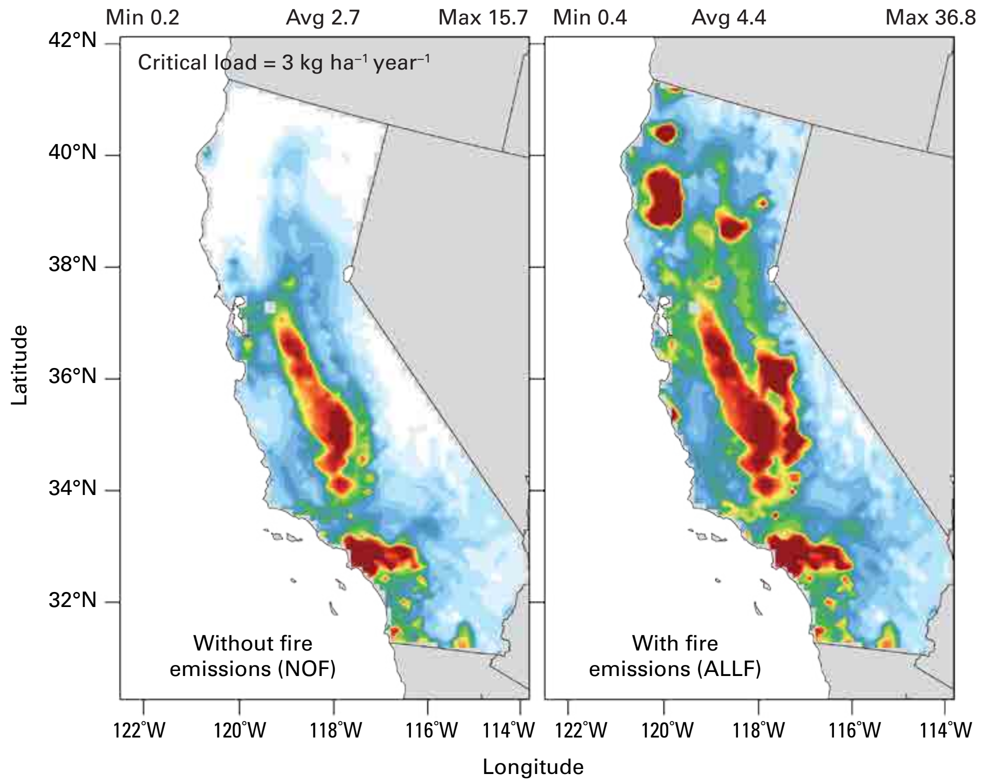

Figure 9. The 2020 annual average ratio of total N deposition (kg ha^{-1} year^{-1}) to a low-end critical load (CL) ~3 kg ha^{-1} year^{-1} for a model simulation case without fires (NOF; left) and with fires (ALLF; right). Ratios > 1 in the colour scale indicate exceedance of the CL, which can result in adverse effects on lichen communities found in Californian mixed conifer forests and some scrub species. The simulations included 24 land use types, including deciduous broadleaf forest, deciduous needle leaf forest, evergreen broadleaf, evergreen needleleaf, other mixed forest, grasslands, shrublands, savanna and croplands.

Source: National Oceanic and Atmospheric Administration (NOAA)/Air Resources Laboratory and George Mason University under the Cooperative Institute for Satellite Earth System Studies (CISESS)

Recent studies (Koplitz et al., 2021; Campbell et al., 2022) highlight the importance of fire as a large, yet poorly understood, source of N deposition to downwind ecosystems. For example, Figure 9 (adapted from Campbell et al., 2022) shows that the George Mason University-Wildfire Forecasting System (GMU-WFS) model predicted a significant increase in total N deposition compared to a critical load threshold in California, due to the historic 2020 wildfire season in the United States. Critical loads are the levels of deposition above which harmful ecosystem effects can occur. In the Campbell et al. (2022) study, biomass burning dramatically increased total N deposition to major natural vegetation types across California, with an average August–October 2020 relative N deposition increase of ~78% (from 7.1 to 12.6 kg N ha^{-1} year^{-1}). The increase in deposition to mixed forests was even larger (~173%, from 6.2 to 16.9 kg N ha^{-1} year^{-1}). Biomass burning-related N deposition was ~6–12 times larger than low-end critical load thresholds for major natural vegetation types (for example, forests at 1.5–3 kg N ha^{-1} year^{-1}) (Figure 9). The high rates of N deposition in the San Joaquin Valley and Los Angeles area seen in the "no fire (NOF)" simulation are associated with ubiquitous enhancements in agricultural and mobile sector emissions, respectively. These regions are typical of high N deposition under both active and quiescent fire conditions; however, critical load thresholds for different ecosystem types may be different in these regions.

