Impact of climate change on aerobiology, rhinitis, and allergen immunotherapy: Work Group Report from the Aerobiology, Rhinitis, Rhinosinusitis & Ocular Allergy, and Immunotherapy, Allergen Standardization & Allergy Diagnostics Committees of the American Academy of Allergy, Asthma & Immunology

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Climate change is imposing a profound effect on health conditions triggered by environmental exposures. Climate change has affected aeroallergens in numerous ways, including: (1) changes in the vegetation microbiome distribution, (2) increases in C_4 grasses globally, (3) increased occurrence of acute weather events, (4) increases in ambient temperature that amplify fungal spore concentration and pollen season duration, and (5) increased allergenicity of pollen and fungi due to exposure to higher levels of carbon dioxide, ozone, and diesel exhaust particles. In addition, greenhouse gases and air pollutants disrupt the epithelial barrier, trigger eosinophilic inflammation, and serve as adjuvants that stimulate IgE-mediated responses. All of these factors have influenced the prevalence and morbidity of allergic rhinitis, nonallergic rhinitis, and chronic rhinosinusitis. Data regarding changes in aeroallergen exposures due to climate change are lacking, and longitudinal sensitization data are rarely available. Allergists need to adapt diagnostic and treatment strategies to limit aeroallergen and air pollutant exposure and facilitate desensitization. Steps needed to address these challenges include: (1) expanding local measurement of pollen and fungal spores, (2) increasing the intensity of allergen avoidance measures, (3) addressing supply chain issues, and (4) promoting collaboration between allergists, insurance companies, aeroallergen manufacturers, and regulatory agencies. (J Allergy Clin Immunol 2025;155:1767-82.)

Key words: *Climate change, aerobiology, rhinitis, sinusitis, immunotherapy*

Abbreviations used

AR: Allergic rhinitis
C_3 grass: Three-atom sugar chloroplast product
C_4 grass: Four-atom sugar chloroplast product
CO_2: Carbon dioxide
CRS: Chronic rhinosinusitis
HDM: House dust mite
NAR: Nonallergic rhinitis
O_3: Ozone
$PM_{2.5}$: Particulate matter with diameter of less than 2.5 μm
SCIT: Subcutaneous allergen immunotherapy
SLIT: Sublingual allergen immunotherapy
SO_2: Sulfur dioxide
SPT: Skin prick test

EXECUTIVE SUMMARY

IMPACT OF CLIMATE CHANGE ON AEROBIOLOGY

Meteorologic parameters are affected by climate change and global warming phenomena occurring on earth.[1] The major source of pollution and greenhouse gases leading to global climate change is combustion of fossil fuels, including oil, coal, and natural gases. As a result of climate change, there have been numerous reports around the globe of increased pollen production, increased duration of pollen seasons, augmented pollen allergenicity, and changes in allergenic plant distribution.[2]

Effects of climate change on plant distribution

Most studies regarding the impact of climate change on plant distribution come from the Americas and Europe. Plant geographic distributions in North America respond to climate change by shifting poleward and up in elevation.[3,4] This includes many taxa that produce allergenic pollen; however, results are species specific, and many processes and time scales remain unquantified. Short ragweed *(Ambrosia artemisiifolia)* is expected to shift poleward in response to climate change.[5] Process-based modeling for climate change has predicted a 66% increased distribution of ragweed throughout Europe in the coming decades.[6] In the central United States, climate change-driven expansion of *Juniperus* woodlands is expected to result in increases in both seasonal pollen index and peak pollen concentration.[7-9]

Effects of climate change on pollen season duration

Numerous reports have indicated that pollen seasons are lengthening, driven by prolonged growing seasons, earlier last spring frost, and later first fall frost.[10,11] Warmer temperatures associated with climate change will continue to cause an earlier onset of spring pollen seasons in temperate ecosystems leading to increased pollen exposures.[12-14] Several studies in North America using long-term measurements of airborne pollen concentrations have generally found advances in seasonal onset and increases in duration.[15-18] In more water-limited ecosystems, including portions of the western United States, precipitation can play a larger role in plant reproductive onset, suggesting that plants in arid ecosystems will have weaker or more idiosyncratic responses to further warming.[19,20] The effect of elevated carbon dioxide (CO_2) concentrations can also result in earlier reproductive onset.[21-25]

Effects of increased temperature on pollen and fungal spore production

The optimal temperature at which plants grow and develop varies among species; therefore, temperature changes could result in increases/decreases in reproductive output depending on the species.[26] Because of global warming, the permanent ice covers on earth are melting, and more of the earth's surface is being occupied by plants and fungi. The type of land cover may also influence the abundance and diversity of fungal species and their airborne spores.[27] It is expected that fungal spore composition will change as a result of local environmental variables, atmospheric transport, and land management practices that can be attributed to climate change. Increased temperatures are also likely to cause increased mycotoxin production.[28]

Effects of increased CO_2 and ozone on aeroallergens

Increasing CO_2 concentration intensifies the efficiency of photosynthesis and the amount of energy available for plants, which may result in increased pollen production.[29] Studies have generally established higher pollen production in elevated CO_2 conditions along existing CO_2 gradients (eg, urban to rural).[30-39] A study performed in Spain compared *Cupressus arizonica* pollen collected from high-pollution areas (next to a busy highway near industrial areas) versus low-pollution areas (in a garden far from highways or industrial areas) and reported altered allergenicity. The pollen grown in highly polluted areas resulted in significantly larger dermal reactivity by skin prick testing (SPT) and 5 times more allergenic potency as determined by RAST (radioallergosorbent) inhibition.[40] In Germany, birch tree pollen derived from trees grown in areas with a higher ozone (O_3) level had a higher content of the major allergen Bet v 1 and elicited an increased skin prick reaction compared to trees grown in areas of lower ambient O_3 levels.[41] Because elevated CO_2 concentrations have been shown to increase plant biomass and carbon-to-nitrogen ratio, climate change is likely associated with an increase in fungal spore production and fungal allergens.[42,43]

Effects of expansion of Hadley cells on grass pollen

Hadley cells represent atmospheric circulation patterns near the 30° parallel across the planet and affect regional climate patterns in tropical areas. Climate change has led to the expansion of Hadley cells, which favors the invasion and survival of species more suitable to withstand droughts, extreme temperatures and higher atmospheric CO_2 levels, such as 4-atom sugar chloroplast product (C_4) plants. Greater increases in CO_2, which is the main source necessary for photosynthesis, can stimulate plant growth and increase pollen production to a greater degree in C_4 plants.[44,45] The subfamily Pooideae (including northern pasture grasses) are 3-atom sugar chloroplast product (C_3) grasses, which thrive in areas with lower temperatures and increased water supply. Chloridoideae (including Bermuda grass) and Panicoideae (including Bahia grass) are C_4 grasses, which grow in warmer environments. It is expected that the relative abundance of C_4 grasses will increase in the Americas by more than 10%, while C_3 grasses are projected to decline except for the northwestern Great Plains of the United States and Canada, and north-central Argentina.[46-50]

Effects of climate change on fungal spores

Changes in fungal spore distribution are mostly supported by indirect evidence or restricted to indoor mold growth associated with catastrophic flooding events.[51] Climate change increases heavy rainfall episodes and catastrophic flooding, leading to heavy microbial and fungi growth indoors. Urbanization is thought to alter airborne fungal spore levels because previously undisturbed land adjacent to urban areas is now being used for housing and industry.[52] Various meteorologic parameters, such as changes in barometric pressure, wind speed and direction, temperature, and rainfall, are also responsible for spore plumes or large increases in the levels of airborne spores over short periods.[53] The fungal genera and species that grow under normal and typical moisture conditions are different than those that originate because of excess moisture.[53] In addition to the potential effect of climate change and global warming on outdoor fungi, there is increasing concern about heavy and long-lasting indoor fungal growth after severe storms and catastrophic flooding. Global warming and climate change could therefore also indirectly be responsible for a change in the fungal species that grow indoors, which may result in new sensitization patterns.

