Clinical Commentary Review

The Effect of Climate Change on Allergen and Irritant Exposure

Sunghyub Kim, DO[a], Athanasios Damialis, PhD[b], Athanasios Charalampopoulos, PhD[b], Dayne H. Voelker, MD[c], and Andrew C. Rorie, MD[a] *Omaha, Neb; Thessaloniki, Greece; and Rochester, Minn*

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1. Describe climate change-driven changes of pollen and fungal spores.
2. Explain direct effects of climate change on human health.
3. Understand limitations of air sampling equipment.

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As the effects of anthropogenic climate change have become more apparent, the influences of climate and extreme weather events on health have continued to gain attention. The fact Earth has warmed over the past century is indisputable and the rate of warming is more alarming. As a result of anthropogenic climate change, an alteration in the air mixture has occurred over time. These changes have increased human exposures to respiratory irritants such as ground-level ozone, volatile organic compounds, nitrogen dioxide, sulfur dioxide, carbon monoxide, and polycyclic aromatic hydrocarbons. A significant amount of research has investigated the effects of climate change on aeroallergens, which has shown that elevated temperatures and increased carbon dioxide levels have produced prolonged and more robust pollen seasons for most taxa studied. In addition, it appears possible that exposure of some plants to air pollution may result in more allergenic pollen. Increased human exposures to these respiratory irritants and aeroallergens appears to disproportionality effect vulnerable populations throughout the world. It is essential to understand that climate change is more than an environmental inconvenience and realize the effects to human health are directly related and conceivably immeasurable. It is vital to conduct additional research related to climate change and health that is collaborative, multisectoral, and transdisciplinary. There should be a focus on risk reduction, mitigation, and preparedness for climate change and extreme weather events for all populations around the globe. © 2024 American Academy of Allergy, Asthma & Immunology (J Allergy Clin Immunol Pract 2025;13:266-73)

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Earth's climate has been shifting throughout history, but these changes have accelerated owing to human activities, most notably

[a]Department of Medicine, Division of Allergy and Immunology, University of Nebraska Medical Center, Omaha, Neb
[b]Department of Ecology, School of Biology, Faculty of Sciences, Aristotle University of Thessaloniki, Thessaloniki, Greece
[c]Division of Allergic Diseases, Mayo Clinic, Rochester, Minn
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Corresponding author: Andrew C. Rorie, MD, [a]Department of Medicine, Division of Allergy and Immunology, University of Nebraska Medical Center, 985990 Nebraska Medical Center, Omaha, NE, 68198-5990. E-mail: arorie@unmc.edu.
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Abbreviations used
CDC- U.S. Centers for Disease Control and Prevention
IPCC- Intergovernmental Panel on Climate Change
NAAQS- National Ambient Air Quality Standards
PM- Particulate matter
VOCs- Volatile organic compounds

the burning of fossil fuels, particularly since the onset of the industrial era. This has created a harmful cycle in which greenhouse gases and air pollutants, emitted from industries, transportation, construction, energy production, and agriculture, contribute to global warming.[1] As a result, the Earth has warmed by approximately 1.1°C since the late 1800s.[2] The past decade (2011−2020) was the hottest ever recorded, with surface temperatures continuing to break records year after year.[3,4] The rising temperatures lead to more frequent heat inversions, trapping pollutants like nitrogen oxides and volatile organic compounds (VOCs). When these interact with ultraviolet light, they generate ozone. The downstream effects of warmer climate also increases the likelihood of wildfires, contributing to higher levels of fine particulate matter with an aerodynamic diameter of 2.5 micrometers or smaller ($PM_{2.5}$), exacerbation of drought conditions, and increased dust and $PM_{2.5-10}$ levels.[5-8]

Although many consider the interplay of anthropogenic climate change and health a 21st century−born concern, it is not. The Swedish scientist Svante Arrhenius raised concerns as far back as 1896 that human activity could increase carbon dioxide (CO_2) and markedly warm the atmosphere.[9] It was not until 1988, however, that the Intergovernmental Panel on Climate Change (IPCC) was commissioned, which has proven to be critical for research, modeling, disseminating information, and better understanding how to address climate change and initiate mitigation measures. The effects of climate change on health are wide-reaching and complex, examples of downstream effects include rising temperatures affecting the spread and transmission of vector-borne disease, increasing short-term mortality due to heat stroke, potential food shortage and malnutrition, population displacement due to oceanic thermal expansion, unreliable access to clean water, and increases in respiratory and allergic diseases.[2,10,11] More specifically, greenhouse gases and air pollutants, directly damage the respiratory tract, further exacerbating health risks.[12] In addition, warmer temperatures have been linked to earlier and more robust pollination seasons, resulting in heightened and altered degree of exposure to aeroallergens. The purpose of this review is to highlight evidence describing the effect of anthropogenic climate change on aeroallergen and irritant exposures.

