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Climate Change–Driven Alterations in PM2.5 and PM10 Levels: Source Apportionment, Atmospheric Transformations, and Public Health Implications

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Abstract

Atmospheric particulate matter (PM2.5 and PM10) is one of the most significant threats to the environment and human health across the globe with climate change increasingly changing the sources, atmospheric transformations and the public health impacts of PM. This review summarizes the current knowledge on the complex interactions between climate change and particulate matter dynamics including effects of increasing temperatures, changing precipitation patterns, changing wind systems and extreme weather events on PM concentrations and composition. Climate change is causing shifts in both anthropogenic and natural emission sources. Wildfires, dust storms and biogenic emissions are increasing in many regions. Changes in atmospheric conditions (secondary organic aerosol formation, sulphate and nitrate chemistry, photochemical reactions) significantly impact atmospheric transformations of PM in a changing climatic environment. Receptor models, isotopic techniques and applications of artificial intelligence are important tools to characterize climate-modified PM profiles in source apportionment approaches. The public health implications are huge, including respiratory diseases, cardiovascular disorders, neurological effects, cancer risks and maternal-child health outcomes, with vulnerable populations facing disproportionate exposure risks. Emerging new monitoring technologies include satellite-based systems and AI-driven forecasting models providing new opportunities for exposure assessment and early warning systems. This review identifies critical research gaps and proposes integrated mitigation strategies that combine climate change and air quality management for safeguarding human health in a rapidly changing world.

Keywords: Wildfires, dust storms, biogenic emissions, maternal-child health

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Introduction

Air pollution is the world's largest environmental risk factor for human health, resulting in millions of premature deaths each year. Ambient particulate matter pollution has been regularly ranked as a major cause of mortality and disability-adjusted life years (DALYs) globally by the Global Burden of Disease Study. In India alone, air pollution caused an estimated 1.67 million deaths in 2019, accounting for 17.8% of total national deaths, with ambient particulate matter pollution accounting for 0.98 million deaths (Sang et al., 2022). The economic costs of these health outcomes are staggering, with total economic losses from air pollution in India estimated at $36.8 billion, or 1.36% of national GDP. The burdens are not evenly distributed, with low per-capita GDP states suffering disproportionately higher economic losses compared to their economic output (deSouza et al., 2023). The global nature of air pollution requires interdisciplinary approaches that combine monitoring networks, satellite retrievals, chemical speciation, and health impact analysis to quantify exposure and inform policy. Exposure-response functions estimating excess mortality, morbidity and DALYs have become key tools to translate air quality data into public health metrics that inform regulatory decisions. Comparative studies across cities, regions and countries have documented persistent inequities in pollution exposure and health outcomes, underscoring the need for targeted mitigation strategies that deliver co-benefits for air quality, human health and climate resilience (Gohlke et al., 2023). Particulate matter is classified according to its aerodynamic diameter, and the most commonly controlled fractions are PM2.5 (particles ≤2.5 μm) and PM10 (particles ≤10 μm). PM2.5 is generally thought to represent the greater health risk because it can penetrate deep into the lungs and enter the bloodstream, which can affect multiple organ systems (Pettit et al., 2018). However, PM10 also represents a serious threat to health, being able to penetrate into the deepest parts of the respiratory tract and to contribute to cardiovascular and respiratory diseases. The mass concentration of PM alone does not determine its health effects; the chemical composition of particles is key to determining toxicity (Manisalidis et al., 2020). Recent high-resolution epidemiological analyses have shown that individual PM2.5 species, such as nitrate, elemental carbon and ammonium, are more strongly associated with childhood anemia, respiratory infections and low birth weight than total PM2.5 mass, indicating that mass-based metrics may underestimate health impacts in the presence of variable species toxicity (Chaudhary et al., 2023). This finding has great implications for air quality standards in that component-specific control strategies

might be more effective than mass-based strategies. In addition, at urban scales, sectoral source apportionment has shown that residential energy use dominates ambient PM2.5 exposure and attributable mortality, but non-linear exposure-response relationships mean that large emission reductions are needed before health benefits accrue measurably (Silva et al., 2016). Climate change and air quality are inextricably linked through common emission sources, atmospheric chemical processes, and meteorological drivers. Climate change has increased the frequency and duration of extreme temperature events, with direct impacts on population health exacerbated by concurrent air pollution exposure. The 2023 United Nations Climate Change Conference (COP 28) emphasized that the increase in global temperature remains below 1.5°C as laid down in the Paris Accord, but 2023 was the hottest year on record. These increasing temperatures have direct consequences on air quality, especially on secondary pollutants such as tropospheric ozone, whose formation is driven by sunlight and high temperatures (P. Wang et al., 2026). The joint effects of climate change and air pollution pose a complex challenge for public health. Studies examining the combined effects of chemical air pollution and extreme temperatures have shown increased risks of hospital admissions for respiratory, cardiovascular and neurological causes during both heatwaves and cold spells. During warm months, stronger associations were seen between ozone and admissions due to respiratory, circulatory and neurological causes; NO_2 and admissions due to respiratory diseases; and PM and admissions due to dementia and Alzheimer's disease (Delgado-Saborit et al., 2021). Admissions for neurological diseases are more sensitive to heat. Only NO_2 has been associated with asthma-related admissions during cold months. These findings highlight the importance of public health prevention plans that take into account air quality as well as temperature thresholds (Ruiz-Páez et al., 2025).