In another study of N deposition from biomass burning across the United States, Koplitz et al. (2021) showed that fires may have contributed as much as 30% of total N deposition during 2008–2012 across areas of the north-west. Deposition occurred at ecologically significant amounts (> 0.5 kg ha^{-1} yr^{-1}) across > 4 million hectares. Ecological modelling of tree growth predicted a range of responses, from a positive fertilization effect to negative species-specific responses in survival and growth.

Several predicted climate trends may influence the occurrence of wildfires over the coming decades, including global increases in temperature and regional increases in the frequency and intensity of heatwaves and droughts (IPCC, 2014). A consensus is emerging that these trends are very likely to increase the frequency and severity of wildfires in many areas across the globe (IPCC, 2022; Smith et al., 2020; Baker, 2022), with potentially serious ramifications for enhanced downwind N deposition and associated impacts. An integrated effort of observation and modelling is needed to better understand the role of fire in N deposition and the resulting ecosystem exposure and impacts.

Interactions of agriculture and air quality

Frank Dentener, Gina Mills, Katrina Sharps, Arlindo da Silva, Ward Smith, Matthew Hort

Intensification of agriculture affects the environment in various ways: it enhances inputs of nutrients and chemicals into soils, watersheds and oceans, and increases emissions of greenhouse gases and air pollutants. On the other hand, air pollution can affect crops and food production. Two WMO reports focusing on ozone and PM elucidate the numerous interactions between crops, meteorological processes and air pollution, and the need for comprehensive observational and modelling infrastructures (WMO, in press-*a*, in press-*b*).

Ozone concentrations are high in many of the world's most important agricultural regions. Ozone can reduce both the quantity and quality of yield of staple food crops (Figure 10). The mechanisms of ozone damage are relatively well understood, and robust impact indicators have been developed for several crops (Mills et al., 2017). Globally, ozone-induced crop losses average 4.4%–12.4% for staple food crops, with wheat and soybean losses as high as 15%–30% in key agricultural areas of India and China (Figure 10). While in recent decades

