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Aerosol Measurements and Decadal Changes: The Role of Climatic Changes and How It Reflects in Respiratory Allergies and Asthma

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Received: 30 November 2024 | **Revised:** 22 April 2025 | **Accepted:** 13 May 2025

Funding: The authors received no specific funding for this work.

Keywords: aerobiology | aerosols | allergy | climate change | epithelial barrier

ABSTRACT

The causative agents of respiratory allergies are bioaerosols, such as house dust mite feces, pollen grains, and fungal spores. Climate change and urbanization are considered to lead to an increase in the load of allergenic bioaerosols due to impacts on plant phenophases and allergenicity. Continuous and efficient monitoring of the atmospheric composition worldwide is essential, given the major changes involved and their impact on climate change. The complexity of the exposome, evolving from single to multiple complex exposures, is explored in this work. Acquiring information from interdisciplinary scientific disciplines, such as aerobiology (for airborne particles of biological origin), aerosol science (for airborne particles of chemical or inorganic material), and integrating this with the actual reactome of patients with respiratory diseases, we aim to provide evidence of the multifactorial nature of this interaction in real life. The objective of this review is to present how we can monitor aerosols and mostly monitor the exposome, especially the biological one, i.e., pollen and fungal spores, and what their impact is, or could be, on respiratory allergies. A huge technological advancement has been required, as traditional methods of particle collection and identification have been based on tedious laboratory procedures, with delays of more than a week. This has limited their practical use to allergic patients and their treating physicians. Automation, real-time high temporal resolution, and the use of artificial intelligence are being increasingly used in medicine. Likewise, this overview summarizes the current aerosol measurement and modeling capabilities and discusses the classification of various aerosol particles and their impact on respiratory allergies. Satellite remote sensing is highlighted as a solution to the gaps in global aerosol representation by examining aerosol load in the atmospheric column in major cities worldwide. We also discuss potential novel threats, such as pioneer bioaerosols and the respiratory epithelial barrier, as well as future insights into the impact of climate change on allergy and asthma. We conclude with a discussion of emerging co-exposures and co-diseases resulting from the ongoing climate change.

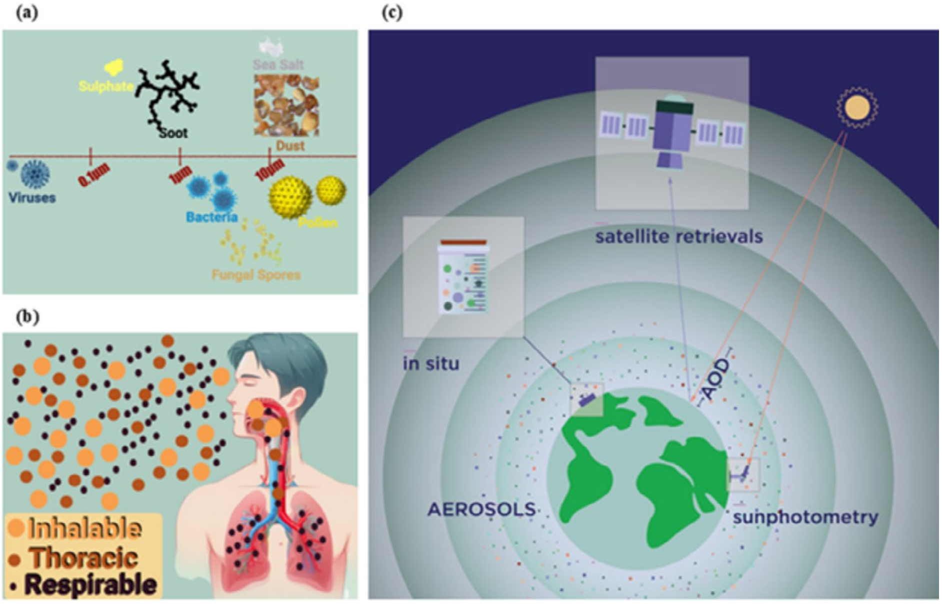

FIGURE 1 | Atmospheric aerosols (a), their categorization based on accumulation regions in the respiratory tract (b), and various observational techniques used for aerosol monitoring (c).

1 | Introduction

Respiratory health can be affected by climate change and the related changes in atmospheric composition. These contribute to the development of respiratory allergies [1–5]. Aerosols have a large impact on human health, either directly or indirectly through their effects on climate and the environment [6]. Highertemperatures and carbon dioxide levels lead to an increase in pollen production. This exacerbates the symptoms of allergic rhinoconjunctivitis and asthma. The epithelial barrier theory suggests that increasing exposure to pollutants and allergens due to climate change can damage the body's protective barriers, allowing allergens to penetrate more easily. This in turn leads to sensitization to airborne allergens and overall inflammation. Clinically, this translates as an increase in airborne allergies, but also other allergic and non-allergic conditions. It is worth mentioning that not only humans but also animals are affected by these developments. This highlights the need for adaptive strategies to address this major public health issue [7–9].

The consequences of air pollution can affect almost every organ system of the human body. This is mainly linked to systemic inflammation and oxidative stress. The health effects can result from both short-term and long-term exposure to air pollutants. Some of the metabolic and inflammatory effects can be seen at low levels of pollution. Studies have linked air pollution exposure to an increased risk of a large spectrum of diseases. These include chronic respiratory diseases, such as chronic obstructive pulmonary disease, asthma, lung cancer, and respiratory infections; cardiovascular diseases, such as myocardial infarction, cerebrovascular accidents, atherosclerosis, and arrhythmias; and neurological diseases, such as multiple sclerosis, Alzheimer's disease, Parkinson's disease, dementia, and cognitive impairment of other etiologies. In addition, air pollution has been suggested to impact the risk for many other conditions, such as cancers, diabetes, arthritis, osteoporosis, and infertility [8]. Motivated by the numerous health effects of aerosols and their changes related to urbanization and climate feedback, we present an overview of the basic aerosol measurement principles, atmospheric trends, and how aerosols are involved in respiratory allergies and asthma pathogenesis. This comprehensive review of various aerosol monitoring methods aims to highlight the need for advanced, real-time monitoring techniques. These could help allergy patients and their treating physicians. This multidisciplinary perspective aims to contribute to a better understanding of the multifactorial nature of the interactions between environmental exposures and respiratory diseases.