The aim of this review is to provide a comprehensive synthesis of current scientific knowledge on climate change-induced changes in PM 2.5 and PM 10 concentrations including source apportionment, atmospheric transformation and public health effects. The review is based on the research from Q1-Q4 journals. It focuses on the evidence of the peer-reviewed studies published in the last years. This includes mechanisms through which climate change impacts PM dynamics, the shifting balance between anthropogenic and natural sources, the chemical transformations of PM under changing climate conditions, and the health effects of these changes. Emerging monitoring technologies, mitigation strategies and research needs for the future are also discussed.

Climate Change as a Driver of Particulate Matter Dynamics

❖ Rising Temperatures and Atmospheric Stability

There are several mechanisms linking increases in global temperatures to concentrations of particulate matter, including effects on atmospheric stability, chemical reaction rates, and emission patterns. While higher temperatures can lead to increased atmospheric instability, enhancing vertical mixing and pollutant dispersion, they can also result in stagnant conditions which trap pollutants near the surface. The phase state and reactivity of atmospheric aerosols are temperature dependent, with implications for multiphase chemistry and the transport of particle-bound pollutants (Kulmala et al., 2023).

The temperature dependence of atmospheric chemistry is not only limited to secondary aerosol formation. Higher temperatures usually increase the rates of photochemical reactions that promote the formation of secondary organic aerosols and sulphate, and influence the gas-to-particle partitioning of semi-volatile compounds (e.g. In Nanjing, China, measurements during the summer months showed that secondary pollutants make up almost 70% of the mass of submicron particles, and photochemical reactions driven by sunlight strongly favour the formation of sulphate and secondary organic aerosols (Shan et al., 2026).

❖ Altered Precipitation Patterns and Aerosol Removal

Precipitation is a major pathway for removal of atmospheric particulate matter by wet deposition and changes in precipitation patterns due to climate change have important consequences for PM concentrations. Changes in the frequency, intensity and spatial distribution of rainfall will affect the efficiency of aerosol scavenging, potentially prolonging pollution episodes in regions with reduced precipitation. On the other hand, increased intensity of rainfall events might increase removal, but could lead to runoff and resuspension of deposited particles. Climate models show large regional differences in precipitation changes, with some regions becoming drier and others wetter, resulting in divergent impacts on PM concentrations across regions (Fuzzi et al., 2015). Interactions with other climate variables add further complication to the relationship between precipitation and PM. Higher temperatures can result in increased water vapor content in the atmosphere, which may affect aerosol hygroscopic growth and wet removal efficiency. The importance of aerosol water content in heterogeneous chemical reactions on haze formation is becoming more and more recognized as a critical factor, with increased particle

matter levels speeding up multiphase production via positive feedback mechanisms (Su et al., 2020).

- **Changes in Wind Systems and Long-Range Transport**

Climate change is impacting global wind patterns with serious consequences for long-range transport of particulate matter. Changes in atmospheric circulation will alter the trajectories and transport distances of aerosol plumes, such as changes in jet streams, monsoon patterns, and trade winds. Regions that have historically received pollution from distant sources may experience changes in transport pathways, while source regions may experience changes in export patterns. Changes in wind systems are particularly sensitive to the long-range transport of desert dust, biomass burning aerosols and industrial pollution (Doherty et al., 2017). A prominent example of climate-sensitive long-range transport are dust storms. Every day 151 countries and more than 300 million people are directly impacted by sand and dust storms. The smaller dust particles can be lifted into the troposphere, where they can stay suspended for weeks or months and travel thousands of kilometers from their source regions. Climate change is increasing the frequency and intensity of these storms, and 25% of dust emissions come from human activities like deforestation and unsustainable land management. Dust storms in the Indo-Gangetic Plain during pre-monsoon months of March-June are due to dust from the Arabian Peninsula and the Thar Desert, affecting air quality across the entire region (Sarkar et al., 2019).