ALTERATIONS OF THE AIR MIXTURE

Climate change and air pollution are interconnected, and climate change has an important impact on air pollutants and air quality. Weather and climate have significant roles in determining patterns of air quality. Furthermore, air quality has significant impact on climate. Air pollution emission, transport, dispersion, chemical transformation, and deposition can be influenced by meteorological variables including temperature, humidity, wind speed/direction, and mixing height.[13] Climate change has been shown to affect air quality, and predictions have revealed that climate change will continue to significantly impact air quality well into the future.[13-15] Air quality may be affected by climate change through several factors including changing atmospheric ventilation and dilution, altered precipitation and modified atmospheric chemistry. The 2 major impacts of climate change on air quality are degrading the removal processes (precipitation and dispersion) and amplifying atmospheric chemistry.[13,16]

Climate change has been shown to influence both particulate air pollutants and gaseous air pollutants.[17] Particulate air pollutants can be of natural origin or generated by human activities. Motor vehicle exhaust is an important source of particulate air pollutants. Other significant anthropogenic sources of particulate air pollutants include industrial plants and power stations, heating and air conditioning systems, and agriculture.[11,17,18] Natural sources of particulate air pollutants include wildfires and dust storms.[13] Particulate matter is characterized based on aerodynamic diameter including PM_{10}, $PM_{10-2.5}$, and $PM_{2.5}$.[17] $PM_{2.5}$ (particles with a diameter < 2.5 μm) may originate from anthropogenic sources including exhaust and road dust as well as natural causes. Climate change associated extreme weather events such as heatwaves, drought, severe storms, and wildfires can intensify air pollution levels.[19] Climate change can contribute to an increase in the number and severity of wildfires, increased frequency of dust storms and dust particle transport, both of which emit large amounts of $PM_{2.5}$.[13,19,20] Increasing evidence links both short- and long-term exposure of $PM_{2.5}$ to acute cardiovascular events, heightened mortality, and reduced life expectancy. Whereas $PM_{2.5}$ and PM_{10} can be inhaled and deposited in the respiratory tract, $PM_{2.5}$ penetrates the distal airways and PM_{10} tends to settle in the upper airways. These particles can cause tissue damage and lung inflammation upon deposition. In particular, $PM_{2.5}$ exposure is associated with increased risks of myocardial infarction, stroke, arrhythmias, heart failure exacerbations, and chronic lung disease exacerbations.[21-24]

Gaseous air pollutants include ground level ozone (O_3), volatile organic compounds, nitrogen dioxide (NO_2), sulfur dioxide, carbon monoxide, and polycyclic aromatic hydrocarbons that are significantly increased by anthropogenic sources.[17] Ground level O_3 forms from the chemical reactions between NO_2 and VOCs in the presence of sunlight and heat. The rate of ground level O_3 formation is temperature-dependent.[13,19] Increases in summer temperature by 1°C corresponds with a 2.90 ppb increase in O_3 concentration.[25] Predictive modeling suggests that urban and regional O_3 concentrations in the United States may increase approximately 5% to 10% between now and 2050 as a result of climate change despite holding anthropogenic emissions and global background concentrations constant.[26,27]

Natural VOCs emissions are also increased by climate change secondary to altered plant metabolism and increased temperature, which further affects O_3 concentration.[13,28] Drier and hotter conditions associated with climate change may lead to amplified O_3 concentration by increasing the rates of photochemical production.[29]

BIOGENIC PARTICLES AND CLIMATE CHANGE

Aerobiologists have been studying airborne bioparticles with allergenic properties for decades. Aeroallergens are proteins dispersed through the air with potential to induce allergic conditions such as rhinitis, conjunctivitis, and asthma. Undoubtedly, extensive research has been conducted on aeroallergens with a