1.1 | Parameters and Measurement Principles of Aerosols

Atmospheric aerosols have a wide range of sizes, shapes, and chemical compositions (Figure 1a). When inhaled by humans, aerosols can be categorized with respect to the accumulation regions in the respiratory tract (Figure 1b). There are many different techniques to observe different aerosol properties. We can divide the observational techniques (Figure 1c) into three categories: "in situ" measurements, as well as passive and active remote sensing observations. "In situ" measurements refer to the direct analysis of aerosol properties in the air. The most common products of in situ measurements are the mass concentrations of aerosols (usually in $\mu g/m^3$) with diameters below $10\,\mu m$ (particulate matter; PM10), $2.5\,\mu m$ (PM2.5), and $1\,\mu m$ (PM1) [10], and of ultrafine particles (with diameters $<0.1\,\mu m$) [11]. Mass concentration is not representative of the number of particles since particles in the accumulation mode dominate the mass. However, the particle number concentration, representing the total number of particles per unit volume of air, can also be measured as well as their size distribution. In situ instruments can also measure aerosols' optical (scattering and absorption coefficients) [12] and chemical properties. Passive remote sensing includes the monitoring of aerosol properties using radiation

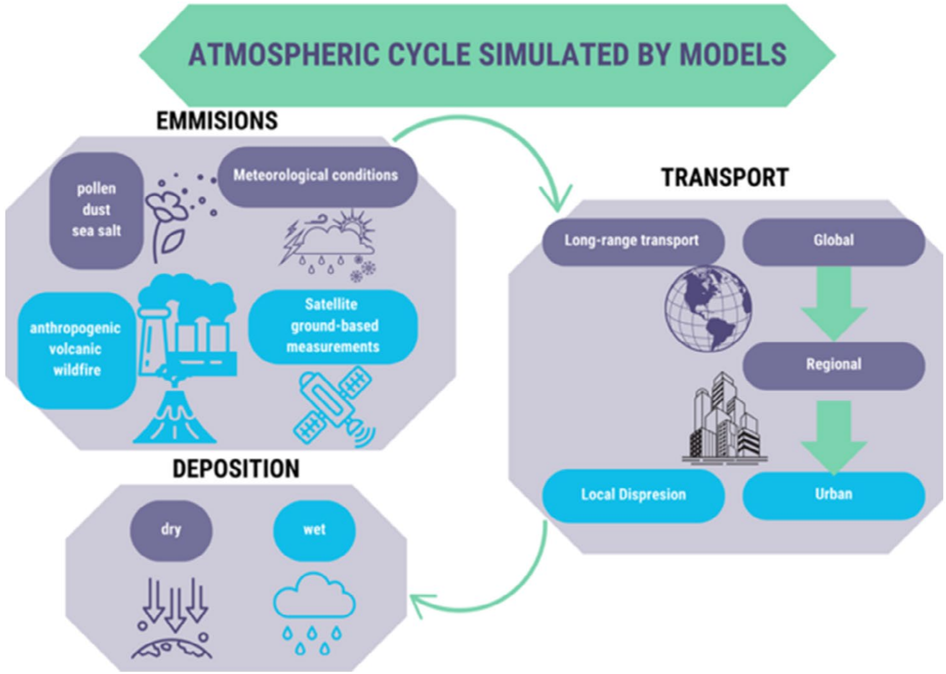

FIGURE 2 | Modeling of the atmospheric state of the cycle of natural and anthropogenic aerosols.

measurements from natural sources (mostly solar radiation) either with ground-based or satellite instruments. Passive remote sensing is used mostly for the retrieval of columnar aerosol optical properties. Active remote sensing is achieved using light sources from an instrument such as the emission of laser beams and the measurement of the backscattered light. It provides information about the vertical profile of aerosol properties.

A commonly measured parameter is the aerosol optical depth (AOD), which is the integrated extinction coefficient over the whole atmospheric column. AOD is widely provided by remote sensing measurements and in most cases can be used as a proxy of air quality [13]. Remote sensing can also be used to retrieve the aerosol size distribution of the whole aerosol column [14] and the vertical profiles of the absorption and scattering coefficients [12]. Particle sizes change continuously as a result of coagulation, fragmentation, condensation, deposition, and evaporation, resulting in the particle number size distribution exhibiting one or several modes. The larger particles are described as the “coarse” mode, middle-size particles as the “accumulation mode” and the smallest particles as the “fine” mode. The accumulation mode of the aerosol size distribution is more populated and is multimodal [15]. The coarse mode mainly includes particles such as pollen [16], sea salt, and dust [17], while accumulation and fine particles originate mostly from combustion processes, secondary aerosol, or new particle formation [17]. Bioaerosols are a subcategory of airborne particles originating from plants/animals [18] and can contain both living or dead microorganisms [19]. Monitoring of bioaerosols is discussed extensively in Section 3.

1.2 | Modeling of Atmospheric Aerosols

Aerosol models aim to simulate the atmospheric state of the cycle of natural and anthropogenic particles, including their emission, transport, and deposition (Figure 2). In the case of wind-derived aerosols such as sea salt, dust, and pollen, the emissions are computed based on the meteorological and surface conditions (e.g., soil moisture, vegetation coverage). In the case of volcanic ash and biomass-burning aerosols, the emissions are modeled based on satellite retrievals and ground-based measurements of volcanic and wildfire activity, respectively.