IMPACT OF CLIMATE CHANGE ON RHINITIS

Multiple aspects of the climate change crisis have influenced the prevalence and morbidity of allergic rhinitis (AR), nonallergic rhinitis (NAR), and chronic rhinosinusitis (CRS). Increases in pollen and fungal spore levels, allergenicity, and distribution directly increase the prevalence and morbidity of AR. Notably, greenhouse gases and air pollutants contribute to sinonasal inflammation by a direct effect on epithelial barrier integrity and eosinophilic inflammation, as well as their roles as adjuvants that stimulate IgE-mediated responses. The impact of air pollutants is particularly relevant as a result of the proinflammatory interaction of particulates with increased aeroallergen exposure caused by climate change.

Effects of climate change and air pollutants on AR

Climate change, air pollution, and alterations in aerobiology patterns influence the development and morbidity of AR via interactions with the epithelial barrier, T_H2 immune responses, and epigenetics. Disruption of the epithelial barrier allows external factors to infiltrate downward, inducing immune responses and exacerbating inflammation.[54,55] Particulate matter with diameter of less than 2.5 μm ($PM_{2.5}$) produced by combustion of petroleum products and wood/wildfires induces nasal epithelial barrier disruption via oxidative stress, decreased expression of tight junction proteins, and increased release of proinflammatory cytokines.[56,57] Increased allergen delivery into subepithelial tissues subsequently contributes to the exacerbation of allergic inflammation. There is a need for additional studies evaluating how climate change and air pollution affect T_H2 responses and AR development.[58]

Effects of climate change and air pollutants on NAR

Combustion products, including $PM_{2.5}$, nitrogen oxides, sulfur dioxide, aromatic hydrocarbons, volatile chemicals, and O_3, as well as heat events, hurricanes, and thunderstorms from increasing CO_2, can worsen NAR.[59,60] Avoidance is a key element of treatment of NAR; N95 and KN95 masks can reduce exposure to excessive dry air from expanding deserts, elevated levels of $PM_{2.5}$, nitrogen oxides, and sulfur dioxide from pollution, mold spores from flooding, and smoke from burning fires.[61] Given that wearing N95 masks is a temporary and ultimately impractical long-term solution, it is imperative to implement strategic plans to reduce multipollutant emissions and air pollution.[62]

Effects of climate change and air pollutants on CRS

CRS involves sinus inflammation that lasts for 12 weeks or longer. Air pollution linked to climate change is associated with CRS, likely through an increased inflammatory response in the sinonasal mucosa.[63,64] Particulate matter, O_3, and nitrogen oxides augment T_H2 inflammatory responses.[65] In addition, exposure to O_3 and particulate matter can lead to upper airway inflammation via impaired phagocytosis by neutrophils and macrophages, poor mucociliary clearance, and generation of reactive oxygen species that deplete antioxidant defenses.[66,67] Studies using human sinonasal epithelial cells from CRS patients demonstrated that *in vitro* exposure to coarse particulate matter elicited disruption of intercellular tight junctions and reduced epithelial barrier function, which may be involved in CRS pathogenesis.[68]

IMPACT OF CLIMATE CHANGE ON ALLERGEN IMMUNOTHERAPY

Diagnostic testing for aeroallergen sensitization and climate change

Studies reporting patterns of SPT sensitization to aeroallergens have been published from many parts of the world for decades (see Table E1 in the Online Repository available at www.jacionline.org). Sensitization patterns in the same climatologic region vary according to the degree of urbanization, month of birth, and indoor and outdoor allergen exposures, among other factors. There are insufficient data in almost all parts of the world regarding changes in allergic sensitivity due to the lack of sequential testing in the same region under the same conditions (Table I). A northward expansion of southern pollens is anticipated, as is a reduction in exposure to dust mites and indoor fungi in some areas as a result of desertification, although the opposite could be true as a result of increased flooding events. It will be important to repeat regional sensitization profiles on the basis of climate changes to adjust aeroallergen panels for SPT and specific IgE. Overall, more research correlating SPT and *in vitro* IgE results with clinically relevant AR is needed. More advanced molecular techniques may prove useful in this regard.[69]

IMPACT OF CLIMATE CHANGE ON SUBLINGUAL ALLERGEN IMMUNOTHERAPY

For pre- and coseasonal sublingual allergen immunotherapy (SLIT), the number of weeks of treatment will likely increase, requiring earlier preseasonal dosing start dates, longer treatment courses, and higher treatment costs. Modeling studies indicate that the impact of climate change on pollen seasons, and thus the need for pollen allergen SLIT, will vary substantially across regions of the United States.[70] On the one hand, convenience-forward immunotherapy options like SLIT decrease travel and related vehicle emissions, and they may provide advantages during climate crises. On the other hand, given that much higher quantities of allergen are needed for production of SLIT, there may be an increased burden on supply chains for immunotherapy if more patients are receiving SLIT.

IMPACT OF CLIMATE CHANGE ON SUBCUTANEOUS ALLERGEN IMMUNOTHERAPY

For most plant species, and in most parts of the world, longitudinal studies examining local sensitization rates and resultant rhinitis symptoms have not been done. Extrapolation of plant distribution and/or pollen count data may be useful in situations where sensitization data are not available. For example, in the United States, several important species of C_4 grass that are still considered southern grasses, such as Johnson and Bermuda grass, both of which do not share homology with northern pasture (C_3) grasses, have been steadily expanding northward.[71] Inclusion of these grasses for testing and immunotherapy should be considered in most of the United States, except possibly the northern Midwest. The invasion and expansion of short ragweed in Europe may necessitate testing and immunotherapy against this pollen for most of the European continent within the next 20 to 40 years.[6] Changes in exposure to tree pollens are especially difficult to account for without local measurements.[72] Lack of standardized allergens for testing and immunotherapy, as well as variable sensitization to major versus minor allergens, further complicates the situation for tree pollens. In addition, given the probable increases in fungal exposure that are due to climate change, updated sensitization data for fungi and higher-quality fungal extracts are needed.

PROPOSALS TO HELP ALLERGISTS ADAPT TO CLIMATE CHANGE

Expand local measurement of pollen and fungal spores

Given the importance of outdoor allergen exposures, it is necessary to expand the activities of the National Allergy Bureau in providing local pollen and spore counts at regular intervals.[73] Diagnostic testing panels will need to be adjusted routinely to reflect local findings.

Increase intensity of allergen avoidance measures. Decreasing indoor humidity and improving indoor ventilation are building interventions that can reduce both fungal and house dust mite exposures.[74] N95 and KN95 masks may reduce exposures to air pollutants as well as heavy aeroallergen exposures.[61,62] High-efficiency particulate air (aka HEPA) filters can serve the dual purpose of reducing fungal and animal allergens, and they have beneficial effects on indoor and outdoor air pollution exposures.[75-79]

Address supply chain issues. Allergen extract supply chains for pollen are dependent on a steady source of raw materials from grasses, shrubs, trees, weeds, or cultivated plants.[80] Climate change will result in an increasing demand for extracts for diagnostics and treatment.[70,81-83] Inventory planning, as well as knowledge of phylogenetic cross-reactivity of various species of pollen, will be important for practicing allergists. As demand increases, current supply chain limitations need to be addressed to create a reliable, consistent supply of SCIT and SLIT.

Address regulatory challenges. Once raw material is obtained, it must be processed following Current Good Manufacturing Practices requirements and undergo several quality control checks, including assessment of protein content before release. Standardized extracts in the United States must also pass tests of potency mandated by the Food and Drug Administration. Adaption to climate change will require greater standardization and efficiency in these processes to quickly adjust the availability of therapies for rapid local changes in allergen exposures and sensitization patterns.