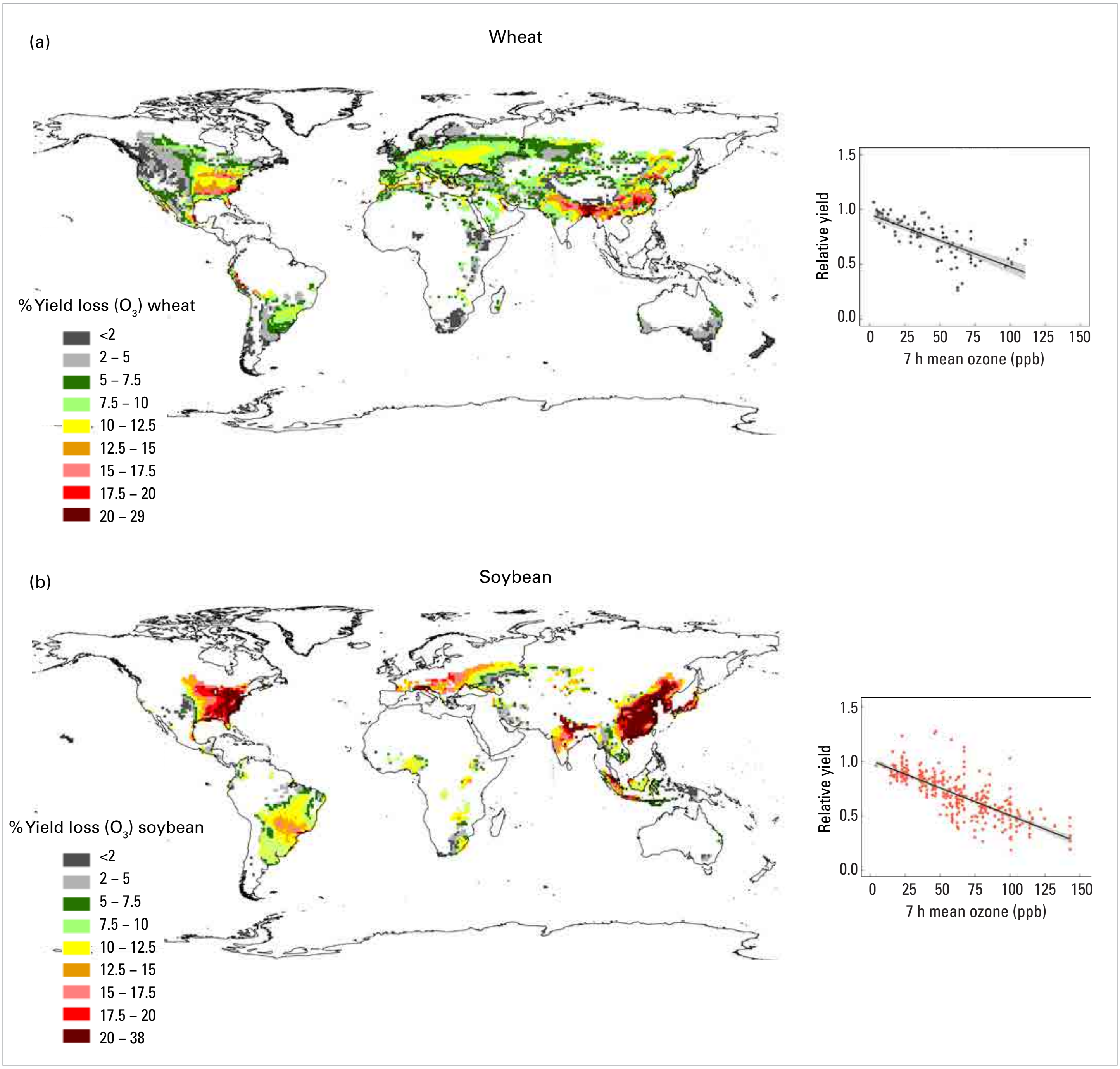

Figure 10. Yield losses [%] of wheat (upper map) and soybean (lower map) due to ozone for 2010–2012. The scatterplots show decrease in wheat (upper) and soybean (lower) yield as a function of 7-hour mean ozone concentration (in parts per billion (ppb), 90-day mean representing the main growing season for each crop). Data was combined from experiments conducted in Asia, North America and Europe with 18 wheat varieties and 52 soybean varieties

Source: Mills et al., 2018

emission controls have reduced ozone pollution in North America and Europe, in emerging economies ozone concentrations are rising (Szopa et al., 2021), and may keep rising unless emissions are strongly abated. In the coming decades, the expected increase of methane will contribute to enhanced ozone formation. Improvements in livestock feeding, manure management, and cropping practices could substantially reduce global methane emissions and therefore contribute to improvements in crop yield.

Agricultural activities are an important contributor to the emission and formation of PM. Storage and spreading of farmyard manure and application of mineral fertilizer can lead to the formation of particulate ammonium nitrate. Land clearing and the burning of crop residues lead to extremely high PM pollution downwind. In regions where aerosol concentrations are high, PM can affect stomatal functioning and plant metabolic processes. PM also changes the solar radiation used by plants, altering ground-level temperatures and changing rainfall patterns and amounts. Available studies estimate both positive and negative impacts of PM on crop yields, but reliable estimates of integrated impacts on crop production do not yet exist. From a health perspective, there is a pressing need to reduce PM air pollution, which is causing 4.14 million deaths annually (Fuller et al., 2022) however the resulting benefits or trade-offs for crops are not yet known.

The numerous interactions of air quality and agriculture deserve more attention from both science and policy. With the prospect of increasing heatwaves from climate change, and growing demand for food and feed, understanding those interactions will become even more critical. An integrated multi-disciplinary approach involving monitoring in agricultural areas, crop exposure experiments, modelling and analysis is needed in order to assess the impacts of pollution on agricultural production, and to enable scientifically-based policies for improving air quality and reducing losses in agricultural production.