- **Extreme Weather Events and PM Episodes**

Climate change is increasing the frequency and intensity of extreme weather events such as heatwaves, droughts, wildfires and severe storms that have great impacts on PM concentrations. During heatwaves, conditions are favorable for the accumulation of air pollutants, with emissions trapped near the surface by stagnant air masses, while photochemical activity accelerates. Heatwaves and air pollution have been shown to have a synergistic effect on respiratory health, with studies showing markedly increased rates of respiratory and cardiopulmonary mortality during periods of high temperature and elevated PM and O_3 levels (Y. Wang et al., 2025). Wildfires are a major contributor to $PM_{2.5}$ and PM_{10}, and are often started or made worse by drought and heatwaves. Wildfires produce a wide spectrum of health-damaging air pollutants ranging from fine particulate matter, black carbon, and carbon monoxide to nitrogen oxides, ozone, and volatile organic compounds. Black carbon emitted from wildfires is particularly concerning because it is 460-

1,500 times more effective as a climate forcing agent than CO_2 on a unit mass basis. This creates a positive feedback loop where fires worsen climate change, which increases fire risk. Wildland-urban interface fires may produce particulate matter containing especially hazardous substances from the burning of man-made structures, such as asbestos (Ali et al., 2025).

Sources of PM2.5 and PM10 Under Climate Change

- **Anthropogenic Sources**

Human-related particulate matter sources include fossil fuel combustion, industrial emissions, transportation, residential energy use, and biomass burning. These categories have been identified as the major contributors to ambient PM concentrations in source apportionment studies in different regions. An analysis of 239 source apportionment studies of PM in China during 1987-2017 showed that the main source categories of fine PM are dust, fossil fuel combustion, transportation, biomass burning, industrial emission, secondary inorganic aerosol and secondary organic aerosol. Among these, secondary inorganic aerosol, industrial emissions and dust were the top three source categories in 2007-2016 period. Fossil fuel combustion and industrial emissions were the major contributors of sulphate (63.5-88.1%) and nitrate (47.3-70%), and ammonium (53.9-90%) was mainly from agricultural emissions (Zhu et al., 2025). Long-term trends of PM sources at megacities such as Beijing and Nanjing show decreasing contributions from fossil fuel and industrial sources after stricter emission controls in recent years. But this has been accompanied by increasing contributions from transport sources, underscoring the need for continued mitigation actions across a variety of sectors. Source apportionment studies in South Korea also indicated that motor vehicles and secondary aerosol were the most common and influential PM sources with secondary aerosol contributing considerably to both PM10 and PM2.5. The results point to the need for component-specific control strategies that target both primary emissions and the precursor gases that form secondary aerosols (Romanello et al., 2025).

- **Natural Sources**

Particulate matter occurs naturally from dust storms, wildfires, sea spray, volcanic emissions and biogenic aerosols. Anthropogenic sources dominate in most urban and industrialized areas but natural sources can make a significant contribution to PM concentrations, especially in areas with high natural emission rates or during

episodic events. Natural sources of PM10 contribute to around 15% of the total in the UK but global estimates suggest that as much as 75% of dust emissions are natural. Climate change is causing an increase in wildfires, dust storms and biogenic emissions in many regions, significantly changing the contributions of natural sources (Öncü et al., 2025).

- **Climate-Induced Shifts in Emission Profiles**

There are a number of ways in which climate change is shifting emission profiles. Natural emission rates and anthropogenic activities that emit are affected by temperature and precipitation variations. Longer growing seasons in a warmer climate mean more pollen and more CO_2 in the atmosphere stimulates plant growth and emissions of biogenic volatile organic compounds. Global warming increases the frequency of thunderstorms, which can shatter pollen grains and spread them around, which can cause more asthma and other health problems (D'Amato & Akdis, 2020). Climate change also influences anthropogenic emissions through changes in energy demand. The increased cooling demand in summer increases the consumption of electricity and the power plant emissions associated with it. Changes in farming practices, driven by climate conditions, affect emissions from biomass burning and disturbance of soils. Wildfires have become substantially more frequent and intense, driven by climate-induced drought and heat waves, and are a major source of PM2.5 and black carbon that contribute to both health impacts and climate feedback. Such climate-driven changes in emission profiles complicate source apportionment efforts and necessitate dynamic approaches considering changing source contributions over time (Winiger et al., 2019).

- **Regional Differences in PM Sources**

Particulate matter sources are very different among regions depending on the level of economic development, energy infrastructure, climatic conditions and regulatory frameworks. Analysis of PM source apportionment studies from seven geographical areas of China showed significant regional differences in source contributions, but secondary inorganic aerosol, industrial emissions and dust were generally the top three categories (Y. Liu et al., 2019). Residential use of coal for heating purposes is a major contributor to winter PM pollution in northern China. Primary sulphate from this source contributes 38.9% and 49.2% of ambient sulphate mass at urban and rural sites respectively during the heating season. The result emphasizes the role of regional climate conditions in determining emission patterns and pollution episodes (Stavroulas et al., 2019). Motor vehicle and secondary aerosol were the most

dominant and prevalent PM sources in South Korea, with population-weighted mean contributions that were highest for these categories. However, study characteristics such as sampling design, analytical methods, and treatment of Asian dust days greatly influenced source apportionment results, indicating the need for cautious interpretation of regional comparisons. Source apportionment of volatile organic compounds at a suburban site in northwest India revealed biofuel use and waste disposal, wheat-residue burning, cars, mixed daytime sources, industrial emissions and two-wheelers as the main contributors, with wheat-residue burning dominating ozone formation potential. These regional differences highlight the importance of local mitigation strategies to address the region-specific source profiles (Pallavi et al., 2019).