In conclusion, climate change has already had a significant global impact on pollen and fungal exposures and allergenicity. An overall increase in allergic sensitization is expected, although in most parts of the world, local aeroallergen measurements and longitudinal sensitization studies have not been done. Increased exposure and sensitization to allergens, as well as an increase in air pollutants, are highly likely to increase the global burden of rhinitis and chronic sinusitis. Allergists will need to adapt diagnostic and therapeutic strategies to limit exposure to aeroallergens and pollutants and facilitate desensitization. To successfully navigate these challenges, it will be necessary to expand local aeroallergen measurements, develop and

TABLE I. Changing sensitization rates to aeroallergens

Study location	Years	Allergen	Population studied	Findings
Northern Italy[129]	1989–2008	• *Ambrosia artemisiifolia* (short ragweed).	• Patients aged >14 years seeking care at allergy unit for respiratory symptoms for first time; ~1100 patients per year.	• Average seasonal pollen index of 4800 for *Ambrosia* pollen (high). • According to SPTs, sensitization rate to *Ambrosia* rose from 24% to 70% among patients sensitized to pollens. • Time lag between *Ambrosia* sensitization and clinical allergy is ~5 years.
Northern Italy[130]	1981–2007	• Birch. • Grasses. • Cypress. • Olive. • *Parietaria*.	• 25,543 patients aged 5-64 years. • 56% male. • 54% with rhinitis only, 35% with asthma plus rhinitis. • Mean duration of disease, 6 years.	*Duration of pollen season:* • Birch: no change • Grasses: no change • Cypress: +18 days • Olive: +18 days • *Parietaria*: +85 days Percentage of patients sensitized to pollens increased throughout years; those sensitized to dust mite remained stable.
Northern Sweden[123]	Two cross-sectional studies, 1994 and 2009	• Birch. • Timothy. • Cat. • Dog. • Mugwort. • Horse. • *Dermatophagoides pteronyssinus*. • *Dermatophagoides farinae*. • *Cladosporium.* • *Alternaria.*	• SPTs from 2 random population samples: 483 subjects in 1994 and 463 subjects in 2009, aged 20-60 years.	*Sensitization rates significantly increased between 1994 and 2009:* • Birch: 13.3% to 18.4%. • Timothy grass: 11.8% to 21.2%. • Cat: 16.1% to 26.1%. • Dog: 13.3% to 25.3%. • Low rates of sensitization to dust mite and molds (typical for region). *Factors positively associated with allergic sensitization:* • Young age. • Family history of allergy. • Urban living.

expand appropriate avoidance measures, alleviate supply chain issues, and promote productive collaboration among allergists, insurance companies, aeroallergen manufacturers, and regulatory agencies.

FULL REPORT

IMPACT OF CLIMATE CHANGE ON AEROBIOLOGY

Meteorologic parameters are among the most relevant environmental considerations responsible for the biodiversity and concentration of pollen and fungal spores present in the outdoor environment.[1] These factors are affected by climate change and global warming phenomena occurring on earth. The combustion of fossil fuels, including oil, coal, and natural gases, are the major source of pollution and greenhouse gases leading to global climate change. As a result of multiple specific effects of climate change, there have been numerous reports around the globe of increased pollen production, increased duration of pollen seasons, augmented pollen allergenicity, and changes in the distribution of allergenic plants.[2] In this section, we emphasize the myriad of worldwide reports of how climate change has affected aeroallergens. A summary is provided in Fig 1.

Effects of climate change on plant distribution

Most studies regarding the impact of climate change on plant distribution come from the Americas and Europe. There are a variety of diverse climates in the Americas, such as humid systems near the equator like the Amazon and arid systems like the Atacama Desert in the north of Chile, which is conducive to a great diversity of fauna and flora.[84-86] The American continents together represent the largest global landmass in latitude extension. Marine or ocean currents that originate off the American continents affect the climate both regionally and globally.[87] Sudden changes in climate exerted by changes in the Pacific Ocean, known as the El Niño and La Niña phenomena, are becoming more extreme and more evident with climate change.[46,88]

There is strong evidence that plant geographic distributions in North America are responding to climate change by shifting poleward and up in elevation.[3,4] This includes many taxa that produce allergenic pollen; however, results are species specific, and many of the processes and time scales remain unquantified. Much of the allergy related research on this topic focuses on herbaceous plants such as short ragweed *(Ambrosia artemisiifolia),* which is expected to shift poleward in response to climate change.[5] In the early 20th century, ragweed was introduced in Europe from North America and has since continued to expand its range.

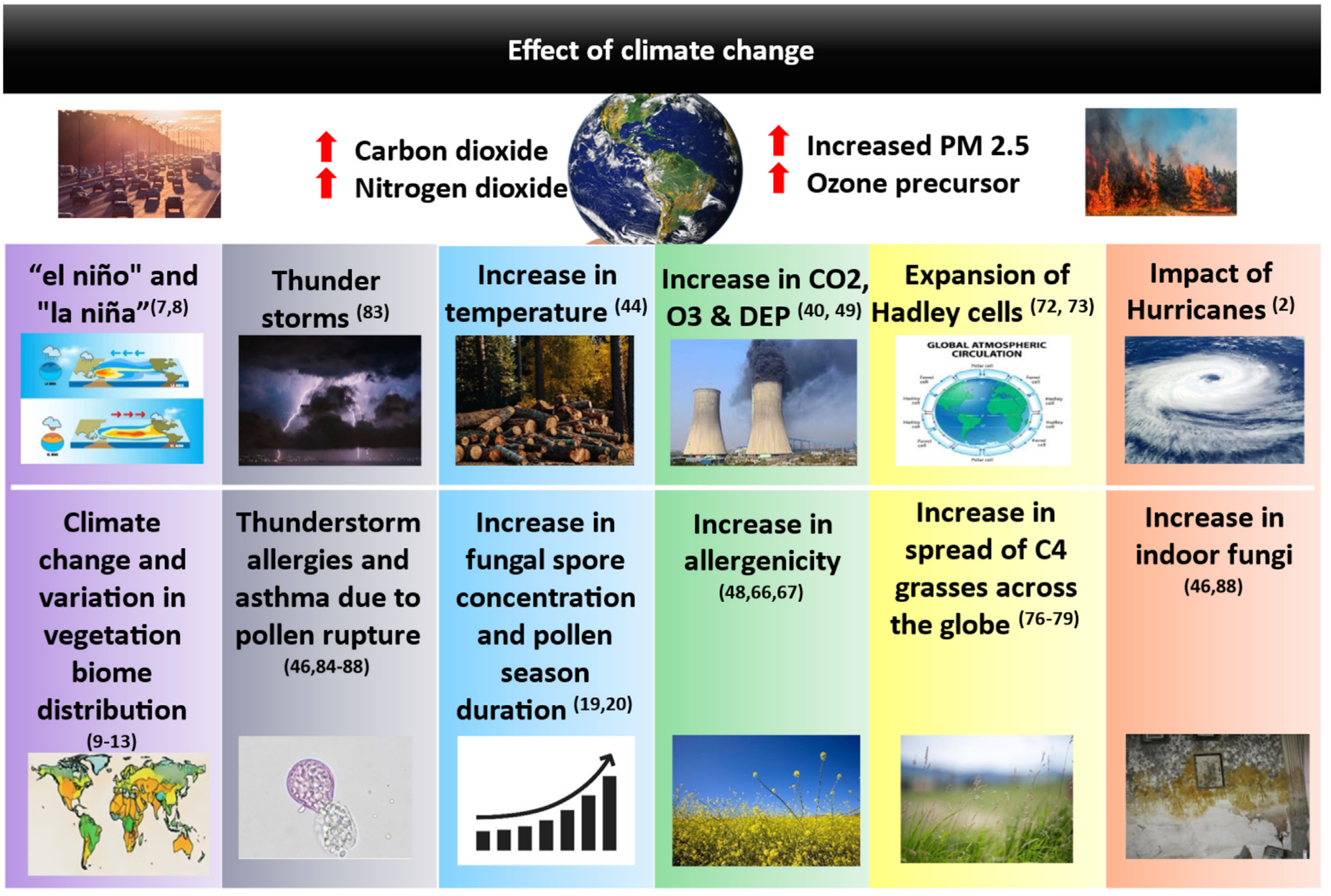

FIG 1. Effect of climate change on pollen and fungi.

