REVIEW ARTICLE

# Projections of the effects of climate change on allergic asthma: the contribution of aerobiology

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**Abstract**

Climate change is unequivocal and represents a possible threat for patients affected by allergic conditions. It has already had an impact on living organisms, including plants and fungi with current scenarios projecting further effects by the end of the century. Over the last three decades, studies have shown changes in production, dispersion and allergen content of pollen and spores, which may be region- and species-specific. In addition, these changes may have been influenced by urban air pollutants interacting directly with pollen. Data suggest an increasing effect of aeroallergens on allergic patients over this period, which may also imply a greater likelihood of the development of an allergic respiratory disease in sensitized subjects and exacerbation of symptomatic patients. There are a number of limitations that make predictions uncertain, and further and specifically designed studies are needed to clarify current effects and future scenarios. We recommend: More stress on pollen/spore exposure in the diagnosis and treatment guidelines of respiratory and allergic diseases; collection of aerobiological data in a structured way at the European level; creation, promotion and support of multidisciplinary research teams in this area; lobbying the European Union and other funders to finance this research.

There is unequivocal evidence that the climate is changing and at an increasing rate. Global average temperature has increased by more than 0.7°C over the past 100 years, and the Intergovernmental Panel on Climate Change (IPCC) projects that the average global surface air temperatures in the years 2090–2099 are likely to be between 1.8 and 4.0°C warmer than those in 1980–1999, depending on which climate scenarios are input into the models (1). In addition to global warming, some regions, including northern Europe, are projected to experience increased rainfall while others, including the Mediterranean, are expected to experience substantial droughts. Extreme weather events, such as heat waves, heavy precipitation and thunderstorms, are also predicted to increase over the next few decades. These changes are as a result of increases in atmospheric carbon dioxide ($CO_2$) and greenhouse gases in which anthropogenic activities play a key role.

All the above climate-related factors can impact on the physiology and distribution of living organisms, such as plants and fungi. In this context, there is evidence that climate change affects pollen and spore production by plants and fungi as well as different phenological events. At the same time, current changes in climate are affecting the different aerobiological processes (emission, dispersion and/or transport, and deposition) of aeroallergens.

Plant biology is directly affected by rising $CO_2$, ($CO_2$ being the sole supplier of carbon for photosynthesis) and by temperature and water availability, among the most relevant environmental factors affecting phenology. (Phenology is the study of periodic plant and animal life cycle events and how these are influenced by seasonal and annual variations in climate). As the concentration of atmospheric $CO_2$ has increased by 22% in the last 50 years, and all climate change scenarios project a further increase by 2100 (2), and given the other projected changes in climate, a number of effects on plants involved in human health can be anticipated in the future. (3).

For the past 40 years, the prevalence of asthma has in general increased and is still increasing worldwide in parallel with other indices of allergy (4). However, the falls in some indices of asthma in children in some countries with a higher prevalence of the disease suggest that the increase may be coming to an end especially in some western countries (5). Nevertheless, climate change might affect the prevalence of respiratory allergic diseases through an effect on important environmental factors, such as aeroallergens and pollutants.

The effects of climate change on both allergic diseases in general (6), respiratory allergic and nonallergic diseases (7–9) and the pediatric population (10) have recently been summarized. Taking into account the main environmental factors affecting respiratory diseases and their possible changes under current climate change scenarios, negative effects are expected. The impact of pollen, spores and pollutants might be greater, with children possibly being the more exposed and susceptible population. On the other hand, the warmer winters may reduce susceptibility to respiratory infections and, as a consequence, respiratory disease–related mortality. However, a focus on aspects related to allergenic pollen and spores is still lacking.

As weather conditions also affect pollutant levels, projected changes in climate will influence air quality, in particular ozone (11), but full consideration of this topic is beyond the remit of this review.

This review has been developed by a joint task force between the European Academy of Allergy and Clinical Immunology (EAACI) and the European Respiratory Society (ERS) to consider the effects of climate change on respiratory allergic diseases and on asthma prevalence.

The article is focused on Europe where most studies have been performed and considers the potential effects of climate change on plant and fungus biology, pollen and spore dispersal, resulting likely changes in exposure and potential impact on human health.