The long-range transport of aerosols at global and regional scales is described by an ensemble of different chemical transport models by the Copernicus Atmosphere Monitoring Service (CAMS) [20, 21]. Such global reanalysis datasets are used for climatological studies but also to provide initial and boundary conditions for higher-resolution limited area models with online coupling of aerosol-meteorology interactions [22]. In addition, CAMS provides forecasts of aerosol speciated AOD (e.g., pollen, dust, etc.). The main aerosol related to allergy is pollen, which can be transported long distances by the wind. Pollen forecasts rely on the combination of a phenological model to describe the maturation stage of the inflorescence, in situ pollen measurements in real time, and an atmospheric dispersion model to describe their long-range transport (using also real-time pollen measurements [23, 24]). Finer urban-scale modeling includes Gaussian dispersion models and land-use regression models that can provide the necessary source apportionment for health- and policy-related studies [25–29].

1.3 | Aerosol Sources

Anthropogenic and natural aerosols constitute the two primary categories of atmospheric particles (Figure 3). Anthropogenic aerosols originate mainly from traffic, industry, construction, housing, and agriculture [30–34] and the energy sector, constituting coal-burning power plants [35], coal combustion for residential needs, and the release of bacteria and fungi from recycling and composting plants [36].

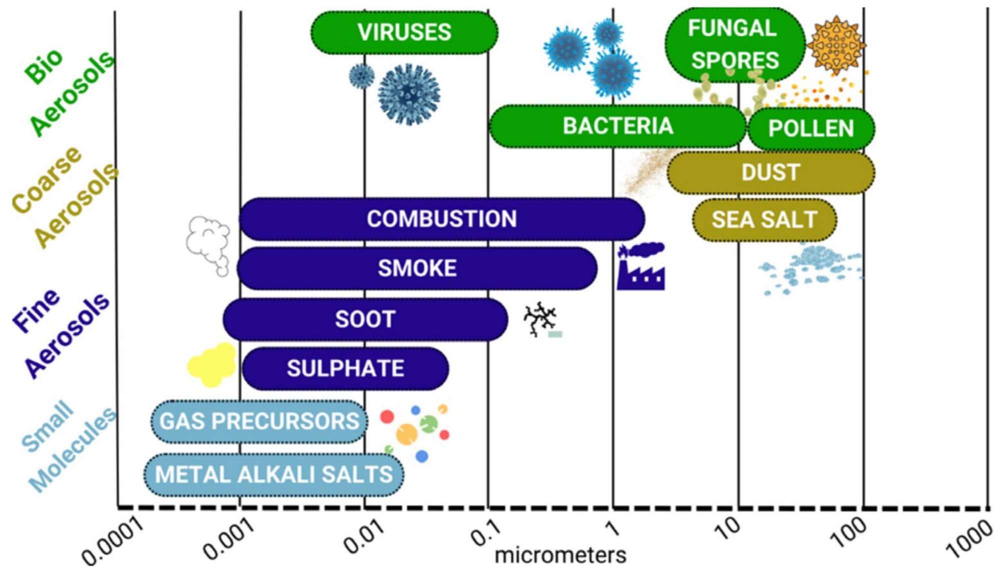

FIGURE 3 | Aerosol sources as a function of their size and type.

One of the main sources of natural aerosols is wind-blown dust from deserts, dry lake beds, as well as ephemeral channels [37, 38], and their long-range transport [39, 40]. A considerable portion of dust is also attributed to anthropogenic activities (overgrazing, irrigation, and oil prospecting [38, 41]). The chemical and mineralogical composition of dust particles depends on their origin, composed of various species such as quartz, hematite, feldspar, iron, illite, kaolinite, and others [42–44]. Along with the air-quality degradation in urban areas [45, 46], dust also plays a crucial role in respiratory diseases [47–51].

Another natural aerosol source is marine particles emitted under the stretch of winds on the sea surface, causing the ejection of droplets during the bursting of bubbles in seawater [52]. Sea-salt aerosols, largely made up of sodium and chloride [53], are confined mainly to the coarse size spectrum [54], and accumulate in the marine boundary layer in open seas and coastal areas. They are occasionally transported long distances inland. Bacteria and viruses can be found in sea-spray aerosols and exacerbate lung function and symptoms in asthma patients [55–59].

Wildfires and biomass burning eject large amounts of fine carbonaceous particles into the atmosphere [53]. Epidemiological studies have demonstrated an increase in hospital admissions for asthma exacerbations [60] and a significant number of premature deaths, as well as cardiovascular and respiratory disorders, have been attributed to smoke particles emitted from megafires [61].

Primary bioaerosols (e.g., bacteria, viruses, fungal spores, pollen, and plant debris), constituting an important subset of the global aerosol budget, are emitted both from marine [62] and terrestrial [63] ecosystems [53, 64–66] and can travel long distances [67, 68]. Allergic airway diseases in humans are linked to inhalation of bioaerosols and their deposition in the respiratory tract. Different deposition mechanisms [63] are driven by particle properties, airway morphology, and breathing characteristics [69–71]. A decline in lung function, a rise in pulmonary disease, and a significant increase in the prevalence of allergic asthma have been associated with exposure to pollen [72, 73]. The inhalation of fungal spores is common in the summer months and is related to chronic health effects [74], whereas the inhalation of pathogenic bacteria and viruses may cause infections and lead to respiratory symptoms [75–77].