Process-based modeling for climate change has predicted a 66% increased distribution of ragweed throughout Europe, which has been estimated may account for 33-77 million additional individuals sensitized by 2060.[16] There have been several studies in the central United States describing climate change–driven expansion of *Juniperus* woodlands and resulting increases in both seasonal pollen index and peak pollen concentration.[7-9]

A comprehensive literature review on the response of Andean vegetation to climate change attempted to predict how different vegetation biomes of the Andes might look within the next 50 years.[89] Main responses were proposed to be (1) changes in elevational distributions of grassy/shrubs biomes, (2) altered species composition due to upward shifts of warm-acclimated species or internal timber dynamics, (3) primary succession in lately deglaciated areas, and (4) changes in tree demographic patterns such as increased tree mortality, decreased growth rates, and fewer instances of new trees being established.

Effects of climate change on pollen season duration

Numerous reports have indicated that pollen seasons are lengthening, driven by prolonged growing seasons, earlier last spring frost, and later first fall frost.[10,11] In the United States, this has been most notable in the northeast and west, while other studies have shown prolonged seasons at higher latitudes.[15] Additional studies from around the globe have reproduced these data.[90-93] Plant pollination and bud break are well studied, and in temperate ecosystems, temperature tends to be the most important driver of reproduction.[94-98] Thus, the general expectation is that the warmer temperatures associated with climate change will continue to cause an earlier onset of spring pollen seasons in temperate ecosystems, leading to increased pollen exposures and associated health effects.[12-14]

Several studies have investigated associations between temperature and pollen season onset and duration in North America using long-term measurements of airborne pollen concentrations and have generally found advances in seasonal onset and increases in duration.[15-18] However, there are cases where further warming could delay reproductive onset—for example, when temperatures do not become low enough to break winter dormancy.[99] Moreover, in more water-limited ecosystems, including portions of the western United States, precipitation can play a large role in plant reproductive onset, suggesting that plants in arid ecosystems will have weaker or more idiosyncratic responses to further warming.[19,20] The effect of elevated carbon dioxide (CO_2) concentrations can also result in earlier reproductive onset, though several counterexamples exist in which elevated CO_2 either had no effect or delayed reproductive onset.[21-25]

Effects of increased temperature on pollen and fungal spore production

The optimal temperature at which plants grow and develop varies among plant species; therefore, changes in temperature could either result in increases or decreases in reproductive output depending on species.[26] Many observational studies of airborne pollen have found correlations between total airborne pollen and temperature over time, whereas others have found negative associations between total plant reproductive output and temperature.[16,18,100] Overall, the balance of studies shows higher total amounts of pollen collected in warmer years for trees and ragweed but not for grasses.[101] Several European studies have confirmed these trends over the past 40 to 50 years. Specifically, most tree pollen taxa have shown either a significant increase or a trend toward an increased annual pollen index that correlated with rising temperatures. These same studies, however, also reported a lower annual pollen index for several weed pollen taxa and grass pollen.[90,91] Modeling studies that are based on the same observational pollen data (and with the same limitations) suggest an increase in pollen production in North America in warmer scenarios, although with substantial differences among regions.[102]

Because of global warming, the permanent ice covers on earth are melting, and more of the earth's surface is being occupied by plants and fungi. The type of land cover may also influence the abundance and diversity of fungal species and their airborne spores. A study identified a strong connection between vegetation type and status, particularly leaf wetness, and the amount, composition, and seasonal variation of the fungal atmospheric microbiome.[27] This study suggested that fungal spore composition will change dramatically as a result of local environmental variables, atmospheric transport, and forest management alteration that can be attributed to climate change. It has also been suggested that increased temperatures will cause an increase in mycotoxin production.[28]

Effects of increased CO_2 and O_3 on aeroallergens

Increasing CO_2 concentration intensifies the efficiency of photosynthesis and the amount of energy available for plants, which may result in increased reproductive output, including pollen production.[29] This topic has been studied experimentally by growing plants in chambers with ambient and increased CO_2 concentrations as well as in open or semienclosed outdoor experiments where ambient CO_2 concentrations are enriched (ie, free air carbon enrichment, or FACE, studies). Results from chamber experiments often show increased reproductive output.[22,23,103-109] Results from FACE experiments are mixed but have generally established higher pollen production in elevated CO_2 conditions along existing CO_2 gradients (eg, urban to rural).[30-39] There may also be differences between plant types (eg, woody plants, grasses, "wildflowers"), photosynthesis type, nitrogen fixation, and other variables. Further quantitative comparison of existing results is needed to better predict the taxa and circumstances in which increasing CO_2 will have the strongest effects on pollen production. Nonetheless, on the basis of available studies, an increase in CO_2 will generally intensify reproductive output including pollen production.

A study performed in Spain compared *Cupressus arizonica* pollen collected from high-pollution areas (next to a busy highway near industrial areas) versus low-pollution areas (in a garden far from highways or industrial areas) and reported altered allergenicity, as demonstrated by *in vitro* and *in vivo* experiments. The pollen grown in highly polluted areas resulted in significantly larger dermal reactivity by skin prick testing (SPT) and 5 times more allergenic potency as determined by RAST (radioallergosorbent) inhibition.[40] In Germany, birch tree pollen collected from areas with different ambient O_3 levels indicated that pollen derived from trees grown in areas with a higher O_3 level had a higher content of the major allergen, Bet v 1, and elicited an increased SPT reaction compared to trees grown in areas of lower ambient O_3 levels.[41] While these studies are thought-provoking, additional studies are warranted to reproduce these data and more closely investigate how air pollutant mixtures affect aeroallergens. This would include more in-depth analysis of how environmental stressors may induce epigenetic modification (DNA methylation, histone modification, RNA interference) of plants and the allergens they produce.[110]

The relationship of plant leaf carbon-to-nitrogen ratio and fungal spore production has shown a positive correlation.[43] Increased fungal growth has been associated with increased plant substrate in part as a result of the alteration of the carbon-to-nitrogen balance.[111] Because elevated CO_2 concentrations have been shown to increase plant biomass and carbon-to-nitrogen ratio, it is likely that climate change is associated with an increased fungal spore production and fungal allergens. One study indicated that increased ambient CO_2 levels amplified the number of fungal colonies in plants.[42] Another study also found that *Alternaria alternata* grown on *Phleum pratense* under increasing concentrations of CO_2 produced more spores and antigens than when grown at atmospheric concentrations.[43]

Effects of expansion of Hadley cells on grass pollen

One consequence of climate change is the expansion of the Hadley cells, also known as the Hadley circulation, which meteorologically defines the tropics. The effect of Hadley cells begins with tropical sun warming equatorial surface air, which becomes less dense and rises. This warm air then spreads out toward the higher latitudes, creating a low-pressure system at the equator that eventually drives formation of the trade winds and weather systems. As the warm, rising air reaches higher altitudes, it is naturally cooled, which causes the air to sink and the development of a high-pressure system. This high-pressure zone of dry air has historically occurred near the 30° latitude, which correlates with the Sahara and Arabian deserts. Climate change has driven a decrease in temperature gradients between the equator and higher latitudes, and thus the expansion of Hadley cells. The consequences have been the disruption of geographic weather norms with varied precipitation patterns, drought, extreme weather events, and alteration of the jet stream.[48,49]