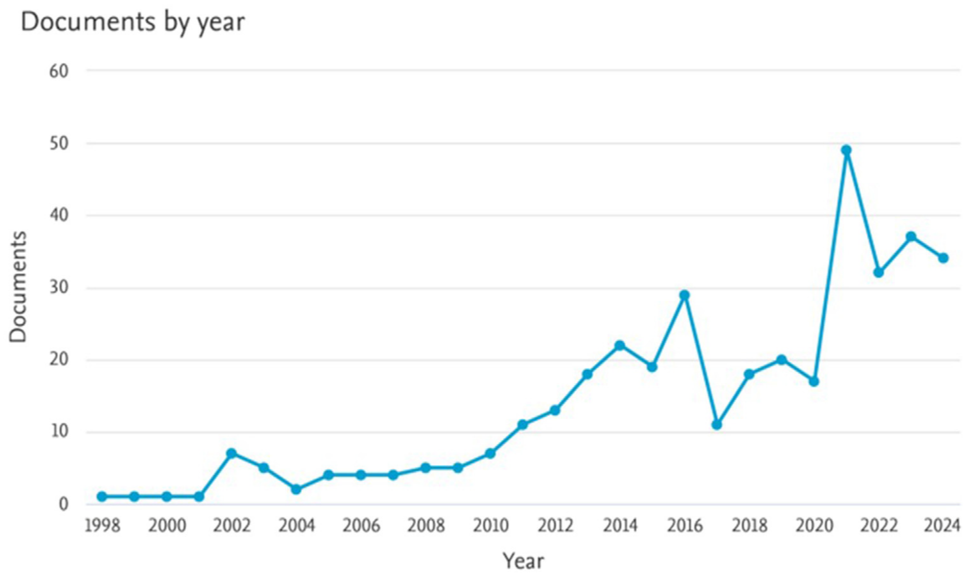

FIGURE 1. Bibliometric search results extracted from the SCOPUS database for the terms [*"climate change" and (pollen* or fung*) and allerg**)] (only English papers) with the number of articles published in the scientific literature per year.

primary emphasis on pollen grains. Over the last 3 years (2022—2024), 103 scientific papers have been published as original articles, according to the largest literature database SCOPUS (Figure 1).

Airborne pollens are not only relevant to human health but also have been applied as an indicator of climate change as stated by the IPCC.[30] A wide array of changing aeroallergen patterns has been observed with a focus primarily on pollen abundance and pollen season characteristics.[7,30-32] In order to provide explanations for observed changes or trends, the behavior of other aspects of plants' reproductive ecology that impact airborne pollen have been studied, including flowering phenology,[33,34] pollen production,[35-37] abundance/type of regional vegetation,[38] and land use changes.[39] In addition, for fungal spores, investigations to assess the ability of sporulation under differing environmental conditions have been conducted.[40] Some of this work has further implicated the role of croplands as fungal spore sources, but such studies are limited.[40]

In order to monitor potential long-term changes in abundance of aeroallergens (and biodiversity), several methodologies have been developed for air sampling. These include manual volumetric or impaction samplers to automatic real-time samplers.[41,42] Moreover, molecular methods have also been implemented to complement or enhance the previously mentioned approaches. However, universal methodology is lacking, posing challenges concerning data comparability and accurate interpretation of results. The gold-standard method for air sampling is Hirst-type samplers, typically positioned on a rooftop in an urban environment. Further research is needed in rural, semi-natural, and natural environments to identify potential trends and compare them with urban areas. Natural environments remain largely untouched by human activity, whereas semi-natural environments are modified by humans but retain significant natural features. The associated impact of aeroallergens on health has promoted the development of faster detecting devices, nearly real-time, in order to catch up to the demand that may allow for more robust data and higher temporal resolution.[43,44] However, many of these new technologies are quite expensive, which at the moment, limits access to some research groups.

Emerging and novel aeroallergens

As a consequence of human activities around the globe and climate change, several plants and other organisms have changed their distribution limits. Many plants have been established in new areas, mainly by seed dispersal or via artificial planting, allowing them to reproduce freely within their new habitats. As newcomers, their pollen can prove to be an emerging or a novel aeroallergen to the area, such as in the cases of *Ambrosia,*[45,46] *Ailanthus,*[47,48] *Broussonetia,*[49] *Cupressus arizonica,*[50] and *Cannabis*.[51] Pollen from several of the aforementioned species have been characterized as allergenic and introduced in various parts of the world. Targeted research and creation of easily accessed databases on these new or emerging aeroallergens are vital for timely detection and implementation of appropriate mitigation strategies.