## Effects of climate change on allergenic pollen

In higher plants, male gametophytes develop in the pollen grains, which are responsible for their transfer to the female reproductive organs. This mechanism occurs in a variety of ways but aerobiology mainly studies pollen grain behavior and biology from wind-pollinated plants. These plants produce pollen in large quantities to compensate for the reduced efficiency of wind pollination. Recent changes in pollen pro-duction by plants are directly related to meteorological factors, but also to other components such as the enriching effects of increased $CO_2$ on rates of photosynthesis. In addition, phenological events in many plants are controlled by local climatic factors. In this context, it is important to consider the role of different meteorological and pheno-climatic variables before the flowering season because of their influence on seasonal blooming.

Different meteorological factors also affect pollen emission, notably temperature, sunlight and humidity. On the other hand, weather patterns influence the movement and dispersion of all aeroallergens in the atmosphere through the action of wind and rainfall but depend in addition on atmospheric stability. Pollen season dates, duration and intensity, and a possible advance in the start of the allergy season because of climate change are under investigation but current data suggest that such changes are possible, although will likely be different between different taxa and species.

The availability of extensive time series of pollen count in the air and field phenological observations in Europe provides an impressive amount of data on possible changes in allergenic plants. Studies performed in other continents confirm these findings (12).

Although pollen production by plant, phenology and the different aerobiological events are interdependent processes, they have been artificially separated in this review.

## Effects on pollen allergen content and allergenicity

Pollen allergenicity is linked to allergen concentrations and is a major determinant of the health effects in sensitized patients. Some studies report an increase in the allergen content of pollen produced by plants growing at higher temperature and in $CO_2$-enriched atmosphere. Concentrations of the ragweed (*Ambrosia artemisiifolia*) major allergen (Amb a 1) increases in a $CO_2$-enriched atmosphere, concentrations being selected according to future climate change scenarios. This suggests that increased $CO_2$ could potentiate the sensitization rate and/or severity of symptoms in ragweed allergy (13). However, in a field experiment, a significantly higher quantity of antigenic protein was extracted from pollen at a rural (a low $CO_2$ area) compared to an urban site (a high $CO_2$ area) (14).

Birch trees growing at higher temperatures produce pollen with an increased content of the major allergen, Bet v 1 (15), which also has higher allergenicity (16). However, these findings are in contrast to findings from a recent study, which showed that despite large individual differences between plants of the same species, there seems to be regional and year-to-year variations in Bet v 1 release from birch pollen (17). Similarly, poison ivy (*Toxicodendron radicans*), not a native European species, shows an increase both in biomass and in the toxicity of urushiol, the cause of the well-known contact dermatitis when grown in higher temperatures (18). So to date, there is some evidence for higher allergenicity of pollen produced in an environment similar to that projected under current climate change scenarios.

## Effects on phenology

In the case of plants, phenology studies the time cycle of the appearance of, for example, the primary leaves, the first flowers and autumn leaf coloration. As pollen emission is linked to the appearance of flowers, this review will be limited to discussion on changes in flowering phenology.

A higher dependency on temperature has been observed in plants that flower in spring and early summer, whereas species that flower in late summer and fall generally are more correlated with photoperiod. Consequently, the former species are more affected by warmer winters and springs, showing an earlier flowering in recent years (12).

Pollen count has been used as evidence of earlier flowering in allergenic taxa, by using aerobiological parameters, such as start and peak date and length of pollen season. Nearly all species and regions analyzed have shown significant changes in seasonal onset of pollination that are consistent with warming trends (19–24). In general, an earlier start of the pollen season has been shown in most studies focused on allergenic plants such as birch (20, 23), mugwort (25), Urticaceae (26), grass (27, 28) and Quercus (29), even when employing different methods and different length datasets. An earlier start of the season have been found also for other allergenic plants at local level, such as Quercus, Juniperus in the Netherlands (23), and Platanus in Italy and Spain (30).