1.4 | How Aerosols Feedback to Climate

Atmospheric aerosols affect the Earth's climate significantly on both global and regional scales [78]. On a global scale, it is estimated that aerosols compensate for part of the warming induced by green house gases (GHGs) [78], which "trap" terrestrial radiation in the atmosphere, while aerosols reflect a certain proportion of solar radiation before it even reaches the Earth's surface. On regional scales, aerosols can cause heating or cooling of the Earth-atmosphere system depending on the prevailing aerosol shape, size, and chemical composition [79–81] and the environmental conditions [82–84]. The radiative effects of aerosols can be direct (aerosols directly interact with shortwave and longwave radiation through scattering and absorption), indirect (aerosols act as cloud condensation nuclei and thus affect the amount, type, and lifetime of clouds) or semi-direct (aerosols absorb solar radiation affecting atmospheric dynamics, which subsequently affects cloud formation and lifetime). Over dark surfaces (e.g., oceans, forests, etc.), aerosols typically result in cooling (i.e., less incoming radiation) of the Earth-atmosphere system. However, absorbing aerosols over relatively bright surfaces or over clouds results in the warming of the system [85, 86]. Despite the fact that significant progress has been made in the last 15 years regarding the understanding of aerosol radiative effects, they are still a major source of uncertainty in global and regional climate model projections. The uncertainty in climate projections of aerosol radiative effects arises from their sensitivity to the aforementioned highly variable parameters (microphysical and optical properties of aerosols, their vertical distribution, ground and atmospheric properties, and their interaction with clouds). Measurement-based constraints are essential for minimizing these uncertainties.

2 | Changes in Aerosols

2.1 | Trends in Near-Surface Aerosols

Globally, the concentration of aerosols near the Earth's surface has decreased over the past 20–30 years, particularly in Western Europe and Northern America, while global trends cannot be assessed due to limited long-term data availability in Africa, South America, and Asia. Nevertheless, a global decrease in black carbon has been observed (negative trends of aerosol absorption coefficient in Figure 4), which is primarily due to the reduction in traffic emissions rather than changes in wood burning and/or industrial emissions [88–90]. Variations in particle size exhibit significant spatial heterogeneity, with trends differing markedly across different locations on a global scale [87–93]. While some sites show an increase or decrease in particle size over time, no uniform global trend has been identified, highlighting the strong influence of local environmental conditions, emission sources, and atmospheric processes. Locally, trends toward smaller particle sizes might be due to an increase in nearby anthropogenic sources, an increase in new particle formation, or a modification of atmospheric chemistry. Trends toward larger particles can be related to a decrease in near-anthropogenic primary and secondary emissions, larger influences of mineral dust caused by variability in desert emissions or dust transport, or changes in local agricultural activities.

Many atmospheric aerosols are formed in the atmosphere rather than being directly emitted, so understanding trends in aerosol precursors is also relevant for understanding changes in the atmospheric aerosol levels. A decreasing trend of sulfate and other gaseous compounds (NO_x, CO, non-methane volatile organic compounds) has been measured across Europe and the US [94–96], whereas increasing sulfate trends have been observed in India, and an increase followed by decreases in Southeast Asia [94].

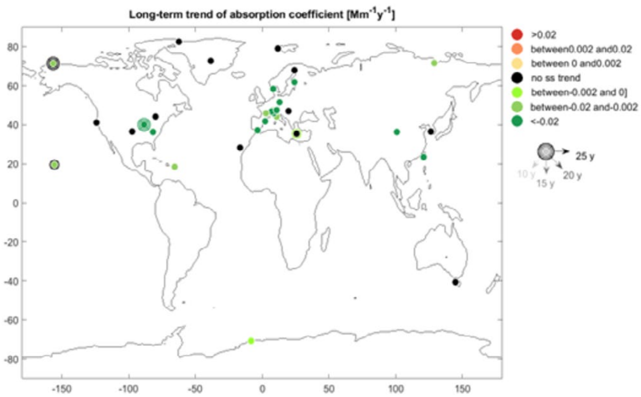

FIGURE 4 | Global trend results for the aerosol absorption coefficient. Black symbols correspond to stations with no significant trends. Green and orange symbols correspond to negative and positive trends, respectively. The magnitude of the trends (slope) is given by the colors as stipulated in the legend. The size of the circles is proportional to the length of the datasets, with the central dots representing the most recent 10-year trend ending in 2016, 2017, or 2018. If possible, trends for longer time periods were calculated and the larger circles denote the trends for 15–40 years in 5-year increments [87].

The long-term trends of aerosol absorption show that policy regulations have induced a decline in aerosol absorption (cooling effect) caused by a reduction in primary particles such as black carbon emissions and, in a second phase, a scattering decrease (warming effect) caused by the reduction of the precursors for secondary particle formation. This illustrates the complex dependency of environmental pollution regulations, which positively impact human health and the environment but may induce adverse effects on efforts to reduce climate change. The last IPCC report [78] emphasizes the low-carbon pathway, namely strategies and policies to reduce GHG emissions to mitigate climate change, which should help both issues.

2.2 | Trends in Aerosol Optical Depth

Although in situ PM measurements are directly related to health effects, they are not readily available everywhere on the planet. Satellite remote sensing of the total column aerosol optical depth (AOD) helps bridge this spatiotemporal gap in aerosol monitoring on a global scale. Globally, mostly negative AOD trends have been reported for the last two decades. For instance, both ground- and satellite-based AOD data from 2001 to 2020 were analyzed [97] and decreasing AOD trends over Eastern North America, Europe, as well as in Eastern/Central China were observed. Positive AOD trends have been reported for the Indian region and the Middle East [97]. For sub-Saharan Africa, the situation remains unclear, with both positive [97, 98] and negative [99, 100] AOD trends having been reported. Negative AOD trends reported for South America, subtropical Eastern and Central China, and Western North Africa can be linked to the reduction in fires related to deforestation [101] as a result of the Air Pollution Prevention and Control Action Plan of China and reductions in surface winds in the main dust source regions [102], respectively. Positive AOD trends in the Middle East and India can be linked to an increase in dust emissions from drying soils, in turn due to increasing temperatures and decreasing humidity [103], and increasing emissions and the more intense long-range transport [97, 104], respectively.