Meteorology and atmospheric flux of urban forested canopies: Implications for air quality and climate

Polari Batista Corrêa, Giuliano Maselli Locosselli, Noele Franchi Leonardo, Mario Gavidia-Calderon, Edmilson Dias de Freitas, Maria de Fatima Andrade, K. Heinke Schlünzen, Ranjeet S. Sokhi

Urban areas often consist of buildings and infrastructure reaching heights of 100 m or more, which influence wind and temperature patterns. To understand how heat dissipates and atmospheric gases mix in a city, the "canopy layer", which is ~1.5 m above ground, is often studied and compared against nearby rural areas. Typically, canopy layer air temperatures are enhanced in urban areas compared to surrounding rural areas at night-time. This effect is usually referred to as the urban heat island (UHI). The magnitude of differences varies with many factors, but may reach up to 9 °C. This effect combines with climate change and has many impacts including: additional heat stress at night, influences on the atmospheric boundary layer height and, in turn, the atmospheric chemistry, and changes in plant growth and the pollen season , which can have ecological and health effects, respectively.

A new WMO report (*Guidance on Measuring, Modelling and Monitoring the Canopy Layer Urban Heat Island (CL-UHI)* (WMO-No. 1292)) provides the scientific fundamentals to understand the evolution of the CL-UHI and makes wide-ranging recommendations on characterizing it through measurements and modelling. The CL-UHI effect is important to monitor because large portions of the population live and/or work in cities, and exposure to high temperatures can increase morbidity and mortality, especially during heatwaves and at night. Examples of recommendations provided in the report focus not only on measuring temperature and winds strategically, but also focus on fluxes, or movement, of heat and gases upward and downward within the city. To demonstrate how such temperature and flux measurements can lead to valuable insights, a study performed in São Paulo, Brazil, is summarized in the following paragraphs.

The Metropolitan Region of São Paulo (RMSP) comprises 39 municipalities with a population exceeding 22 million inhabitants. Situated in an area characterized by intricate topography and influenced by the sea breeze, this region presents a unique case for investigating urban temperatures and thus the UHI effect. Considering the rapid growth of urban areas in the tropics, it is crucial to recognize the potential implications of UHI effects in these regions.

As the study of the urban canopy layer has evolved, more attention has been given to the role of vegetation as a nature-based solution to address heat islands and CO_2 emissions, and to aid in the mitigation of the impact of cities as sources of greenhouse gases. Vegetation plays a crucial role in reducing UHI effects through various mechanisms. For example, vegetation can lower surface temperatures by providing shade, intercepting solar radiation and facilitating evaporative cooling, thereby locally reducing the UHI intensity. Recognizing the significance of monitoring CO_2 flux and concentrations in urban areas worldwide, measurements are being collected in two vegetated areas in São Paulo: an urban park, "Parque do Ibirapuera" (hereinafter "Ibira" Park, covering an area of 1.58 km^2) and "Parque do Ipiranga" (hereinafter "PEFI", covering an area of 4.76 km^2). PEFI is a fragment of the Atlantic Forest located within the urban area of the RMSP, with several preserved springs and streams, and high biodiversity, including endangered species. In contrast, Ibira Park includes a range of green cover and amenities such as a cycling path, 13 illuminated sports courts, running tracks, promenades, resting areas and open spaces for concerts. Additionally, the park is home to public buildings and museums.

Figure 11 illustrates the spatial distribution of surface temperature in the city of São Paulo during the early afternoon. The surface temperature depicted in the figure is derived from data acquired by the Landsat 8 satellite. The figure clearly shows higher temperatures in the urban areas compared to surrounding areas. However, within the urban areas, sharp differences in temperature can be observed.

For both air quality and climate impact studies, flux measurements are crucial for understanding the physio-chemical processes of chemical species such as carbon emissions and sinks and for evaluating emissions inventories. Diverse green areas contribute to the surrounding climate balance and air quality. Figure 12(a) illustrates, with hourly observations for January 2023, that the positive flow of CO_2 is directly influenced by anthropogenic processes occurring in the location at a given time of day (such as the traffic that releases CO_2), while the negative flow of CO_2 is related to absorption by the vegetation. The differences between the parks are directly related to their size, distinct land use, the height at which the measurements were taken and extent of the canopy cover.