Altered and more robust aeroallergens

Aeroallergens such as pollen grains and fungal spores have proven to be bioindicators of climate change. Pollen grains have been the center of interest and certain pollen taxa have been more robustly studied than others. Examples of more readily studied taxa include *Ambrosia* and Cupresssaceae in North America, *Betula* and Poaceae in central and north Europe, and *Olea* and *Quercus* in southern Europe. Studies have shown that aeroallergen expression can increase through differing stimuli such as increasing temperature,[52] pollutants,[52-54] specifically NO_2 for *Betula*[37] and CO_2 for *Ambrosia*.[55-57] In addition, other biological factors can promote aeroallergen expression, such as in the case of bacteria or fungi growth on pollen.[58]

In several cases, pollen abundance of *Carpinus*, *Corylus*, Cupressaceae, Pinaceae, *Quercus*, and Urticaceae in Greece[40,59];

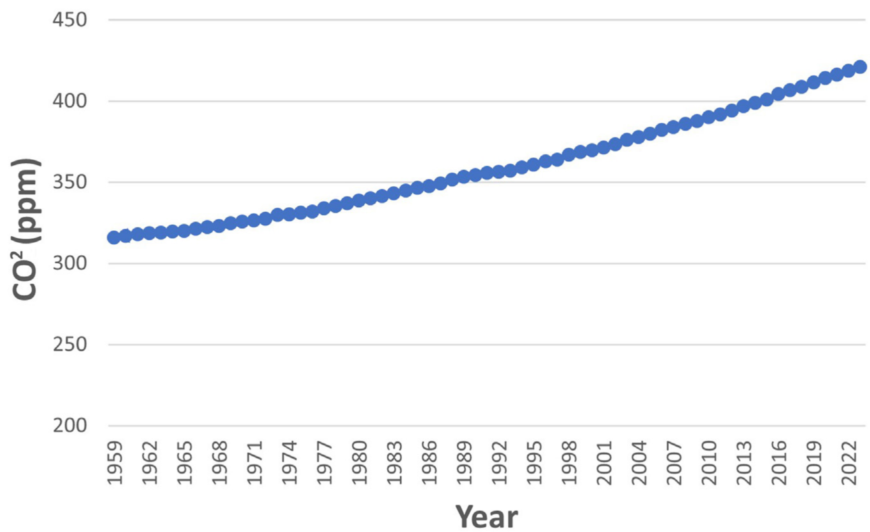

FIGURE 2. Trend of annual mean CO_2 (ppm) record from 1959 to 2023 at Mauna Loa Observatory, Hawaii.[90]

Alnus, *Corylus*, *Betula*, *Fraxinus*, *Quercus*, *Platanus*, Poaceae, and *Artemisia* in Benelux[60]; Cupressaceae/Taxaceae, *Ulmus*, *Populus*, *Salix*, *Ostrya*, *Quercus*, *Olea*, *Plantago*, Cannabaceae, and *Ambrosia* in Italy[61]; *Alnus*, *Quercus*, Poaceae, *Olea,* Poaceae, *Quercus*, Poaceae, and *Betula* in Spain[58,62,63]; and *Betula* and Poaceae in the United Kingdom[64] exhibited an increasing trend with rising CO_2 and temperature. On the contrary, significantly fewer pollen concentrations have been reported as decreasing over time, such as for *Populus* in Greece[40]; *Juniperus*, *Populus*, *Ulmus*, and *Morus* in New Mexico[65]; and similarly for the fungal taxa *Agrocybe*, *Botrytis*, *Cladosporium*, and *Nigrospora*[40] also in Greece.

Apart from changes in abundance of these bioparticles, their seasonality is also subject to variability due to climate change pressure.[7,32] The onset of pollen season occurs earlier in the majority of the pollen taxa studied, but end of the season remains marginally changed. This phenomenon has been observed for *Alnus*, *Betula,* and *Corylus* in Spain.[66] Also, Poaceae pollen season began earlier, although later end dates or no trends were found for herbaceous pollen types (ie, Poaceae and Urticaceae).[66] These results indicate a general increase in the duration of pollen seasons, which increases the potential pollen risk period for allergic sufferers.[6,67]