However, in some cases, a dependency on temperature trends is seen during the years studied, by different regions or for different plants. For example, over a period of 30 years, data provided by the International Phenological Gardens network showed that spring events advanced by 6 days, the highest rate of phenological changes being observed in Western Europe and Baltic regions (31). Conversely, phenological trends appear to be different in eastern part of Europe, sometimes showing a 1–2-week delay in start of the spring phases (32). Recent findings show that experimental warming aimed at inducing flowering also depends on blooming season: in a North American prairie setting, an advanced flowering phenology was observed for species that began to flower before the summer temperature peak with a delay in those species that started flowering after the summer peak, particularly for ragweed (33).

Several studies based on long time series of airborne pollen counts showed an earlier start of the birch pollen season in Europe although with regional differences (20, 22, 23, 34). This shift was especially pronounced in the late 70s (35). Some studies have projected an advance of the pollen season start of 1–3 weeks for Olea europea (21) and 1 month for Quercus by the end of the century (29). There is also evidence that the duration of the pollen season is also extended, especially in summer and in late flowering species (36), and in the case of Urticaceae in Italy (26).

Cities provide an interesting model for studying the effects of both temperature and $CO_2$ increases on phenology. Urban areas have horizontal and vertical surfaces that modify the physical characteristics of the lower layers of the atmosphere resulting in a variation in the net balance of radiation, which creates a dome of warm air called the urban "heat island".

An earlier start of flowering in urban compared to rural areas has been shown for Ambrosia (14) and Platanus acerifolia (37) and for some nonallergenic plants. However, in the case of Ambrosia, urban populations declined significantly despite the continued higher temperature and $CO_2$ concentrations (38), implying that other factors could come into play to limit the effects of the increase in both $CO_2$ and temperature.

In summary, changes in start date and duration of pollination and flowering appear to be a relatively consistent finding in association with temperature rise although there are both regional and species differences in the described patterns.

## Effects on pollen production by plant and pollen season severity

A meta-analysis to assess the effects of $CO_2$ enrichment (500–800 ppm) on reproductive organs of plants showed that total plant mass increased by 31% in elevated $CO_2$ environments compared with controls (39). In addition, flower intensity increased by 19% in both crop and wild species with similar results being obtained in studies on woody plants (40). The expected consequence would be an increase in pollen production, which has been confirmed in several experimental studies on A. artemisiifolia (ragweed) in which, under heightened $CO_2$ levels, both pollen production (41, 42) and floral spikes per plant were increased (43). In general, the literature to date suggests that preseason temperature and precipitation are predictors of floral intensity for both woody plants and for weeds and grasses.

Spieksma et al. (44) analyzed the cumulative, annual, airborne total pollen grain counts (annual pollen index) for several pollen types in five cities, data on birch showed a increasing trend at all stations. In a long Swiss study of birch pollen counts, both the annual pollen index and daily peak levels increased over a 38-year period (35). A study in Genoa, Italy, observed that total yearly pollen counts for Parietaria increased significantly from 1981 to 1997 but that pollen sensitivity in the population did not show much year-to-year variability. However, in the same study, Poaceae and Artemisia pollen counts did not show any significant upward trends (45).

## Effects on thunderstorm asthma

So-called "thunderstorm asthma" is characterized by asthma outbreaks possibly caused by the dispersion of more respirable allergenic particles derived from pollen and spores by osmotic rupture (46–48). Since the first report of this phenomenon in the United Kingdom in 1985 (49), further episodes characterized by increases in emergency room visits and hospital admissions by asthma in association with thunderstorms have been reported in several parts of the world (50–54). According to current climate change scenarios, there will be an increase in intensity and frequency of heavy rainfall episodes, including thunderstorms, over the next few decades (55), which can be expected to be associated with an increase in the number and severity of asthma attacks both in adults and in children (55).

### Effects on allergenic plant distribution

Airborne pollen counts can be represented by distribution maps, which are useful tools for both allergists and patients. While, clearly, local pollen counts and land cover are not completely overlapping, as pollen can travel long distances, it is reasonable to use pollen counts as a guide to symptom risk. These can therefore theoretically be used to assess the influence of climate change. Global warming is related to altitudinal and latitudinal plant migrations, changing plant species' diversity and density, and consequently, provoking habitat alteration or fragmentation. For example, an extension of the northern limit of birch, olive trees and ragweed and a corresponding increase in height of the altitudinal tree line and contraction of its range in the south have been projected by Emberlin et al. (56). On the contrary, global warming and increased $CO_2$ concentration are thought to favor a northward expansion of some species of grasses (57). Equally, either habitat alteration or fragmentation may contribute to local extinctions by altering biodiversity.