Air temperature measured from November 2022 to the end of April 2023 in both parks (PEFI and Ibira) is compared to data from an air quality station of the *Companhia Ambiental do Estado de São Paulo* (CETESB) network in an urbanized area in the city, as shown in Figure 12(b). The temperature is higher in PEFI, as the denser vegetation causes a difference in thermal capacity compared to Ibira. The largest difference between the two can be seen in the early morning (between 0500 and 0700, local time) and in the early afternoon (between 1300 and 1600, local time). In Ibira, the measurements are performed at higher altitudes than in PEFI. However, both Ibira and PEFI are considered cool islands within the city of São Paulo compared to their surroundings. These green islands are essential for the well-being of the population, as they not only cool the air but also provide various ecosystem services, including atmospheric carbon uptake.

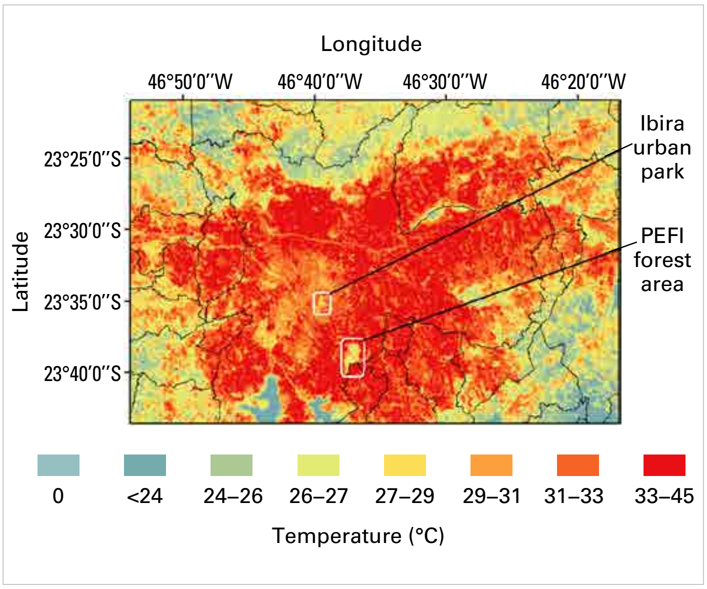

Figure 11. Land surface temperature (°C) for the RMSP, on 23 September 2015, at 1304 local time

Source: Institute of Astronomy, Geophysics and Atmospheric Sciences, University of São Paulo

Conclusions

This third edition of the *WMO Air Quality and Climate Bulletin* examines the numerous ways in which heatwaves can affect air quality, with some examples from 2022. While large fire events and desert dust storms were less prevalent overall, as compared to previous years, many local fires and storms of this nature still occurred, leading to large quantities of aerosols or PM impacting highly-populated regions. Heatwaves leading to fires in the western United States, and heatwaves accompanied by desert dust intrusions across Europe, led to dangerous levels of PM exposure. Both high temperatures and large concentrations of PM, as occurred in these two very different events from 2022, can pose substantial health risks, especially to vulnerable populations.