These regional climate changes favor the invasion and survival of species more suitable to withstand droughts and extreme temperatures, and the expansion of those able to take advantage of higher environmental CO_2 levels, such as C_4 plants.[46,47] Grass is subdivided into subfamilies, and these differ, among other things, in the enzyme that photosynthesis uses to produce the sugars of environmental respiration. This enzyme, called Rubisco (for ribulose-1,5-bisphosphate carboxylase/oxygenase), incorporates CO_2 from the environment and produces sugars for the plant's energy. This enzyme in different subfamilies can produce a 3-carbon sugar or a 4-carbon sugar, which defines C_3- or C_4-type plants. C_3-type grasses tend to grow in areas with lower temperatures and increased water supply (temperate zones), while C_4-type grasses grow in warmer environments. The subfamily Pooideae (including northern pasture grasses) are the most representative

C_3 grasses. Chloridoideae (Bermuda grass, among others) and Panicoideae (Bahia grass, among others) are mostly C_4 grasses. Plants using C_3-type photosynthesis allow water vapor loss through their stoma (leaf pores), which is a survival disadvantage during drought and in high-temperature environments. Therefore, greater increases in CO_2, which is the main source necessary for photosynthesis, can stimulate plant growth and increase pollen production to a greater degree in C_4 plants that capture more CO_2 from the environment.[44-49]

It has been projected that the relative abundance of C_4 grasses will increase in the Americas by more than 10% at the expense of C_3 grasses.[50] C_3 grasses are projected to decline throughout the Americas except for the northwestern Great Plains of the United States and Canada, and north-central Argentina. Projected changes in shrub abundance are mixed, with some projected increases in Patagonia and the desert regions of the southwestern United States; there were also projected decreases, but the locations varied across models.[50,112]

Effects of climate change on fungal spores

There are limited studies investigating the effects of climate change and air pollution on allergenic fungi. A few growth chamber studies have separately investigated *Erysiphe cichoracearum* and *Alternaria alternata* grown under elevated versus ambient CO_2 conditions and have reported significantly more *E cichoracearum* mycelia production and *A alternata* total antigen production at higher atmospheric CO_2 levels.[42,43] Changes in fungal distribution are mostly supported by indirect evidence or are restricted to indoor mold growth associated with catastrophic flooding events.[51] Climate change is responsible for an increase in heavy rainfall episodes and catastrophic flooding. These events cause heavy microbial and fungi growth indoors, thereby affecting human health.

Urbanization is thought to alter airborne fungal spore levels because land adjacent to urban areas that was previously undisturbed is now being used for housing and industry.[52] Another phenomenon is that while light rainfall briefly washes pollen and fungal spores from the air, it may release submicronic pollen particles and allergenic materials as a result of osmotic stress.[113] Also, large increases in the levels of fungal spores during thunderstorms have been described and may affect respiratory health.[114,115] While some fungal spores prefer dry conditions, others, such as basidiospores and ascospores, prefer wet conditions for spore release, and spore concentrations typically increase during and after rain events. Another factor is dew point, which is high preceding a thunderstorm and has been associated with an increase in multiple different spore types and the development of spore plumes.[116,117] Various meteorologic parameters, such as changes in barometric pressure, wind speed and direction, temperature, and rainfall, are also responsible for spore plumes or large increases in the levels of airborne spores over short periods; indeed, *Alternaria* and *Cladosporium* are associated with this phenomenon.[53]

The fungal genera and species that grow under normal and typical moisture conditions are different than those that originate as a result of excess moisture. Different species of *Penicillium* and *Aspergillus* grow within an ample range of water activity; however, species of *Stachybotrys, Memnoniella, Chaetomium, Trichoderma,* and *Aureobasidium* require high-moisture conditions.[53] Therefore, in addition to the potential effect of climate change and global warming on outdoor fungi, there is increasing concern about heavy and long-lasting indoor fungal growth after severe storms and catastrophic flooding.

The long-lasting effects of Hurricane Katrina, which devastated New Orleans, Louisiana, in 2004, were extensively discussed in a previous group report and are relevant to future events.[2] It was suggested that the composition of the indoor fungal species had changed after the hurricane and included the following predominant fungal spores: *Aspergillus spp, Penicillium spp, Trichoderma, Syncephalastrum spp, Cladosporium, Chaetomium,* and *Paecilomyces*.[118] Sixteen major hurricanes, which occurred between 2019 and 2022, particularly affected the southeastern United States. For example, Hurricane Ian, a category 5 hurricane, damaged more than 30,000 homes in Florida alone (Figs 2 and 3).[119] Global warming and climate change could therefore also indirectly be responsible for a change in the fungal species that grow indoors, which may result in new sensitization patterns.

IMPACT OF CLIMATE CHANGE ON RHINITIS

Multiple aspects of the climate change crisis have influenced the prevalence and morbidity of allergic rhinitis (AR), nonallergic rhinitis (NAR), and chronic rhinosinusitis (CRS). Increases in pollen and fungal spore levels, allergenicity, and distribution directly increase the prevalence and morbidity of AR. Unfortunately, the harm done by combustion, along with its associated pollution and climate changes, has a greater impact on those from lower-income countries and those who are socially and economically disadvantaged, particularly children.[59,120] Notably, greenhouse gases and air pollutants contribute to sinonasal inflammation by a direct effect on epithelial barrier integrity and eosinophilic inflammation, as well as their roles as adjuvants that stimulate IgE-mediated responses.[57,121,122] The impact of air pollutants is particularly relevant because of the proinflammatory interaction of particulates with increased aeroallergen exposure caused by climate change.

Effects of climate change and air pollutants on AR

AR is an IgE-mediated inflammatory disorder of the nasal passages produced in response to seasonal or perennial environmental allergens such as pollen, fungal spores, and dust mites in a sensitized individual. AR significantly impairs quality of life and may cause disturbed sleep, daytime somnolence and fatigue, irritability, depression, impairment of physical, mental, and social functioning, and attention, learning, and memory deficits.[123-126] As climate change has increased pollen and fungal spore levels and the duration of the allergen season, AR morbidity would be expected to increase with greater effects on individuals' quality of life, work interference, school performance, and medical costs.

Climate change, air pollution, and alterations in aerobiology patterns have been shown to influence the development and morbidity of AR via interactions with the epithelial barrier, T_H2 immune responses, and epigenetics. The epithelial barrier is the first line of defense against allergens or irritants.[127] Disruption of the epithelial barrier allows external factors to infiltrate downward, inducing immune responses and exacerbating inflammation, a phenomenon known as the *epithelial barrier hypothesis*.[54,55] Studies have shown that particulate matter with a diameter of less than 2.5 μm ($PM_{2.5}$) produced by combustion

FIG 2. House interior after major hurricane. Photo courtesy of Rosa Codina, PhD, FAAAAI.

FIG 3. House exterior after major hurricane. Photo courtesy of Rosa Codina, PhD, FAAAAI.

of petroleum products and wood/wildfires induces nasal epithelial barrier disruption via oxidative stress, decreased expression of tight junction proteins, and increased release of proinflammatory cytokines.[56,57] Moreover, diesel exhaust particles disrupt the epithelial tight junctions in human nasal epithelial cells and mouse models with AR. These result in the promotion of allergen delivery into subepithelial tissues contributing to the exacerbation of allergic inflammation.