In a recent satellite-based AOD trend analysis [105] for 81 megacities with the highest population over the period 2003–2020, European and American cities were found to have lower aerosol loads and a decrease in AOD due to the series of air quality control measures that have been implemented over the past half century (Figure 5). Chinese cities, with high mean AOD values, exhibited the largest AOD decreasing trend in response to the implementation of rigorous emission control measures, especially after 2010. On the other hand, for Latin America, Africa, and the remaining Asian cities (Indian subcontinent and Middle East), significant AOD increases were found, with the highest values observed for the Indian cities, reflecting the increasing urbanization and industrialization of the country. Figure 5 also includes population information for the cities (represented by the size of the symbols), with the key takeaway that, despite cities in the Indian subcontinent and eastern Asia (primarily in China) being among the most populated areas on the planet and having the highest mean AOD values, they exhibit opposite AOD trends (increase and decrease, respectively). The study found that population growth and emission regulation measures are two competing factors for air quality, as in cities in the Indian subcontinent, population growth was correlated with the

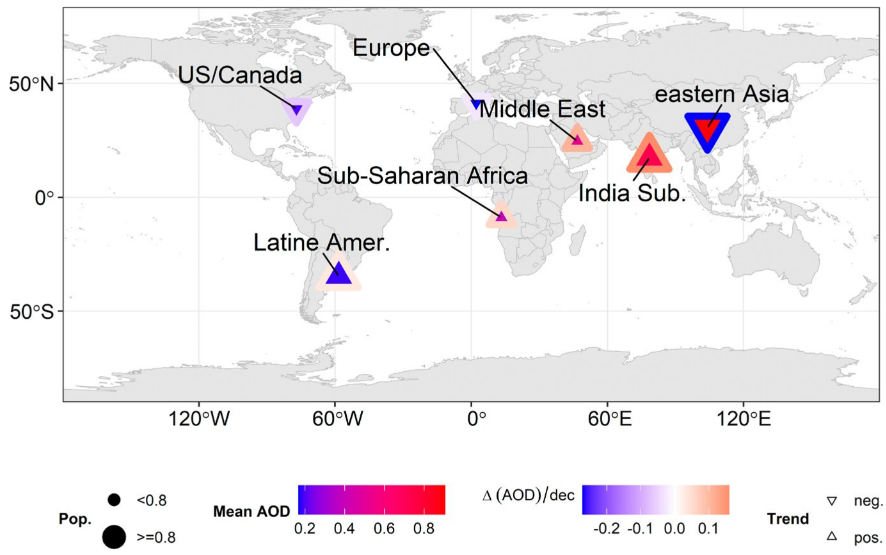

FIGURE 5 | Summary statistics based on satellite-based aerosol optical depth (AOD) from 81 megacities of the world. The long-term mean AOD (fill of symbols) and AOD changes per decade (outline of symbols) are the extreme values reported per geographical domain derived from daily satellite AOD retrievals over the period 2003–2020. The downward and upward arrows represent negative and positive trends, respectively, and the size of the symbols is based on normalized values of the sum of the city's populations in the respective regions.

AOD increase, while in Chinese megacities, despite population growth, the deployed environmental measures led to considerable decreases in AOD.

3 | Bioaerosols

Bioaerosols can be described as "airborne particles of biological origin, including plants, fungi, bacteria and viruses, as well as their debris, living or dead" [106]. They include all matter of living or dead organisms that can be lifted into the atmosphere, ranging in size from viruses to large agglomerations of fungal spores. This section focuses on pollen and fungal spores that are relevant to airborne allergies.

3.1 | Pollen and Fungal Spores

Transport of pollen, the male reproductive cells of plants, is intended to reach the female organs of other or the same plant by insects, wind, or, occasionally, water, and is the evolutionary solution that allows genetic mixing even among spatially distant members of the same species. Most pollen is dispersed by insects, with a much smaller subset of plants being pollinated by the wind (anemophilous species) [107]. In most bioclimatic regions, a seemingly limited number of pollen taxa, families, and genera with potentially numerous species included therein (e.g., in central Europe, around 50) are anemophilous and can be measured in the atmosphere in significant quantities, while < 20 of them are epidemiologically relevant for pollen allergies [108, 109], even though these numbers may increase with climate change contributing to the appearance of new or emerging aeroallergens [110]. Much less is known about tropical pollen taxa, where the majority consists of animal-pollinated species, but also because the westernized world has invested more in the field of aerobiology over the last several decades; hence, there is also more knowledge on allergic diseases. Tropical plants also have relatively lower pollen production per se compared to northern-latitude plant species. An exception is India, with a wide range of different climates and whose aerobiome has been more thoroughly studied (e.g., by Singh and Kumar [111] and references therein).

Some fungal spores, which are the mobile reproductive elements of fungi, are known to contain allergens that induce respiratory allergies [112] and, in severe cases, can cause asthma [113]. In contrast to pollen, much less is known about the realm of airborne fungal spores, regardless of the region of the world. This is because less research has focused on it and is also due to the fungal diversity in a huge variety of ecosystems and the enormous variability of their spores' morphology, literally everywhere around the globe, on all continents.

3.2 | Pollen and Fungal Spore Monitoring

Over the decades, a standard monitoring method has been developed (EN16868:2019), collecting particles through impaction and then using optical microscopy to count and identify particles [114]. This method has been widely used across the aerobiological community [115] and has proven useful for delivering information to health practitioners and their patients as well as being an indicator for plant phenology and biodiversity studies. However, there is a significant delay in data delivery associated with this method (typically up to 10 days in operational networks), which precludes its use in numerical forecast models and thus reduces the predictive accuracy of these models. In addition, the manual counting procedure and associated costs for expert personnel limit the spatial coverage of such monitoring networks.