Climate-Driven Atmospheric Transformations of PM

- **Formation of Secondary Organic Aerosols**

Secondary organic aerosol formation is a key pathway for particulate matter formation and climate change influences the precursor emissions and the chemical processes involved. Secondary organic aerosol is formed when volatile organic compounds from anthropogenic and biogenic sources are oxidized and then undergo gas-to-particle partitioning or multiphase reactions. Two types of secondary organic aerosol were identified in Nanjing: one formed rapidly in the early afternoon by fresh photochemical reactions, and the other representing more aged and oxidized particles that accumulated later in the day. These results suggest that primary organic particles emitted from traffic, cooking and industrial sources can chemically evolve to more oxidized secondary aerosols with atmospheric ageing (Robinson et al., 2007). Biogenic volatile organic compounds are a significant source of secondary organic aerosol and are emitted from vegetation at highly temperature-dependent rates. In China, biogenic emissions were identified as the most important source of secondary organic aerosol during summer, while residential and industrial emissions dominated in winter. Climate change is expected to change both biogenic emissions and photochemical activity, which will change the seasonal and spatial patterns of secondary organic aerosol formation. The interaction of anthropogenic and biogenic precursors giving rise to organosulfate and nitrooxy-organosulfate formation adds to the complexity of secondary organic aerosol formation processes (L. Xu et al., 2021).

❖ Sulfate and Nitrate Aerosol Chemistry

Sulphate and nitrate are major constituents of atmospheric fine particulate matter and their formation chemistry is strongly dependent on temperature, humidity, and the availability of oxidants. Observed sulphate concentrations are generally high in summer and low in winter at the global scale, consistent with the temperature dependence of sulphate formation pathways. However, current air quality models usually cannot reproduce the high winter sulphate concentrations observed during pollution episodes in northern China, indicating the gaps in the understanding of multiphase sulphate formation mechanisms. Recent studies have shown that primary sulphate emissions from residential coal burning are an important source during the winter heating season, challenging the traditional view that sulphate is primarily a secondary species (P. Liu et al., 2020).

❖ Photochemical Reactions Under Elevated Temperatures

Photochemical reactions are important in the formation of secondary inorganic and organic aerosols, with their rates being strongly temperature-dependent. Elevated temperatures accelerate photochemical oxidation reactions, which in turn promotes the generation of sulphate, secondary organic aerosols and tropospheric ozone. In summer measurements in Nanjing, sunlight-driven photochemical reactions greatly enhanced sulphate and secondary organic aerosol formation, with secondary pollutants accounting for nearly 70% of the submicron particle mass. Photochemical oxidation of primary organic particles leads to their transformation to more oxidised secondary aerosols as they age in the atmosphere (Hu et al., 2016). The temperature dependence of photochemical reactions has implications for diurnal and seasonal patterns of PM pollution. Nighttime enhancements of nitrooxy-organosulfate species were noticed during both pre-monsoon and post-monsoon campaigns in Delhi, pointing to the significant role of nighttime chemistry in the formation of secondary organic aerosol. This nocturnal production differs from the daytime photochemical formation pathways indicating that different chemical regimes are in place depending on the availability of solar radiation, oxidants and aerosol water content. Knowledge of these photochemical pathways is important for predicting the response of PM concentrations and composition to climate change through changes in temperature and solar radiation (Leresche et al., 2021).

❖ Aging and Chemical Evolution of Particulate Matter

Ageing processes such as oxidation, condensation and aqueous-phase reactions convert freshly emitted particles into chemically aged aerosol with different physical and chemical properties. As particles age in the atmosphere, they become more oxidised and can accumulate additional secondary aerosol components. Ageing of black carbon due to wildfire emissions has been observed in the lowermost stratosphere, illustrating long-range transport and chemical evolution of combustion aerosols. Aged particles often exhibit different optical properties, hygroscopic behaviour, and health impacts compared to fresh emissions (Pratt et al., 2011). The chemical evolution of particulate matter is affected by various factors such as oxidant availability, relative humidity, temperature and aerosol water content. Multiphase chemistry on particle surfaces and in the bulk of aerosol particles plays an increasingly recognized role in aerosol transformation, particularly under high PM conditions. However, the multiphase chemistry of the atmosphere is poorly understood because of its intrinsic complexity and the difficulties of separating its effect from gas-phase reactions. Studies of multiphase chemistry involved in atmospheric aerosol formation and transformation have improved understanding of different chemical regimes of sulphate, nitrate and secondary organic aerosols under haze conditions, and the effects of aerosol water content, pH, phase state and nanoparticle size (G. Wang et al., 2016).