There is a need for additional studies evaluating how climate change and air pollution affect the T_H2 response and AR development.[58] Components of air pollution, notably diesel exhaust particles, enhance basophil activation in birch pollen–allergic individuals, resulting in increased IL-4 and IL-8 secretion.[121] Moreover, the particles promote *de novo* nasal mucosal IgE response to an allergen in individuals without previous sensitization, suggesting an adjuvant role in enhancing IgE response to neoantigens.[122] Recent studies showing a link between early childhood exposure to $PM_{2.5}$ and altered methylation of immunoregulatory genes *FOXP3, IL4, IL10,* and *IFNG* demonstrate that mechanistically, early life exposure to air pollutants can promote inflammatory epigenetic modifications through oxidative stress, leading to dysregulation and the potential development of allergic conditions over the life-span.[65,128,129]

Effects of climate change and air pollutants on NAR

NAR is an inflammatory disorder of the nasal tissues secondary to triggers of cold, excessive dryness, irritants, vapors, gases, small airborne particles, air pollution, smoke, and strong smells. Neurologic simulation from these triggers activates mast cell mediator release in mucosal and submucosal tissues, leading to edema, increased secretions, and congestion.[130] Combustion products, including $PM_{2.5}$, nitrogen oxides, sulfur dioxide (SO_2), aromatic hydrocarbons, volatile chemicals, and O_3, as well as heat events, hurricanes, and thunderstorms from increasing CO_2, can worsen NAR.[59,60] Often subjects with NAR also have AR, which amplifies signs and symptoms.[130]

Avoidance is a key element of treatment of NAR but may not be feasible in a changing climate without a filtration barrier for the nose and mouth. Exposure to excessive dry air from expanding deserts, elevated levels of $PM_{2.5}$, nitrogen oxides, and SO_2 from pollution, mold spores from flooding, and smoke from burning fires can all be reduced by masks. With natural fiber and surgical masks, the benefit may be minimal; however, N95 and KN95 respirators, which filter out 95% of airborne particles, offer significant reduction in exposure to air pollution. During fires, N95 masks can reduce exposure by a factor of 14 and even reduce hospitalization due to smoke exposure by approximately 30%.[61] Given that wearing N95 masks is a temporary and ultimately impractical long-term solution, there is an imperative for government and community implementation of strategic plans focused on reduction of multipollutant emission as well as overall reduction in air pollution.[62]

Effects of climate change and air pollutants on CRS

CRS involves sinus inflammation that lasts for 3 months or longer. CRS contributes to poor quality of life and is a major socioeconomic burden.[131,132] Air pollution linked to climate change is associated with CRS, likely through an increased inflammatory response in the sinonasal mucosa.[63,64] There is an unmet need in our understanding of how levels of air pollutants, allergens, and the earth's temperature and humidity, which are the direct result of climate change, interact to affect CRS.

While the underlying mechanistic link between air pollution and CRS is not fully known, particulate matter, O_3, and nitrogen oxides have been shown to augment T_H2 inflammatory responses.[65] These air pollutants can enhance eosinophilic airway inflammation through an increase in allergen-specific IgE and T_H2 cytokines, including IL-4, IL-5, and IL-13.[121,133] Nonallergic mechanisms likely play a role as well. When combined with the increase in aeroallergen levels, the shift to greater T_H2 inflammation from air pollutants may drive a greater burden of CRS disease. In addition, exposure to O_3 and particulate matter can lead to airway inflammation via impaired phagocytosis by neutrophils and macrophages, poor mucociliary clearance, and generation of reactive oxygen species that deplete antioxidant defenses.[66,67] Studies using human sinonasal epithelial cells from CRS patients demonstrated that *in vitro* exposure to coarse particulate matter elicited disruption of intercellular tight junctions and reduced epithelial barrier function.[68]

The effect of climate change on global warming also has the potential to directly exacerbate allergic fungal sinusitis. This form of eosinophilic rhinosinusitis is often seen in areas of the world with warmer climates and increased humidity.[134] Treatment of this severe variant of CRS often requires intense surgical and medical therapy.[135]

IMPACT OF CLIMATE CHANGE ON ALLERGEN IMMUNOTHERAPY

Diagnostic testing for aeroallergen sensitization and climate change

Studies reporting patterns of SPT sensitization to aeroallergens have been published from many parts of the world for decades. Table E1 in the Online Repository available at www.jacionline.org shows available results of SPT sensitization rates for house dust mite (HDM), pollen, and fungi in different parts of the world.

It is known that early life exposures affect sensitization patterns. For example, an Irish study showed that patients born during the grass pollen season were 5 to 7 times more likely to be sensitized to grass pollens.[136] In part because of factors cited in the aerobiology and rhinitis sections, urban dwellers have more allergic sensitizations compared to rural populations; this effect has been seen in multiple age groups, including older adults.[137-139] In humid climates, HDM is generally the prime sensitizing allergen, while in drier areas, pollen and animal dander may predominate. High SPT positivity to fungi has also been reported in some zones (up to 50% in the inner city), but these data should be interpreted with caution because fungal extracts are often heterogeneous in composition.[140,141]

Attempts have been made to determine a minimal number of allergens that should be tested to capture clinically relevant sensitizations. A pan-European study from 2006 showed that 18 allergens could cover 90% of all sensitizations. In northeastern, northwestern, and southern China 6 allergens were enough, while in central China 8 allergens were sufficient.[142] Thus, a sweeping global recommendation regarding how many allergens to test cannot be made at this time, particularly in the setting of climate change.

Longitudinal studies on the evolution of allergic sensitization profiles are scarce (Table I). The best known relate to sensitization to *A artemisiifolia* pollen in northern Italy between 1989 and 2008, where sensitization rates rose from 24% to 70%.[143] Another study from northern Italy between 1981 and 2007 found a progressive increase in the duration of pollen seasons for *Parietaria* (+85 days), olive (+18 days), and cypress (+18 days), with an overall earlier start date to the seasons.[144] In Sweden, from 1994 to 2009, SPT sensitization to cat (16% to 26%, $P < .001$), dog (13% to 25%, $P < .001$), birch (13% to 18%, $P = .031$), and timothy grass (12% to 21%, $P < .001$) increased significantly; the proportion having ≥3 positive SPT reactions increased from 40% to 56% ($P = .002$).[137]

To summarize, sensitization patterns in the same climatologic region vary according to degree of urbanization and month of birth as well as indoor and outdoor allergen exposures, among other factors. There are insufficient data in almost all parts of the world regarding changes in allergic sensitivity due to a lack of sequential testing in the same region under the same conditions. Plants have expanded their distribution poleward as a result of increased temperatures in the northern hemisphere, and a shift in rainfall that is creating arid lands; thus, a northward expansion of southern pollens could be anticipated, and even a reduction in exposure to dust mites and indoor fungi in some areas as a result of desertification, although the opposite could be true as a result of increased flooding events. It will be important to repeat regional sensitization profiles based on climatic changes in order to adjust aeroallergen panels for SPT and specific IgE. Overall, more research correlating SPT and *in vitro* IgE results with clinically relevant AR is needed. More advanced molecular techniques may prove useful in this regard.[69]

Molecular diagnostics and climate change

More precise measures of clinically relevant allergic sensitization are needed. Component-resolved diagnosis can be useful for determination of allergens for immunotherapy and for tracking changes related to climate change.[145] Climate change is altering the expression of some proteins, and more often it is altering the locations where allergenic plants grow. For example, a recent study using the multiplex allergy Alex^2 test to evaluate sensitization patterns for grass pollen among 20,033 people aged 1 to 89 years from Ukraine (typically predominated by northern pasture grasses, which are C_3 grasses) found an unexpectedly high degree of monosensitization to Cyn d 1 (from subtropical Bermuda grass, a C_4 grass), especially among children.[146] Thus, component-resolved diagnosis may theoretically be more sensitive than traditional SPT or *in vitro* IgE testing in detecting early shifts in allergen sensitization patterns as a result of climate change. Questions arise about the utility of using component-resolved diagnostics more broadly for diagnosis in the United States and elsewhere; however, strategies that allow for more widespread implementation of this tool, including lowering the cost of such assays, may improve understanding regarding the impact of climate change on global sensitization patterns.[147,148]

IMPACT OF CLIMATE CHANGE ON CLINICAL PRACTICES RELATED TO SUBLINGUAL ALLERGEN IMMUNOTHERAPY

Climate change may affect prescribing practices related to sublingual allergen immunotherapy (SLIT) in substantial ways. For allergists prescribing a pre- and coseasonal SLIT administration schedule, the number of weeks of treatment in that region could increase, requiring earlier preseasonal dosing start dates. Longer treatment courses translate into higher costs of treatment. Accounting for potentially increased adverse effects of dosing given an increased number of days of excessive pollen exposure, there is a theoretical increased risk of adverse events from SLIT, although rates of systemic reactions from SLIT are notably lower than for subcutaneous allergen immunotherapy (SCIT).[149] SLIT is contraindicated in patients with eosinophilic esophagitis, and the risk of developing it from SLIT should be taken into account when selecting this therapy.[150]