To respond to increasing end-user demands and meet the challenge of providing real-time data and forecasts to the public, a number of automatic pollen monitors have recently been developed (see overview in [116–118]). They are based on a wide variety of technologies, ranging from robotic versions of the manual method [119], through to flow cytometry coupled to fluorescence [120] and digital holography [121]. All automatic instruments rely on artificial intelligence algorithms that identify and count airborne pollen grains, with two recent instruments being further developed to identify *Alternaria* spores [122, 123]. The data produced by these automatic devices is available within minutes to hours and thus can be provided to end-users in near-real-time and be used to improve numerical forecasts [24, 124, 125]. A recent large intercomparison campaign found that some automatic instruments perform at least as well as the traditional manual method, with the added advantage of providing higher temporal resolution or even real-time data [126]. A summary of the pollen and fungal spore monitoring methods is provided in Table 1.

4 | Human Health and Aerosols: Respiratory Epithelial Barrier

Humans are experiencing changes in their exposome due to environmental pollution, especially indoor and outdoor air pollution. Additional exposome changes include altered nutritional habits, increased use of unregulated antibiotics, exposure to surfactants from the widespread use of household cleaners and detergents, and the use of food additives such as emulsifiers and sweeteners in processed foods [7, 128–131]. All of these factors have increased over the past 60 years with the westernization, industrialization, and modernization of the world. The alteration to the human exposome has occurred at the same time as a steep increase in the prevalence and incidence of non-communicable diseases such as allergic, autoimmune, and metabolic conditions.

TABLE 1 | Summary table of pollen and fungal spore monitoring methods.

Method	Description	Reference
EN16868:2019	Count and identify particles using impactors and optical microscopy (traditional manual method)	Hirst [114]
BAA500	Robotic versions of the manual method	Oteros et al. [119]
Rapid E	Flow cytometry coupled to fluorescence	Sauliene et al. [120]
SwisensPoleno	Digital holography	Sauvegeat et al. [121]
SwisensPoleno	Digital holography coupled to fluorescence	Erb et al. [127]

According to the World Health Organization's database, air pollution alone is responsible for 3.7 to 4.2 million deaths each year. There is a significant connection between asthma development and exposure to traffic-related pollutants such as black carbon, NO_2, and fine PM. Epidemiologic studies have demonstrated an increase in hospital admissions for asthma [60] whereas a significant number of premature deaths, cardiovascular, and respiratory disorders have been attributed to smoke particles emitted from megafires [61]. Particularly, PM from urban areas and wildfires has been linked to increased hospital and emergency room visits for asthma, chronic obstructive pulmonary disease, and respiratory infections. Beyond their effects on the lungs, these pollutants have neurotoxic effects, which damage cognitive functions, learning, and brain development. The sources of primary biogenic aerosols and their connection to respiratory allergic diseases are discussed in Section 1.3.

The epithelial barrier theory explains the increased cases of non-communicable diseases due to exposure to epithelial barrier-damaging compounds and subsequent pathological events such as epithelial cell death and inflammation (epithelitis), microbial dysbiosis, opportunistic pathogen colonization, immune responses to environmental substances and microbiota, as well as defective epithelial barrier healing. Therefore, epithelial barrier damage causes a disturbed homeostasis in the respiratory system that drives the pathomechanisms of allergic rhinitis and asthma.

Air pollutants, pollen, and fungal spores cause respiratory epithelial barrier damage. PM2.5 and PM10 cause apoptosis, necrosis, autophagy, and pyroptosis in epithelial cells. In addition, they cause oxidative stress, MAPK and NFκB activation, and inflammation mediated by IL-1β, IL-6, IL-8, IL-12, and IL-18 [132]. This results in airway barrier dysfunction, breaking of tolerance to inhalants, and sensitization to allergens. Diesel exhaust particles, volatile organic compounds, and ozone are also major respiratory epithelial barrier disruptors. They cause epithelial alarmin releases, such as IL-33, and cause a type 2 immune response. Pollen and other allergens, such as house dust mites, cause respiratory epithelial barrier damage through their protease activity [133]. For example, the proteases found in *Chenopodium album*, *Plantago lanceolata*, and *Eucalyptus globulus* pollen cleave the tight junction complexes via disruption of occludin and zonula occludens-1 (ZO-1) proteins [134]. Some pollen types, such as grass pollen, also cause chemokine and cytokine release [135].

Exposure to all the above-mentioned epithelial barrier-damaging compounds may have synergistic effects. Air pollutants in urban locations co-occur with airborne allergens. This causes transcriptomic, physicochemical, and surface changes in pollen. Altogether, it alters the biological functions of pollen, which may lead to an increase in their allergenic potential through pro-inflammatory properties [136]. With this perspective, other epithelial barrier-damaging substances may act as an adjuvant to pollen exposure and can cause or aggravate respiratory inflammation. This is particularly important in the context of respiratory health since impairment of epithelial barrier integrity and inflammation can result in a vicious cycle, including microbial dysbiosis and defective epithelial barrier healing (Figure 6).