Source Apportionment Approaches for Climate-Modified PM

❖ Chemical Characterization of PM

Chemical characterization is an important step in source apportionment to provide compositional data to distinguish different emission sources and atmospheric processes. The chemical composition of particulate matter (PM) varies considerably with source; fossil fuel combustion is characterized by elemental carbon, sulphate, and some trace metals; biomass burning by organic carbon and potassium; dust by crustal elements; and sea salt by sodium and chloride. The identification and quantification of these chemical tracers allow the source apportionment of contributions by different modelling approaches. Recent developments in chemical speciation have enhanced the resolution of source apportionment studies. High resolution mass spectrometry has enabled the identification of individual organic compounds and their sources (Crippa et al., 2013). Results of source apportionment are strongly dependent on the choice of measured chemical components. Studies in South Korea have reported that source apportionment results were based on

different subsets of chemical speciation data collected at single sampling sites with variable sampling methods and laboratory analyses. This heterogeneity in study characteristics introduces uncertainty in comparisons of source apportionment across studies and regions. Key source categories are resolved by including tracers such as organic carbon, elemental carbon, sulphate, nitrate, ammonium, and trace metals, with advanced organic molecular markers providing the ability to further differentiate sources such as different types of combustion (Z.-L. Chen et al., 2022).

- **Receptor-Based Models (PMF, CMB)**

The most commonly used receptor-based models for PM source apportionment are positive matrix factorization and chemical mass balance. Positive matrix factorization is a multivariate factor analysis method that decomposes the concentration data matrix into source profiles and source contributions without a priori knowledge of source profiles. This approach is a good candidate for data-driven source identification, especially when the source profiles are uncertain or variable. Chemical mass balance, by contrast, is a deterministic approach that uses known source profiles to estimate contributions through mass conservation, requiring prior knowledge of source compositions (Chow et al., 2007). The positive matrix factorization application to volatile organic compound data in northwest India resolved six sources: biofuel use and waste disposal, wheat-residue burning, cars, mixed daytime sources, industrial emissions and two-wheelers. Comparison with emission inventories showed large discrepancies, with the positive matrix factorization solution indicating that emissions from the transport sector may be underestimated by some inventories and overestimated by others. This result emphasizes the importance of reconciling the receptor-based source apportionment with bottom-up emission inventories to improve emission estimates and mitigation strategies (López-Aparicio et al., 2017).

- **Isotopic and Molecular Marker Approaches**

Isotopic techniques are powerful tools for source apportionment since they exploit the characteristic isotopic signatures of different emission sources. Multi-isotopic fingerprinting with stable isotopes of carbon and nitrogen can identify sources such as traffic, waste incineration and coal combustion. In Tarragona, Spain, an isotope-based approach reduced the “unaccounted” PM mass fraction from 45% (chemical models) to as low as 5%, indicating significant contribution of local and regional sources. Molecular diagnostic ratios of polycyclic aromatic hydrocarbons and lead isotope ratios confirmed a dominant anthropogenic origin mainly associated with

traffic emissions and waste incineration, and with additional contributions from coal combustion at long range (De La Torre-Roche et al., 2009). Compound-specific isotope analysis has also been used to study the photodegradation of polycyclic aromatic hydrocarbons, and found no significant carbon isotope fractionation but strong inverse hydrogen isotope fractionation for benzo pyrene in soil under simulated climate change conditions. This isotopic approach provides insights into the transformation mechanisms of particle bound pollutants with implications for understanding their fate and transport. The coupling of isotopic techniques with conventional chemical modelling approaches provides new insights into source apportionment, environmental monitoring and health risk-based air quality management (Chang et al., 2019).

- **Artificial Intelligence and Machine Learning Applications**

Artificial intelligence (AI) and machine learning (ML) applications are emerging as powerful tools for source apportionment, air quality forecasting and exposure assessment. Such approaches can detect complex patterns in large datasets, and can increase the resolution and accuracy of source attribution compared to traditional statistical approaches. Machine learning algorithms can combine several data streams such as chemical speciation, meteorological variables and satellite observations to provide near real time source apportionment and predictive capabilities. The climate projections used in AI-based models allow to predict long-term changes of PM concentrations and source contributions under different climate scenarios (Alotaibi & Nassif, 2024). Recent progress in AI-based air quality forecasting models offers new opportunities for early warning systems and policy support. State-of-the-art advances in health impact assessment include high-resolution exposure mapping, toxicity assessments for specific components, and the use of climate projections to inform long-term burden projections. These techniques feed policy through the identification of high impact interventions ranging from traffic management to cleaner fuels, supported by robust risk assessment frameworks. Integrated assessment remains central to formulating targeted mitigation strategies as climate change and urbanization drive changing emission patterns (Johns et al., 2012).