The neglected aeroallergens, fungal spores

Whereas the main focus of research on climate change and aeroallergens has centered on pollen grains, the effect of other bioparticles on health has been understudied. This is the case for fungal spores, which only a few studies have been conducted to date.[41,64,68,69] It is important to understand spore behavior under climate change scenarios because they may affect plants' physiology through host-microbe relationships and act synergistically to provoke allergic symptoms in humans.[70] Recently, Demain et al[71] reported that sporulation of fungi is likely to be amplified as CO_2 concentration increases with climate change, potentially contributing to the increasing prevalence and severity of asthma and other respiratory disorders. For fungal or arthropod allergen production, there are rational links to climatic change that could influence seasonality; however, unlike plant aeroallergens, clear indications of seasonal changes are lacking.[72] Finally, phytopathogenic microfungi of various vegetation types (common crops, ornamental plants, and weeds) can potentially be allergens, many of which have not yet been studied, although climate change may contribute to the expanding range of many plants and, consequently, their fungal pathogens.[73]

Another effect of climate change has been an increase in heavy precipitation and extreme weather events resulting in both inland and coastal flooding. These events may lead to significant indoor fungi growth, which can have a direct impact on human health. Research in this area has primarily focused on post-hurricane flooding and subsequent indoor fungi growth. These studies have reported increased fungal spore production and altered composition of indoor fungal species post-hurricane.[74-76]

CLIMATE CHANGE IMPACT ON HUMAN HEALTH

Ambient air pollutants pose significant health risks to individuals of all ages, regardless of preexisting respiratory disease. At high concentrations, these pollutants directly inflame airway epithelium and, even at lower concentrations, can provoke airway hyperresponsiveness and inflammation.[77,78] In a 2023 study, Bi and colleagues[79] analyzed 3.19 million asthma-related emergency department visits from 2005 to 2014 across the United States, finding positive associations between multiday exposure to fine and coarse PM, gaseous pollutants, and increased asthma emergency department visits. Their findings indicated that $PM_{2.5}$ had significant effects across all age groups, whereas O_3 was more impactful on adults, and pollutant effects were especially pronounced in children.[79] Patients with asthma, particularly the elderly, may be more vulnerable to diminished lung function and increased risk of hospital admissions due to exposure to $PM_{2.5}$, O_3, and NO_2.[80-82] Whereas numerous studies[81-84] have linked elevated pollutant levels to higher rates of hospital admissions and exacerbations of asthma and chronic obstructive pulmonary disease, the 2022 report by Wei and colleagues[85] suggests that even short-term exposure to $PM_{2.5}$, O_3, and NO_2 at concentrations below the National Ambient Air Quality Standards (NAAQS) is associated with an increased risk of hospitalization owing to asthma exacerbation.[85] In addition, there is growing evidence that early exposure to air pollutants, potentially even *in utero,* is linked to the development of asthma. A 2015 population-based birth cohort study assessed annual average concentrations of air pollutants, including NO_2, $PM_{2.5}$, PM_{10}, PM_{coarse}, and soot, at the birth addresses of participants.[86] The study demonstrated that elevated exposure to NO_2 and soot at the birth address is associated with an increased risk of asthma development by adolescents. The meta-analysis reported an adjusted odds ratio of 1.13 per 10 $\mu g/m^3$ of NO_2 (95% confidence interval 1.02−1.25) and a 1.29 per unit increase in $PM_{2.5}$ absorbance, which is an indicator of soot (95% confidence interval 1.00−1.66).[86] Furthermore, exposures to ambient pollutants (PM_1, $PM_{2.5}$, PM_{10}) during pregnancy and the first year of life have showed a significant association between early-life exposure to PM, particularly during gestation, and an elevated risk of childhood asthma and wheezing.[87]

Whereas pollutant exposure significantly impacts asthma, it is also strongly linked to respiratory infections. In a 2018 study, Horne and colleagues[88] examined 146,397 individuals on Utah's Wasatch Front diagnosed with acute lower respiratory infections and discovered that higher $PM_{2.5}$ levels were associated with increased odds of acute lower respiratory infection−related health care encounters, particularly among children aged 0 to 2 years, with an odds ratio of 1.15 per 10 $\mu g/m^3$ increase in $PM_{2.5}$. The study also reported a surge in cases of respiratory syncytial virus and influenza following elevated $PM_{2.5}$ levels, with more pronounced effects among those who were overweight or smokers.[88] Similarly, Anderson and colleagues[89] explored the relationship between air pollution and pneumonia in a cohort of 325,367 participants from the ELAPSE project across 6 European countries. This showed that exposure to NO_2 and black carbon was associated with a 10% to 12% increase in mortality from pneumonia and influenza, although the hazard ratios suggested a trend toward statistical significance. The findings reveal that, even at relatively low concentrations, long-term exposure to air pollution is linked to higher mortality rates. This suggests that current air quality standards may not adequately protect public health and highlights the need for stricter regulations to reduce exposure to harmful pollutants.[89]