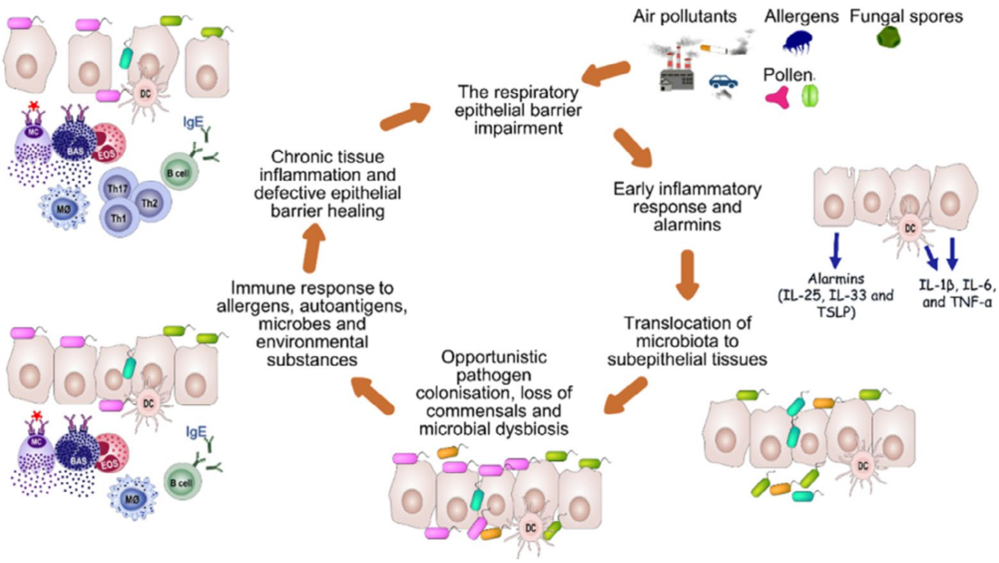

FIGURE 6 | Respiratory epithelial barrier and aerosols. Various aerosols cause epithelial barrier damage and inflammation of the respiratory mucosa. Upon exposure to pollen, fungal spores, and air pollutants such as particulate matter, diesel exhaust particles, ozone, and volatile organic compounds, cell death, epithelial barrier damage, and inflammation occur in the respiratory system. This leads to a vicious cycle consisting of microbial dysbiosis, opportunistic pathogen colonization, and defective barrier healing.

5 | Climate Change Impacts on the Environment and Human Health

5.1 | Climate Change Effects on Plants and Fungi

Climate change has been dramatically affecting organisms, species, and ecosystems. While a large number of factors are influenced by climate change, their direct (and indirect) impacts on exacerbations or manifestations of allergic symptoms in sensitized individuals are not yet clear. Some of the most pronounced effects are:

- Increased pollution, including that of the air, water, and soils, at various spatial and temporal scales.
- (Extreme) weather events, including droughts, heat waves, extreme rainfalls, changes in precipitation regimes, wind gusts, thunderstorms, hurricanes, and any other kind of extreme micro- or macro-meteorological events [137].
- Land use changes, land management, habitat fracturing, and ecosystem shifts to higher altitudes or latitudes.
- Enhanced plant growth, resulting from the combination of elevated greenhouse gases (i.e., carbon dioxide) and higher air temperatures.
- Increased pollen production of many plant species, as expressed by increased pollen or flower production per inflorescence or by a higher number of inflorescences per plant and, consequently, per species, population, and ecosystem (e.g., [138]).
- Earlier onset and sometimes longer duration of the pollen season, as influenced by meteorological and climatic factors, per site, among sites, and among years, and for a number of pollen types (i.e., [139, 140]).
- Increased pollen allergenicity as a result of air pollutants (e.g., higher ozone and/or nitrogen dioxide) and air temperature, but also in inverse correlation to pollen production per plant, after taking into account available resources as a limiting factor.
- Effects on plant microbiome (plant, leaf, inflorescence, and pollen microbiome), as determined by a wide variety of environmental factors, including the per se biodiversity and its temporal variability.

Air pollution and climate change not only affect plant growth, pollen and flower production, and the duration of the pollen season but can also result in more direct health impacts by increasing the amount of allergenic proteins in pollen [141, 142]. According to a study [141], elevated levels of certain pollutants, such as nitrogen dioxide (NO_2), increase overall pollen allergenicity, which further increases the relevant allergy risk for sensitized individuals. Studies have shown that elevated pollutants change the transcriptome of ragweed pollen; therefore, under global change scenarios, the allergenic potential of pollen is also expected to change [142, 143]. Epidemiological studies have demonstrated that urbanization, high levels of vehicle emissions, and a westernized lifestyle are correlated with an increase in the frequency of pollen-induced respiratory allergy, more prominent in urban populations than in rural areas [144]. Having said the above, climate change will indirectly influence respiratory allergies in humans, with possible impacts on the magnitude, timing, and quality of the disease.

5.2 | From Bioaerosol Exposure to Increased Risk of Co- and Multi-Exposure

Changing climate and an increasing trend of urbanization bring about more complex aerosol exposures with potential adverse health effects. However, whereas the interaction of pollen grains, microbes, or chemical air pollutants with cells and tissues of the respiratory tract may in many cases be rather well studied, little is known about real-life frequencies, health impacts, and pathomechanisms of combined exposures. For instance, earlier-shifted spring pollen seasons [145–148] prolong the temporal overlap of pollen and virus seasons in temperate climates, with the possible consequence of increased transmission of some viral pathogens in humans [149–152]. Likewise, aeroallergen co- and multi-exposures could become more relevant with shifting seasons.

Recently, a study has demonstrated the frequent co-occurrence of grass pollen grains with fungal spores of *Cladosporium* and *Alternaria* [153], which are both aeroallergens themselves and could cause problems in multi-sensitized allergic individuals. But not only do allergen particles from different sources co-occur in the air, pollen and microbes may even be physically associated with each other, which was demonstrated in various publications on pollen-specific, bacterial, and fungal microbiomes [154–157]. *Bacillus cereus* and *Bacillus subtilis*, gram-positive bacteria isolated from grass pollen samples, were shown to induce maturation and pro-inflammatory cytokine production of dendritic cells (DCs) from grass pollen-allergic donors, and $CD4^+$ T cells exposed to these bacteria in combination with grass pollen allergen-pulsed, autologous DCs underwent enhanced Th1, Th2, and Th17 differentiation as compared to T cells primed by allergen-pulsed DCs in the absence of the bacteria [157]. This suggests that pollen-associated microbes provide signals that activate pattern recognition receptors on host immune cells, favoring adoptive immune responses. Whether co-exposure to airborne fungi or bacteria indeed favors allergic sensitization to grass pollen remains to be studied.