Climate-Enhanced Natural PM Events

❖ Wildfires and Biomass Burning Aerosols

Wildfires are a major and increasing source of PM2.5 and PM10, and climate change is increasing the frequency, severity, and duration of wildfires. Wildfires emit ash in the form of PM2.5 and PM10 as well as black carbon, carbon monoxide, nitrogen oxides, ozone, carbon dioxide and volatile organic compounds. Of particular concern is black carbon from wildfires which has been linked to adverse health effects and climate forcing at rates 460-1,500 times that of CO_2 per unit mass. Wildfire PM10 emissions may be more harmful to health than PM10 from other sources, and smoky days are associated with higher mortality rates (Gould et al., 2024). The effect of wildfires on air quality is not confined to the area of the fire itself, as the smoke plumes can be carried for thousands of kilometers. Wildfire pollutants can lead to a variety of adverse health outcomes including difficulty breathing, increased risk of asthma, heart failure, and premature death. The inhalation of particulate matter from wildland-urban interface fires may include particularly hazardous substances from the burning of man-made structures and houses such as asbestos. This source category is becoming increasingly important for regional air quality and global climate as the frequency of wildfires driven by climate-induced droughts and heatwaves increases (R. Xu et al., 2023).

❖ Dust Storms and Desertification

Sand and dust storms are a major natural source of PM10 and PM2.5, and desertification, drought and unsustainable land management are increasing their frequency and intensity through climate change. These storms occur when strong winds blow over dry, fine-grained materials with sparse or no vegetation cover, mainly in arid and semi-arid environments. During severe dust storms, PM10 dust concentrations can reach 15,000 μg/m3, well above the US National Ambient Air Quality Standards for PM10 of 150 μg/m3 for any 24-hour period . Around 25% of dust emissions are caused by human activities such as deforestation and unsustainable land management practices (Intergovernmental Panel On Climate Change, 2022a).

❖ Volcanic and Marine Aerosol Contributions

Volcanic activity contributes to PM10 and PM2.5 by throwing out fragments of lava and ash particles as well as secondary aerosols of volcanic salts. Volcanic tephra, the

term for all the bits of rock blown into the air by eruptions, can be transported hundreds or even thousands of miles away from the eruption site. Small quantities of falling tephra (500–1500 g m –2) can generate high PM10 concentrations because basaltic ash and other coarse particles are susceptible to breakage by normal ground disturbance such as passing traffic. Explosive eruptions send ash into the air for days or weeks, but smaller, more frequent eruptions can lower air quality for months (Titos et al., 2014).

Climate–Aerosol Interactions and Feedback Mechanisms

- **Aerosol–Radiation Interactions**

Aerosols affect climate by scattering and absorption of solar and terrestrial radiation and influence the earth's energy balance. So, light-absorbing aerosols (like black carbon and brown carbon) have a warming effect (they absorb solar radiation), whereas scattering aerosols like sulphate and some organics have a cooling effect. The net radiative effect of aerosols is determined by their optical properties, which are determined by their chemical composition, size distribution, and mixing state. Aerosol-radiation interactions are modified by climate change through changes in aerosol emissions, transport and chemical transformation (Horwell et al., 2013).

- **Aerosol–Cloud Interactions**

Aerosols act as cloud condensation nuclei and ice nuclei, affecting cloud formation, properties and precipitation. Aerosol-cloud interactions are one of the largest uncertainties in climate projections, and have impacts that can either amplify or dampen warming, depending on the aerosol type, cloud conditions, and atmospheric dynamics. Anthropogenic and natural aerosol emissions affect cloud albedo, lifetime and precipitation efficiency, and have regional and global climate implications. Climate change subsequently affects aerosol-cloud interactions via variations in atmospheric temperature, humidity and circulation (Seinfeld et al., 2016). In heavily polluted areas, aerosol-cloud interactions can enhance haze formation through positive feedbacks. Higher particle matter levels cause quicker multiphase production which boosts aerosol concentrations and causes pollution events to break records. The importance of aerosol water content, pH, phase state and nanoparticle size effects on cloud processing is increasingly recognised, with advances in the understanding of the chemical regimes of sulphate, nitrate and secondary organic aerosols in haze conditions. Improving our understanding of aerosol-cloud interactions requires a synthetic approach involving laboratory

experiments, field measurements, instrument development and model simulations (Hallquist et al., 2009).

- **Feedback Effects on Regional and Global Climate**

The interactions between aerosols and climate operate at a variety of spatial and temporal scales, with regional and global implications. Of particular concern are positive feedback loops where climate change leads to greater aerosol emissions that in turn change climate. Wildfires provide a good example: climate-driven drought and heatwaves increase fire frequency and severity, releasing black carbon that helps warm, which increases fire risk . Similarly, desertification caused by climate change and unsustainable land management increases dust emissions and impacts on the regional climate through changes in the radiation balance and cloud properties (Intergovernmental Panel On Climate Change, 2022b). Regional climate feedbacks are appearing in pollution hotspots such as the Indo-Gangetic Plain and northern China. Interactions of aerosols with radiation influence atmospheric stability and boundary layer processes, which in turn affect the buildup and dispersion of pollution. Aerosol-cloud interactions affect precipitation patterns with implications for water resources and ecosystem health. The cascade of effects from aerosol emissions to climate change to human health points to the need for integrated assessment approaches that encompass the full range of feedback mechanisms in developing mitigation and adaptation strategies (Huang et al., 2023).