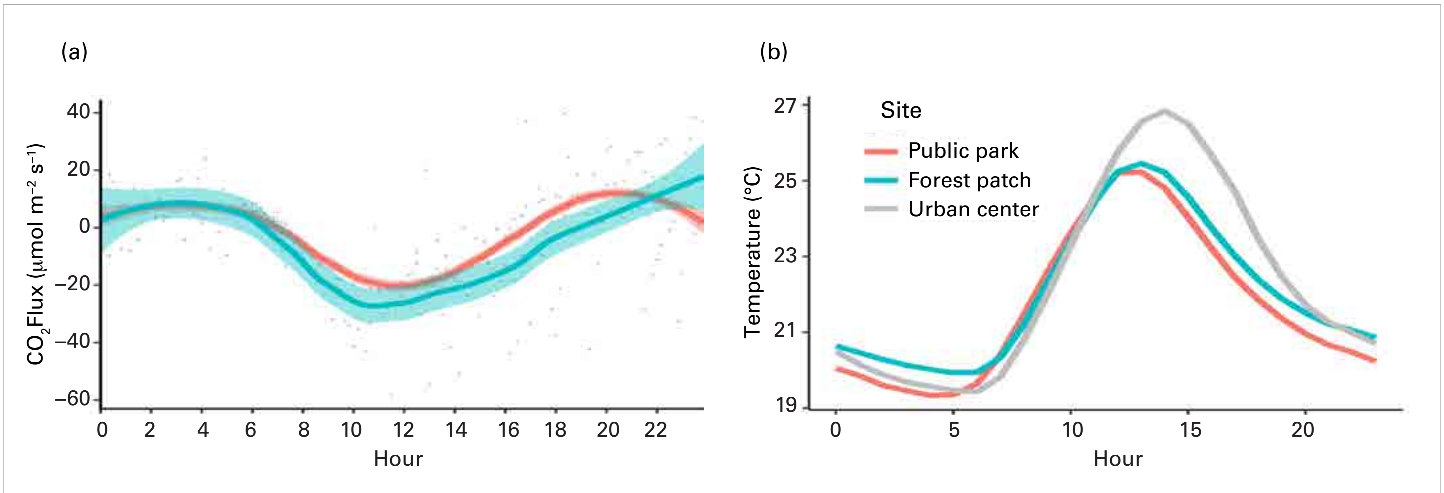

Figure 12. (a) Comparison of carbon flux and (b) temperature in Ibira Park (in pink) and PEFI (in green). In (a), flux values above zero indicate emission of CO2, whereas values below zero indicate absorption of CO_2. In (b), the temperature measured at downtown São Paulo is also displayed (in grey).

Source: Center for Nuclear Energy in Agriculture, University of São Paulo

Heatwaves also influence gas-phase chemical reactions, most often leading to increased concentrations of ozone, the other main air pollutant of concern alongside PM. This was exhibited in the heatwave that impacted almost all of Europe in July 2022. During that heatwave, temperature anomalies and ozone exceedances, which were above the safe threshold set by WHO, were observed, in near-perfect coordination, as the heatwave moved over the continent over 10 days. The underlying chemical reactions and emissions of compounds that determine ozone concentrations are well understood, so measures to control emissions and lessen the population's exposure to the air pollutant are particularly beneficial under heatwave conditions.

Atmospheric deposition of nitrogen-containing compounds downwind of fires and its impact on ecosystems, a phenomenon that will increase with warming climate and heatwaves, was also explored. N deposition from fires has been poorly understood previously; however, through two new model-based studies, it has been quantified for certain regions of the United States. In California and the north-west United States, fires were found to contribute large proportions of N deposition in several natural ecosystems, often exceeding critical load thresholds and negatively impacting biodiversity, clean drinking water, and even air quality via emissions that lead to further air pollution.

The present Bulletin summarized two WMO reports that explore in depth the linkages between agriculture and air quality. The two main air pollutants, ozone and PM, play complex roles: both affect agriculture and are in turn affected by agricultural practices. While ozone is known to be harmful to crops, the effect of PM on plants is mixed, as PM impacts solar radiation, temperatures, rainfall and growth processes, which can be both beneficial and detrimental. Crop losses due to ozone have been quantified globally, with examples of wheat and soybean provided in the present Bulletin. However, the net influence of PM on crops is unknown, emphasizing the importance of further observations and studies to understand how air quality policies will affect food production and vice versa.

Finally, the present Bulletin concluded with an overview of how urban environments impact air quality and climate. A new WMO report, *Guidance on Measuring, Modelling and Monitoring the Canopy Layer Urban Heat Island (CLUHI)* (WMO-No. 1292), examines current understanding in this domain and the need for better assessing the canopy layer urban heat island and the contrasts in temperature between urban and rural settings slightly above the surface (~1.5 m), where human health is most directly affected. Observations of the type suggested by the report were recently collected in São Paulo, Brazil: both temperature and CO_2 measurements from two parks indicated that the urban heat island effect is reduced and CO_2 emissions are partly mitigated by incorporating more green spaces within cities, pointing to the benefits of nature-based solutions for climate change.

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