All these different events alter the local airborne allergenic pollen count and diversity. These findings are potentially biased by the occurrence of long and medium distance transport episodes of allergenic pollen as shown in several European countries (58–61). In addition, spores from allergenic fungi have been shown to travel even longer distances, such as from Africa or Asia to America (62–64). The projected alteration of wind patterns associated with climate change might induce an increase in such episodes, although this has to remain conjectural. Such trends can be reflected in clinical outcomes. The decreasing pollen counts for grass and birch pollen in the period 1991–2007 reported by Frei and Gassner (35) was suggested by the authors to be a possible explanation for the reversing (or stable) trend of prevalence of allergic rhinitis in Switzerland (65) and potentially in other countries (5).

A declining trend is reported for yearly *Poaceae* pollen counts in Leiden (NL) (66), London and Derby (UK) (27, 67), Parma (Italy) (68), and even if with a shorter dataset, in two Spanish studies (69, 70). In the latter study, a trend toward a lower number of days with a grass pollen count above the clinical threshold was observed, which could be explained by a change in land use (56). Considering that the pollen sampling stations used in allergenic pollen studies are usually located in urban or sub-urban settings, urbanization, by an unrecognized mechanism, could be responsible for this marked decrease in herbs and grass pollen counts.

Changes in ragweed (*A. artemisiifolia*) distribution need to be separately evaluated. Ragweed was first identified in Europe in 1860, and its pollen is increasingly important from an allergological point of view in parts of Central and Eastern Europe. Its distribution covers an area at medium latitude, characterized by a continental climate with Hungary and certain areas of France and Italy being the most ragweed-polluted countries. (71). Several factors contribute to this pattern by accelerating the migration of this invasive allergenic plant with climate change only playing a secondary role. For example, in eastern European countries, the expansion of ragweed seems to be associated with major socio-economic transitions rather than with climate change. This observation could be explained by the increase in areas of disturbed land (suitable for ragweed proliferation), which occurred during the collapse of communism (72). Interestingly, airborne pollen counts of *Ambrosia spp* have decreased in the last 20 years in Tulsa, USA, one of the original sites where the plant became established. (12) Authors suggest that urbanization and an increased August temperature are possible factors determining this effect.

## Effects of climate change on indoor allergens

In addition to potential effects on outdoor mold growth and allergen release related to changing climatic variables, there is also concern about indoor mold growth in association with rising air moisture, especially after extreme storms and flooding. Although mold allergy is uncommon, it has been shown that asthma and respiratory symptoms are 30–50% more prevalent in damp houses (73).

Under current projections, it is possible that people will spend more time indoor because of extreme summer weather events, but less in winter months. This implies that a change in exposure pattern can more likely than not be expected with climate change rather than an overall simple variation in the amount of exposure.

Asthma in children in mild climates is often associated with mite allergy. In colder climates in winter in the north or in mountainous areas, heated indoor air has a low humidity. Significant house dust mite exposure in such settings is unusual, which explains why mite allergy is rare in these areas. Unusually cold winters have resulted in reduced mite allergen levels in Germany (74). High elevation and large temperature differences between summer and winter are associated with less asthma (75, 76). Consequently, it is possible that with milder and more humid winters, new regions may face increasing house dust mite exposure and subsequent mite allergy.

## Effects of climate change on the interaction between pollen and pollutants

Plants are continuously exposed to abiotic and biotic environmental stress and respond to pathogen attacks and/or external stress by rapid changes in gene expression, resulting in the de novo synthesis of specific proteins. Pollutants are among the main stressors, especially in urban areas, and are thought to interact mainly in three ways.