A significant area of concern is the impact of climate change on aeroallergens and patients with respiratory and allergic diseases. Elevated temperatures and increased CO_2 levels are expected to shift earlier and intensify pollination periods for certain plants, leading to increased production of highly allergenic pollen (Figure 2).[90] These changes, coupled with the pro-inflammatory effects of pollen-associated lipid mediators, are reshaping the trajectory of allergic diseases.[32,91] Shifts in plant habitat patterns have also been observed, with species gradually migrating poleward, northward to the Northern Hemisphere and southward to the Southern Hemisphere.[92,93] Climate change triggers not only the migration of plants but also the displacement of human populations in affected regions. Without substantial efforts to mitigate climate change, the number of "climate change migrants" is expected to reach 1 billion by 2050.[94,95] Population migration can be a consequence of extreme weather events, such as major storms and hurricanes, that cause economic devastation, leading to unemployment, poor living conditions, injuries, and severe damage to infrastructure and health care facilities.[96,97] This forced displacement is linked to a higher incidence of acute respiratory infections, tuberculosis, and sleep-related disorders. Moreover, the shift from rural to urban areas has been associated with an increase in allergic diseases, including asthma.[97-99]

There is also an interplay between individual components of the air mixture and health outcomes. For example, PM and diesel exhaust can exacerbate allergic responses by increasing mucosal permeability, disrupting allergen clearance, and facilitating allergen transport, with effects mediated by reactive oxygen species. Higher air pollution levels, combined with ambient aeroallergens, are associated with increased asthma hospitalizations, highlighting the potential benefit of reducing air pollution to mitigate allergic asthma exacerbations.[100,101] How and which components of the air pollutant mixture may augment allergic airway responses warrant further study.

WHAT HAPPENS NEXT AND WHERE DO WE GO FROM HERE?

It is critical to appreciate that climate change is not simply an environmental problem but the potential effects to health are interrelated and perhaps immeasurable. Climate change will continue to affect organisms, plants and fungi, and consequently aeroallergens.[102] This could mean (1) intensification of the allergenic capacity to induce allergic symptoms via increased allergenicity or quantity of pollen/spores produced, (2) changes in seasonality or duration of specific aeroallergens, and/or (3) altering the synergistic effect with other biological or chemical factors.[31] Based on the aforementioned data reviewed, established international literature, and research, it is essential to continue monitoring climate driven changes of aeroallergens. The U.S. Centers for Disease Control and Prevention (CDC) have suggested a One Health[103] method, which is described as a "collaborative, multisectoral and transdisciplinary approach—working at the local, regional, national and global level—with the goal of achieving optimal health outcomes recognizing the interconnection between people, animals, plants, and their shared environments." Through this perspective of the One Health approach, research, mitigation, and adaptation should focus on the following pillars:

- Reassess the design and management of urban green spaces to incorporate and maintain drought-resistant flora that possess minimal allergic potential.
- More robustly study the effect of various environmental influences (eg, climatological, pollution, land use) on aeroallergens.
- Conduct considerably more research on how climate change effects vulnerable populations and effective mitigation strategies.
- Develop new or advance the existing air sampling technologies; enabling results to be more accurate, robust, and comparable among different regions.
- Development of early warning systems for extreme weather events.
- Conduct additional research on indoor air quality with regard to aeroallergens.
- Promote collaboration among scientific experts (eg, biologists, agronomists, public health experts, medical doctors) and local governmental agencies.

- Patients can protect their health from climate change by staying informed, minimizing exposure to pollutants and allergens, adopting preventive health measures, engaging in community initiatives, and working with health care providers to manage risks and adaptation effectively.
- Physicians play a vital role in addressing the health impacts of climate change by educating and advocating for patients, conducting and supporting research, engaging in public health and policy initiatives, and collaborating globally to promote prevention, preparedness, adaptation, and equitable health strategies.

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