Both fungal spores and grass pollen grains have been implied as causative agents in thunderstorm asthma [158–164], the phenomenon of sudden increases in respiratory emergencies (and sometimes even fatalities) associated with major thunderstorm events [159]. Atmospheric conditions during thunderstorms, such as high relative humidity, strong up- and downdrifts of wind, and high voltage potentials have been suggested to favor the rupture of pollen grains, resulting in high concentrations of airborne sub-pollen particles [165], which are presumed to be derived from starch granules and may carry allergenic proteins as well as bacterial endotoxins [165]. Sub-pollen particles have been isolated from different pollen types, such as birch, grass, and ragweed, in controlled laboratory experiments mimicking thunderstorm [166] and ice nucleating conditions [167, 168]. According to the current paradigm, inhalation of such particles may lead to their deposition in the lower bronchi, where they can trigger asthma in susceptible individuals. It has to be mentioned that despite the high number of reviews and position papers published on the topic of thunderstorm asthma (e.g., [169, 170]), the pathophysiological and environmental factors involved are still controversial, and more original—epidemiological as well as preclinical—studies are needed to clarify the issue. Air pollutants like ozone could play a role as anthropogenic co-factors as well [171], but their exact role during thunderstorm asthma events also needs further clarification.

Another type of bioaerosol interaction that deserves to be mentioned with respect to its potential adverse health effects is the modification of pollen grains and their major allergens by gaseous air pollutants. Nitric oxides (NOx), and specifically NO_2, have been shown to interact with the major allergen of birch pollen, Bet v 1, under experimental conditions and induce its nitration [172, 173]. This renders Bet v 1 more prone to being presented by dendritic cells and enhances its antigenic potential [174]. The modification of pollen allergens by reactive intermediates of air pollutants, such as NOx and ozone, can also increase their capacity to activate toll-like receptors (TLRs), as previously suggested for the grass pollen major allergen Phl p 5 [175]. Moreover, nitrated pollen allergens may oligomerize [176], which could increase their IgE binding capacity. Other studies have demonstrated that the exposure of ragweed plants to gaseous pollutants, such as NO_2 and O_3, during their growth leads to modifications of the protein and lipid content of their pollen grains [142, 143, 177], highlighting the importance of indirect effects of air pollution on pollen allergenicity. Pollen grains from ragweed plants grown under elevated CO_2 levels in climate chamber experiments were also shown to exert enhanced immune stimulatory capacity in vitro and in vivo [136], suggesting that climate change could indirectly increase the allergy risk of humans via an indirect effect on allergenic plants.

6 | Conclusion and Recommendations

Addressing aerosol-related respiratory medical conditions requires a multidisciplinary approach involving atmospheric scientists, medical professionals, policymakers, and industry stakeholders. Key measures include emission reduction, industrial pollution control, and improved understanding of aerosol transport and climate effects. A crucial step is fostering collaboration between the atmospheric and medical communities to refine aerosol measurement parameters tailored to healthcare needs, ensuring accuracy, uncertainty assessment, and spatial–temporal resolution.

Aerosols, particularly PM2.5, PM10, together with ozone and VOCs, are significant triggers for respiratory allergies and asthma. To mitigate these impacts, research priorities include:

- Health impact assessment: Investigating the composition, sources, and health effects of aerosols, particularly their role in asthma exacerbation.
- Advanced monitoring systems: Developing synergies among real-time air quality sensors, satellite observations, and predictive models for aerosol distribution.
- Source identification and control: Differentiating between natural and anthropogenic aerosol sources to guide targeted emission reduction efforts.
- Spatiotemporal variability analysis: Examining global aerosol fluctuations influenced by meteorological conditions, human activity, and seasonal changes.

7 | Recommendations for Future Implementation

Future implementation efforts should focus on integrating atmospheric and medical sciences through interdisciplinary research initiatives that align aerosol measurement standards with medical requirements and the development of comprehensive health-based air quality indices, incorporating aerosol composition and exposure thresholds. Advancements in monitoring technologies are also essential, including the expansion of low-cost sensors with increased accuracy for localized air quality assessments, improvements in satellite-based aerosol (especially toward surface-based PM pollution), and for early detection of pollution events affecting respiratory health. Policy and public health strategies could consider enforcing stricter regulations on industrial emissions and vehicular pollution, enhancing public awareness campaigns about the health risks of aerosol exposure, and developing region-specific action plans addressing seasonal and climatic variations in pollution levels. Additionally, data-driven decision-making should be prioritized by fostering open-access databases that link aerosol levels with respiratory health outcomes and strengthening predictive modeling for proactive air quality management and emergency response planning. By integrating such strategies, the impact of aerosols on respiratory health management can be improved, with the main aim of reducing the burden of asthma and related conditions.

Author Contributions

S.K. conception and article supervising. I.F., S.N., I.P.R., S.S., N.K., A.Mo. paper section 1. A.G., K.P., M.C.C., A.Ma. paper section 2. F.T., B.Cr., B.Cl. sections 3.1 and 3.2. Y.P., C.A.A. section 4. A.D., S.G. section 5. M.C.B. clinical review.

Acknowledgments

S.K., and I.R., S.S., I.F., A.M. and N.K. would like to acknowledge HARMONIA (International Network for Harmonization of Atmospheric Aerosol Retrievals from Ground-Based Photometers; grant no. CA21119), supported by COST (European Cooperation in Science and Technology). Stavros Solomos acknowledges support by the Hellenic Foundation for Research and Innovation project Mineralogy of Dust Emissions and Impacts on Environment and Health (MegDeth—HFRI no. 703). Antonis Gkikas acknowledges support by the Hellenic Foundation for Research and Innovation (H.F.R.I.) under the “2nd Call for H.F.R.I. Research Projects to support Post-Doctoral Researchers” (Project Number: 544). Stelios Kazadzis would like to acknowledge the Aerosols, Clouds, and Trace Gases Research Infrastructure (ACTRIS) Switzerland project supported by the Swiss State Secretariat for Education, Research, and Innovation.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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