1 Air pollution can increase the expression of allergenic proteins, as response of plants to environmental threats. *Cupressus arizonica* pollen grains from polluted cities showed a higher Cup a three concentration (a thaumatin-like protein (TLP) of the pathogenesis-related (PR) proteins family) than that found in pollen of less polluted areas. This mechanism could determine an increase in the allergenicity of cypress pollen in urban areas (77)

2 Components of air pollution can interact with inhalant allergens carried by pollen grains (78, 79). A study in four

European cities showed that allergens from pollens, latex and β-glucans were bound to ambient air particles. Thus, combustion particles in ambient air can act as carriers of allergens and as depots of allergens inhaled into the airways (80). In experimental conditions, *Phleum pratense* (timothy grass) pollen releases more allergen-containing granules when exposed to increasing concentrations of $NO_2$ and $O_3$. These effects might lead to an increase in bioavailability of airborne pollen allergens (81).

**3** Air pollution may enhance the risk of exacerbation of symptoms in sensitized subjects (78, 82), inducing airway mucosal damage and impaired mucociliary clearance that may facilitate the access of inhaled allergens to the cells of the immune system (81, 83, 84).

### Effects of climate change on allergenic fungal spores

Most fungi are well adapted for wind spore dispersal. Species such as *Alternaria*, *Cladosporium* and *Aspergillus* have been associated in some but not all studies with a higher prevalence of asthma hospital admissions. Increased humidity along with higher winds speed can trigger spore production and dissemination.

The effects of elevated $CO_2$ on spore production and allergenicity have not been fully elucidated. There is limited and inconsistent evidence of increasing trends in mold production, mainly derived from observational analyses of long-term data sets. A study from Derby, UK, showed *Alternaria* spore counts to be increasing, especially after 1992 (85). Differences between Derby and Cardiff were speculatively attributed to both increased cereal production and changes in climate (86). With a continued rise in atmospheric $CO_2$ concentrations and early arrival of spring, a significant jump in winter and summer warming is likely to be accompanied by a step-wise advance in the hydrological cycle and ensuing growth of weeds, pollen and fungi (87, 88).

Extreme weather events might favor an increase in spore counts. Thunderstorms and asthma exacerbations have been correlated with a doubling of ambient fungal spores (89, 90), while changes in precipitation, with heavier downpours and more widespread flooding, may provoke a higher likelihood of wet interior surfaces that are prone to fungal growth.

There is however limited clinical evidence to support this possibility although co-exposure to both ozone and outdoor fungal spores has been significantly associated with markers of asthma severity, with an increase in asthma symptoms and rescue medication use (91).

### Effects of climate change on the prevalence of asthma and atopic diseases

Exposure to elevated pollen and mold concentrations may lead to a greater likelihood of development of an allergic respiratory disease in sensitized subjects and an aggravation in patients already symptomatic. Current projections generally indicate an increase in pollen exposure (6, 7, 9), which could lead to an increase in the prevalence of allergic diseases.

However, the limited availability of extensive aerobiological and epidemiological datasets present difficulties in making an association between changes in the prevalence of asthma and atopic diseases and observed climatic changes, as climatological studies are usually based on at least 30 years long datasets.

Furthermore, allergenic pollens arriving in new areas (because of changes in environment and land use or long distance transport) could be responsible for new sensitizations in atopic individuals who did not have prior allergies to that pollen. Even anthropogenic factors could play a direct role. For example, the increase in birch pollen allergies has been attributed to the introduction of birch trees into the suburbs north of Milan in the 1970s and 1980s (92).

### Perinatal effects

An association between the month of birth and the risk of allergic sensitization (93,94, 95) or asthma (96–99) later in life has been found in numerous studies. One possible explanation is that exposure to seasonal allergens in the perinatal period may contribute to the development of atopic disease. Children born after a season of extremely high birch pollen (whose mothers were exposed during pregnancy) do not have an increased risk for developing atopy (100). On the other hand, higher exposure to spores and pollens in the first 3 months of life has been associated with an increased risk of early wheezing (101). This indicates that exposure to aeroallergens before birth is less important in the development of allergy than exposure in possibly the most susceptible period during the first 3 months of life.

### Conclusions

Climate change is unequivocal and represents one of the greatest environmental, social and economic threats facing the planet. Projected global warming this century is likely to trigger serious consequences for mankind and other life forms, including those plants and fungi, which produce allergenic pollen and spores.

The evidence to date suggests that changes in phenology, pollen production and allergenicity and geographic distribution of plants have been occurring in recent decades and that nature of the changes may be region- and species-specific. Changes in the timing of aeroallergen production, in particular an advance of the flowering period, have been clearly shown for woody plants, and partially for grasses weeds and mold spores.