Modeling studies indicate that the impact of climate change on pollen seasons will vary substantially across regions of the United States.[70] For example, there may be increased grass pollen exposure and sensitization to grasses in the northeast, resulting in increased prescriptions for grass pollen SLIT. Areas of significantly increased weed pollen exposure may see a trend in increased autumn allergy exacerbations. This presents an opportunity for a more focused approach to encouraging early adoption of allergen immunotherapy, including SLIT for short ragweed in the United States, to reduce weed pollen–related fall exacerbations. Using a model to estimate the effect of climate change on ragweed sensitization, it is predicted that sensitization to this pollen will more than double in Europe, from 33 million to 77 million by 2041-60, which, if true, will surely also affect short ragweed SLIT prescribing patterns in Europe.[6]

Home-based SLIT dosing may provide advantages during climate crises. Climate change–related disasters like wildfires or floods disrupt health care access.[81] Home-based medications like SLIT tablets and drops are portable and can be continued during such crises. Convenience-forward immunotherapy options like SLIT also decrease travel and related vehicle emissions. However, given that much higher quantities of allergen are needed for production of SLIT, there may be an increased burden on supply chains for immunotherapy if more patients are receiving SLIT. In addition, US Food and Drug Administration–approved SLIT tablets are not currently available for many allergens.

IMPACT OF CLIMATE CHANGE ON CLINICAL PRACTICES RELATED TO SCIT

When selecting allergens to include in mixes for SCIT, there are several important concepts to consider: (1) an allergenic source may contain several allergenic molecules, and each one may have different epitopes that stimulate specific IgE; (2) allergens may be cross-reactive as a result of sequence homology and common epitopes; and (3) it is important to include relevant allergens but avoid inclusion of cross-reactive allergens.[151-153] In most situations, major allergens are the most clinically relevant, but there are some cases in which minor allergens are clinically significant as well.[151,154,155] Climate change has affected pollen and fungus exposures and sensitization through multiple mechanisms, including lengthening of pollen seasons, increased pollen production, increased pollen allergenicity, and changes in spatial distribution of allergenic plants. In addition, microclimate effects such as urban heat islands, and changes in rainfall can significantly affect local exposure and sensitization rates to pollen and fungi.

Few studies have directly measured changes in pollen and fungal exposures that are attributable to climate change, and even fewer have considered the impact of these changes on sensitization and clinical management of AR.[6,72,144,156,157] For most plant species, and in most parts of the world, longitudinal studies examining local sensitization rates and resultant rhinitis symptoms have not been done. Extrapolation of plant distribution and/or pollen count data may therefore be useful in situations where sensitization data are not available. For example, in the United States, several important species of C_4 grass that are still considered southern grasses, such as Johnson and Bermuda grass, both of which do not share homology with northern pasture (C_3) grasses, have been steadily expanding northward.[71] Inclusion of these grasses for testing and immunotherapy should now be considered in most of the United States, except possibly the northern Midwest. The invasion and expansion of short ragweed in Europe may necessitate testing and immunotherapy against this pollen for most of the European continent within the next 20 to 40 years.[6] Changes in exposure to tree pollens are especially difficult to account for without local measurements, given that local conditions such as rainfall, elevation, and CO_2 exposure may exert markedly different effects in adjoining geographic areas, as is predicted for birch pollen in Bavaria.[72] Lack of standardized allergens for testing and immunotherapy, and variable sensitization to major versus minor allergens further complicate the situation for tree pollens. In addition, given the probable increases in fungal exposure resulting from climate change, updated sensitization data for fungi and higher-quality fungal extracts are needed to optimize prescribing patterns for immunotherapy.

PROPOSALS TO HELP ALLERGISTS ADAPT TO CLIMATE CHANGE

Considering all of the above, we propose the following solutions (Fig 4).

Expand local measurement of pollen and fungal spores. Timely pollen and fungal measurements are essential for informing allergists and their patients of their risk of allergen exposure; climate change is anticipated to make this even more important. Pollen and spore counts inform about the need for avoidance measures and potential worsening of symptoms. Higher pollen concentrations also enhance the efficacy of immunotherapy for pollens.[158,159] Given the importance of outdoor allergen exposures, it is necessary to expand the activities of the National Allergy Bureau in providing local pollen and spore counts at regular intervals.[73] This will likely necessitate a coordinated, collaborative effort between professional organizations, and academic and governmental institutions. In addition, diagnostic testing panels will need to be routinely adjusted to accommodate local findings.

Increase intensity of allergen avoidance measures. Climate change affects both outdoor and indoor allergen exposures. As daily temperatures rise and indoor flooding events occur more frequently, the risk of indoor fungal exposures will increase.[157] HDM sensitization has already increased in subtropical areas.[160] Decreasing indoor humidity and improving indoor ventilation are building interventions that can reduce both fungal and HDM exposures.[74] N95 and KN95 masks may reduce exposures to air pollutants, as well as heavy aeroallergen exposures in some circumstances.[61,62] Additionally, when placed appropriately, the use of high-efficiency particulate air (aka HEPA) filters can serve the dual purpose of reducing fungal and animal allergens.[75-77] These filters also have beneficial effects on indoor and outdoor air pollution exposures by reducing pollutants from the outdoors that enter dwellings, which may reduce adjuvant effects on allergic sensitization.[78,79]

Address supply chain issues. Allergen extract supply chains for pollen are mostly dependent on a steady source of raw materials from grasses, shrubs, trees, weeds, or cultivated plants.[80] Climate change will overall result in an increasing demand for extracts for diagnostics and treatment.[70,81-83] Because extreme weather events are likely to become more frequent or intense, more variability in the supply of source materials such as pollen and fungi is expected.[80,161] It is already not uncommon for manufactured pollen extracts to be on backorder or only available in limited offerings.[80] Extracts that are cultured in the laboratory are more insulated from the variability.[162] In order to manage disruptions effectively, inventory planning, as well as knowledge of phylogenetic cross-reactivity of various species of pollen, will be important for practicing allergists. SLIT presents a unique supply chain challenge in that effective SLIT