Human Exposure Pathways in a Changing Climate

- **Urban Heat Islands and Exposure Risks**

Heat islands are urban areas that are hotter than their rural surroundings, due to the surface characteristics of cities and the release of anthropogenic heat . Higher urban temperatures enhance photochemical reactions resulting in greater formation of secondary pollutants such as ozone and secondary organic aerosols. Synergistic health effects exist for the combined impact of heat and air pollution exposure. During episodes of high PM and O_3 under high temperature conditions, higher rates of respiratory and cardiopulmonary mortality have been observed. The health impacts are more pronounced in elderly cohorts and in young children (Rai et al., 2023). Heatwaves can create ideal conditions for the build-up of pollutants as photochemical activity is enhanced and stagnant air masses keep emissions near the surface. In Madrid, greater associations were detected between ozone and admissions due to respiratory, circulatory and neurological causes, NO_2 and

admissions due to respiratory diseases and PM and admissions due to dementia and Alzheimer´s disease in warm months. Sustainable urban planning and smart city design can significantly reduce the urban heat island effect and air pollution, providing opportunities for climate-resilient development (Piracha & Chaudhary, 2022).

- **Indoor–Outdoor PM Dynamics**

Climate change may affect sources of indoor PM including cooking, heating, and resuspension via changes in occupant behaviour and building characteristics. Residential energy use, including biomass and coal combustion for heating, is a major source of both indoor and outdoor PM exposure. Residential energy use is a significant contributor to ambient PM2.5 exposure and attributable mortality in China, but due to non-linear exposure-response relationships, significant emission reductions will be needed before measurable health benefits can be achieved. Measures that decrease indoor and outdoor PM exposure, such as improved cooking and heating technologies, are linked to significant health benefits (Apte et al., 2015).

- **Environmental Exposure**

PM can enter the body through a variety of routes including inhalation, ingestion and dermal contact. Climate change influences environmental exposure through changes in concentrations and composition of PM, and in patterns of deposition. Combustion-derived dust and aerosols are transported and deposited to ecosystems, impacting food safety, water quality, and ecosystem health. In Tarragona, health risk assessments about organic and inorganic compounds related to PM showed relatively low carcinogenic risk in the current exposure scenarios, but highlighted the toxicity of some trace metals and polycyclic aromatic hydrocarbons. The main contributors to adult lifetime lung cancer risk were compounds with 5-6 aromatic rings, with higher risks in the colder seasons in seasonal variation (Grmasha et al., 2023).

Public Health Implications of Climate-Driven PM Pollution

- **Respiratory Diseases**

The association between exposure to PM and respiratory diseases is well documented. Climate change modifies exposure levels and health outcome. PM2.5 can penetrate deep into the lungs, causing oxidative stress, inflammation, and airway hyperresponsiveness. Short-term exposure to PM has been associated with

increased hospital admissions for chronic obstructive pulmonary disease, asthma, acute bronchitis, and respiratory infections (10–12). Long-term exposure is linked to the development and progression of chronic respiratory diseases, decreased lung function and increased mortality. Climate-driven changes in PM composition, including increases in secondary organic aerosol and oxidant species, may affect respiratory toxicity (Gomez et al., 2023a). PM and extreme temperatures act synergistically to affect respiratory health, with higher rates of respiratory and cardiopulmonary mortality under combined exposure. In Madrid, the full series presented a predominance of admissions for respiratory causes, with increases in cold months and decreases in warm months. PM concentrations affected admissions due to dementia and Alzheimer's disease, representing 4% of attributable admissions. During summer months, the main pollutant responsible for admissions due to respiratory causes was NO2 (2% of attributable admissions in pneumonia (Chamberlain et al., 2023).

- **Cardiovascular Disorders**

PM exposure is a major risk factor for cardiovascular disease, and effects are mediated through systemic inflammation, oxidative stress, autonomic dysfunction, and direct translocation of particles into the circulation. Short-term elevations in PM concentrations induce acute cardiovascular events such as myocardial infarction, stroke and heart failure exacerbations. Long-term exposure accelerates atherogenesis, hypertension and vascular dysfunction, which contribute to the development and progression of cardiovascular disease. Climate change may influence cardiovascular disease risks through changes in PM composition, co-exposure with heat and changes in physical activity patterns (Kazi et al., 2024). In Madrid, studies observed stronger associations in the warm months between PM concentrations and hospitalizations due to circulatory causes, with noise being the pollutant with the highest proportion of attributable hospitalizations. PM concentrations were associated with admissions for dementia and Alzheimer's disease, suggesting cardiovascular pathways may be involved in neurologic outcomes. The cardiovascular effects of PM are especially pronounced in the elderly, who are at higher baseline risk and more vulnerable to combined heat and pollution exposure (Krittanawong et al., 2023).