Possible effects of these observations on respiratory allergic diseases are speculative and have not to date been elucidated. The increase in prevalence of allergic diseases parallel the changes in phenology and pollen production of some plants observed in the last 20–30 years. Although these similar trends are suggestive, a causal relationship has not been demonstrated so far. Moreover, the trend in prevalence of allergic diseases is decreasing in some western countries, in contrast to pollen production and phenology.

On the basis of current knowledge, some projections for the impact of climate change on plant aerobiology can be proposed.

1 An early start of the pollen release is likely, which can be expected to be associated with an earlier appearance of symptoms of allergic diseases in the same year.

2 A longer duration of exposure during the sensitization phase may lead to greater likelihood of the development of allergy.

3 Exposure to a higher airborne allergen load may lead to a greater likelihood of more severe atopic and respiratory symptoms and of new sensitizations. To our knowledge, none of these effects have been demonstrated, to date.

There is little question that air quality will be influenced by climate changes. The challenge is to understand these interactions and influences better and to quantify the direction and magnitude of resulting air quality and the impact on human health.

## Limitations and Future reasearch

Some limitations make predictions uncertain. First of all, current knowledge shows that the magnitude and characteristics of climate change varies by different geographic areas. Thus, projections on climate change in general and on the effects on plants at continental scale are speculative. Moreover, there is a limited availability of long time series of data of airborne pollen and spore counts. This limitation is relevant considering that climatologic studies need to be at least 30 years long.

Regarding effects on respiratory disease, there are gaps in what we know about asthma exacerbations associated with aeroallergens; epidemiological studies aimed at studying the effects of pollen, and spore counts on asthma provide inconsistent results. One of the main points is the lack of information on clinical thresholds (i.e. the level of a specific pollen or spore able to induce symptoms in a sensitized subject) with different studies indicating that thresholds are very variable. Molecular aerobiology, which is the measurement of allergen content of pollen and/or airborne particles, could shed a new light on this issue.

Although some of the above-mentioned limitations will not be easily overcome, an improvement of our knowledge in this field is both feasible and desirable.

1 Long datasets are needed for this type of study. National aerobiological networks have to be improved in terms of number of monitoring stations with extended datasets to provide information on trends and possible changes in pollen counts. This will be important to implement models able to project future scenarios. The development of molecular aero-

biology will provide a more detailed approach in term of health impacts.

2 Possible effects on allergic patients of the earlier appearance of some allergenic pollens and longer duration of pollen seasons are still speculative and needs to be addressed by specific studies.

3 Studies on possible socio-economic effects of climate change on allergic diseases in Europe are lacking especially in children, an issue recently discussed by the US environmental protection agency (9). Furthermore, future scenarios on allergic diseases should take also into consideration possible effects of climate change on pollen and spores.

4 A multidisciplinary approach is mandatory to address the full spectrum of issues implicit in studying climate change, aerobiology and clinical outcomes.

## Recommendations

1 Efforts should be made to elucidate the role of climate change on the development of atopy in infants and children in the coming decades.

2 The role of changes in pollen and spore exposure on the development of atopy and asthma in future scenarios deserves more attention in national and international guidelines for the diagnosis and management of respiratory allergic diseases.

3 A crucial issue is the need of short and long-term data. For this reason, we recommend that national pollen networks are improved and extended, possibly converging in a common European network, which could then be able to spread information about pollen count. Continuous aerobiological monitoring is the cornerstone for observing changes in pollen and spore production forming the basis to build up long time series, a prerequisite for studies on the effect of climate change. These networks should be adequately financed.

4 More attention should be paid to the urban areas and especially to building materials able to reduce the indoor humidity levels. The implantation of new trees should be attentively evaluated by allergy and aerobiology specialists to avoid high allergenic species.

5 Reducing air pollution might contribute to lessening of the impact of climate change on pollen and directly on patients, while recognizing that ozone, the key pollutant associated with climate change, may be the major driver of pollutant/pollen interactions.

6 The influence of climate change on early and late allergic sensitization is very complex and potential effects on the development of asthma and atopy, and the consequent economic impact underlines the importance of the creation of Collaborative European networks.

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