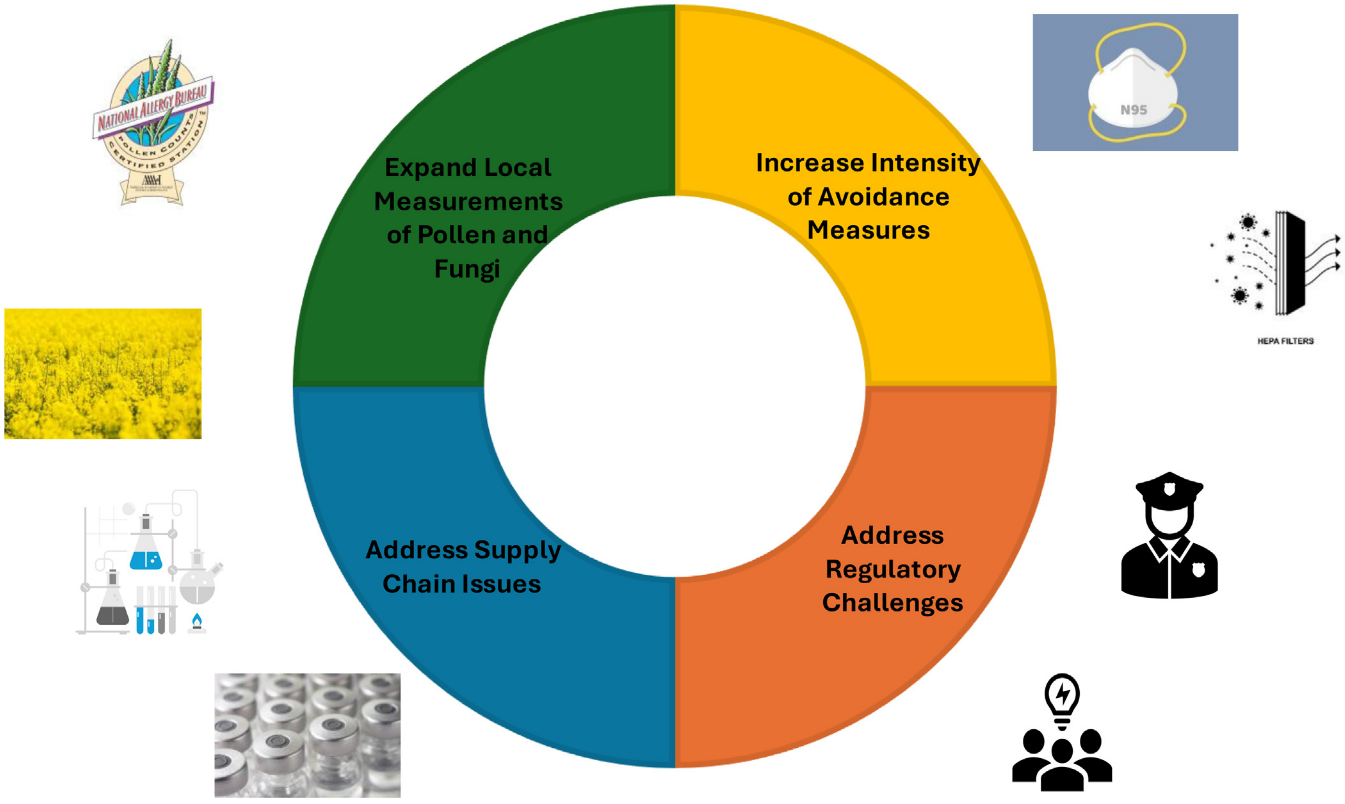

FIG 4. Proposals to help allergists adapt to climate change.

dosing depends on high allergen extract volumes (for off-label drops) or commercial tablet production, both dependent on manufacturer's availability. As demand increases, current supply chain limitations need to be addressed to create a reliable, consistent supply of SCIT and SLIT. A collaborative effort among allergists, manufacturers, and those in positions to determine health insurance coverage is also needed to position us to meet a growing demand for allergy treatment.

Address regulatory challenges. Once raw material is obtained, it must be processed following Current Good Manufacturing Practices requirements and undergo several quality control checks, including assessment of protein content before release. At each step, issues can arise as a result of the variable availability of raw natural materials or of any materials required during processing, cleaning, standardizing, and quality control procedures. In addition to following good practices, standardized extracts in the United States must also pass tests of potency mandated by the Food and Drug Administration. Worldwide regulatory burdens are very different in each country, although members of the European Union have some commonality, such as the Marketing Authorization.[163] Adaption to climate change will require greater standardization and efficiency in these processes in order to quickly adjust the availability of therapies to rapid local changes in allergen exposures and sensitization patterns.

In conclusion, climate change has already had a significant global impact on pollen and fungal exposures and allergenicity. An overall increase in allergic sensitization is expected, although in most parts of the world local aeroallergen measurements and longitudinal sensitization studies have not been done. Increased exposure and sensitization to allergens, as well as an increase in air pollutants, are highly likely to increase the global burden of rhinitis and chronic sinusitis. Allergists will need to adapt diagnostic and therapeutic strategies to limit exposure to aeroallergens and pollutants and to facilitate desensitization. To successfully navigate these challenges, it will be necessary to expand local aeroallergen measurements, develop and expand appropriate avoidance measures, alleviate supply chain issues, and promote productive collaboration among allergists, insurance companies, aeroallergen manufacturers, and regulatory agencies.

DISCLOSURE STATEMENT

Disclosure of potential conflict of interest: P. Ponda is site principal investigator on clinical trials with Allakos, ALK, DBV, Novartis, Regeneron, and Siolta Therapeutics; and advisory board member for Regeneron Pharmaceuticals, both outside the current report. The rest of the authors declare that they have no relevant conflicts of interest.

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TABLE E1. Results of various sensitization rates for allergens in different parts of the world

Study	Year	Country, climate zone*	Disorder	Age (years), range or mean	No. (no. SPT+)	HDM	Trees	Grasses	Weeds	Fungi
E1	2014	United States, many	[General population]	6-80	7268	18.7% *Dpt*	11.4% oak	19.5% rye	15.5% ragweed	8.6% *Alternaria*
E2	2009	Northern Europe, Dfb	R/A	39	377	16.8% *Dpt*	34% birch	30.8% mix	17.6% *Artemisia*	2.5% *Aspergillus*
E2	2009	Central Europe, Cfb	R/A	35	1849	22–51% *Dpt*	57% birch	78% mix	44.3% *Artemisia*	0.5-7.9% *Aspergillus*
E2	2009	Southern, Europe, Csb, Csa	R/A	25	808	38.9% *Dpt*	23.3% olive	34.4% mix	33.2% *Parietaria*	0.4% *Aspergillus*
E3	2020	Turkey, Csa	R/A	30-49	545 (316)	50% *Df*	33.2% olive	43% grass–rye mix	22.5%	14.6% *Fusarium*
E4	2022	Egypt, Bwh	R/A	16-66	200	32% *Dpt*	16% alder	28.5 timothy	24% Russian thistle	11% *Aspergillus*
E5	2012	African Congo, Af	R	4-89†	423 (149)	68.5% *Dpt*	2% cypress	10% mix	3.4% *Parietaria*	2.7% *Aspergillus*
E6	2017	China (northeast), Dwa	R/A	6-75	290 (249)	43.1% *Df*	19.9%	9.4% mix	33.6% mugwort	4.4% *Curvularia*
E6	2017	China (northwest), Bwk	R/A	6-75	346 (301)	24.2% *Df*	28.7%	26.7% mix	58.2% mugwort	4.3% *Curvularia*
E6	2017	China (central), Bsk, Dwb	R/A	6-75	6236 (5531)	47.3% *Df*	22.0%	12.8% mix	27.1% mugwort	4.6% *Alternaria*
E6	2017	China (south), Cwa,Cfa	R/A	6-75	276 (250)	69.2% *Df*	7.7%	6.4%	14.9% mugwort	5.7% *Penicillium*
E7	2018	Pakistan, Bwh	A	29	105 (59)	33.3% mix	31.4% paper mulberry	26.7%	7.6% dandelion	7.6% *Aspergillus*
E8	2022	India, Aw, Bsh	R/A	18-60	327 (271)	49.8% *Dpt*	Not done	26.3% Bermuda	15.3% mugwort ragweed	19.6% *Aspergillus*
E9	2022	Bangalore, Aw	R/A	18-65	400 (228)	41%	Not done	4.1% Bermuda	6.1% mugwort	2.3% *Aspergillus*
E10	2021	Thailand, Aw	R/A	9	315 (261)	77.1% *Dpt*	6.8% acacia	25.7% Bermuda	2.3% *Amaranth*	1.3% *Cladosporium*

Dandelion, *Taraxacum*; *Df, Dermatophagoides farinae*; *Dpt, Dermatophagoides pteronyssinus*; mugwort, *Artemisia*; *NR,* not reported; *R/A,* rhinitis/asthma; Russian thistle, *Salsola*; rye grass, *Lolium perenne.*

*Köppen-Geiger climate zone map abbreviations are as follows: *Af,* Tropical rainforest; *Aw,* tropical savanna, dry winter; *BSk,* arid, steppe, cold; *Bwh,* arid, desert, hot; *Bwk,* arid, desert, cold; *Cfa,* temperate, no dry season, hot summer; *Csa,* hot-summer Mediterranean climate; *Cwa,* temperate, dry winter, hot summer; *Dwa,* cold, dry winter, hot summer; *Dwb,* cold, dry winter, warm summer.[E11]

†Mean, 36.