- **Neurological and Cognitive Effects**

There is growing evidence of neuropsychological and neurocognitive effects associated with PM exposure, including accelerated cognitive decline, increased risk

of dementia and Alzheimer's disease, and neurodevelopmental effects in children. Plausible mechanisms for neurological effects include translocation of ultrafine particles from the respiratory tract to the brain, as well as systemic inflammation and oxidative stress. Climate-driven changes in PM constituents such as higher secondary organic aerosol and different trace metal levels may affect neurotoxicity. Associations of PM with hospital admissions for dementia and Alzheimer disease were observed during warm months in Madrid (Roy & D'Angiulli, 2024).

- **Cancer Risks**

The carcinogenicity of PM is well characterized, and outdoor air pollution and PM have been classified as Group 1 carcinogens by the International Agency for Research on Cancer. Polycyclic aromatic hydrocarbons, heavy metals and other toxic compounds bound to PM are linked to the risk of lung cancer, exerting their effects via DNA damage, oxidative stress and epigenetic modifications. Climate change may impact cancer risks by changing the composition of PM, such as increasing concentrations of carcinogenic compounds from wildfires and changing secondary aerosol formation. Health risk assessments have recognized the toxicity of some PM components like polycyclic aromatic hydrocarbons with 5–6 aromatic rings (Gomez et al., 2023b). In Tarragona the most important contributors to adult lifetime risk of lung cancer were compounds with 5-6 aromatic rings such as benzo[a]pyrene, dibenz[a,h]anthracene and benzo[b+k]fluoranthene, with seasonal variations indicating a higher risk in the colder seasons. These findings emphasise the importance of component-specific toxicity in health risk assessments and the necessity for source-specific control strategies targeting the most toxic compounds. The health effects of air pollution go far beyond death, with the contribution of morbidity and reduced quality of life being significant (F. Chen et al., 2024).

Research Gaps and Future Directions

Significant knowledge gaps remain in understanding the interaction of climate change with PM concentrations, composition and health effects. The climate-PM interactions are complex and non-linear, with feedbacks, thresholds and tipping points, and are still not fully understood. Because global average projections may mask considerable spatial variability, research is needed on the regional and local impacts of climate change on PM. The influence of climate change on the toxicity of PM such as changes of chemical composition and physical properties needs to be further studied. A key research priority is the interaction between climate change and the health effects of PM, including the potential for synergistic and antagonistic

effects with temperature and other stressors (Pinho-Gomes et al., 2023). The multiphase chemistry, which is important for the formation of aerosols during haze events, is poorly understood because of its intrinsic complexity. To achieve a comprehensive understanding of atmospheric multiphase reactions, a synthetic approach will be required that integrates laboratory experiments, field measurements, instrument development and model simulations. Research on the different chemical regimes of sulphate, nitrate, and secondary organic aerosols under haze conditions, and the effects of aerosol water content, pH, phase state, and nanoparticle size effects, will improve the representation of PM formation and transformation in the climate models (Li et al., 2024).

Conclusions

Climate change has important effects on the dynamics of PM2.5 and PM10 pollution related to emission sources, atmospheric transformations and public health effects. PM concentrations and composition are affected by rising temperatures, changes in wind systems, altered precipitation patterns and extreme weather events, and exhibit regional differences that reflect differences in source profiles, climate conditions and regulatory environments. In many regions, both anthropogenic and natural sources are affected with intensification of wildfires, dust storms and biogenic emissions. Secondary organic aerosol formation, sulphate and nitrate chemistry, photochemical reactions, and other atmospheric transformations are hugely affected in a changing climate.

The public health implications of climate-driven PM pollution are profound, including respiratory diseases, cardiovascular disorders, neurological effects, cancer risks, and maternal-child health outcomes. The elderly, children, and those with socioeconomic disadvantages are among vulnerable populations that face disproportionate exposure risks and health impacts. The economic cost is significant, with lost output from premature death and morbidity due to air pollution representing a sizeable share of GDP in affected areas. Emerging monitoring technologies such as satellite-based systems, remote sensing, low-cost sensor networks and AI-based forecasting models provide new opportunities for exposure assessment, early warning systems and policy support. Opportunities for co-benefits are provided by integrated mitigation strategies addressing climate change and air quality, such as sustainable urban planning, clean energy transitions, and climate-smart air quality management. More research is required to fill knowledge gaps, such as the mechanisms of climate-PM interactions, improvements

in source apportionment, and precision exposure assessment. In a rapidly changing world, integrated action across disciplines and sectors can protect health and build climate resilience.

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