



CME review

Impact of climate change on aeroallergens

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At the conclusion of this activity, participants should be able to:

- Describe the techniques involved in the assessment of global climate change.
- Summarize the importance of changes in vegetation phenology on assessing climate change.
- Discuss the impact of changes in ambient carbon dioxide and temperature on aeroallergenic plants and their production of pollen.
- Discuss the impact of ambient carbon dioxide changes on plant-fungi interactions and airborne fungal allergen burden.

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Introduction

Few recent topics have spurred discussion and controversy more than climate change and global warming. The contentiousness of opinion surrounding this issue is apparent by the difficulty in achieving international accords at the Climate Change Conference held in Copenhagen, Denmark, in December 2009. Climate change, however, is not a new phenomenon in the history of the

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planet. Mass extinctions have occurred, documented in the fossil record, of which the most prominent is the disappearance of the dinosaurs, postulated as being due to either the Yucatan or the Indian subcontinent meteor strikes. The resultant burden of atmospheric ash is hypothesized to have caused the abrupt climate change of a “global winter.” However, even in the more recent paleohistory of the globe, several warming and cooling cycles can be demonstrated. The Pleistocene epoch encompassed the 4 major glacial periods, as well as 2 final warming periods called the Bølling and the Allerød, spanning from 14,700 to 12,900 years before the present, and a final cooling period called the Younger Dryas from 12,900 to 11,700 years before the present. This latter period was postulated as being due to another comet strike over the Laurentide icesheet.¹ The Holocene epoch followed, extending into the present, with rapid warming following a cold event 8,200 years before the present. More recently, there was a medieval warm period, from the 10th to the 13th centuries, followed by the Little Ice Age, from the 14th to the mid-19th century. The cooling was not as severe as that previously experienced in the Pleistocene glacial periods.

Significant human activity is limited to the Holocene epoch. It appears uncontroversial that temperatures have been rising during the past 150 years, coincident with the advent of the industrial revolution. The question is whether this increase in temperature reflects inherent fluctuations, astronomic perturbations, or anthropogenic factors. Inherent fluctuations are probably multifactorial and may include shifts in the earth’s magma core with resultant volcanic activity, wobbling of the earth’s axis and varying angular tilt from the plane of the orbit, and shifts in the orbit itself around the sun. Other astronomic perturbations would include variations in solar flare activity and a resultant impact on the solar radiation stream and impact from extraterrestrial bodies, such as meteors and comets. Fluctuations of the Alaskan boreal-forest and tundra interface during the last 700 years are thought to reflect changes in solar activity.²

Anthropogenic climate change is due to human activity: primarily generations of carbon dioxide from fossil fuel burning as a consequence of the industrial revolution but also from the impact of fluorocarbon emissions on the protective ozone layer. The Fourth Assessment Report by the Intergovernmental Panel on Climate Change, released in 2007, stated warming of the global climate

system is unequivocal and there is a more than 95% certainty that the cause is extrinsic.³ The finding that human activities resulting in greenhouse gas emissions have a net warming effect is likely at the more than 90% confidence level.⁴ Greenhouse gas molecules cause warming by reflecting infrared radiation back toward the earth rather than allowing dissipation out through the atmosphere. Carbon dioxide is not the only greenhouse gas; methane and nitrous oxide gases also have similar properties. Considering the long residence time of carbon dioxide, methane, and nitrous oxide in the atmosphere and the inertia of the climate system, even if emissions were abruptly reduced to zero, global warming would continue throughout the 21st century and likely persist for hundreds of years.⁵

Evaluating Climate Change

Investigation of abrupt climate change has used a number of techniques, including ice core and sediment sampling for isotope shifts, pollen changes, and beetle and midge larval responses.^{6,7} Vegetation changes have proven to be sensitive in this regard, easily showing changes within a century, and when transitional zones are examined, vegetation responses could occur within a decade of climate change.⁶ Comparison of aerial photography of such a mountainous zone in the Spanish Central Range from 1957 to 1991 revealed encroachment of high-mountain grassland previously dominated by *Festuca aragonensis*, *Juniperus communis*, and *Cytisus oromediterraneus*, shrubs from lower altitudes.⁸ Because yearly total precipitation showed no significant variation, the advance of woody species was believed to be due to the demonstrated warming of the region.

The study of pollen affords different ways to gauge vegetation shifts in response to changing climatic conditions across the spectrum of time. Paleopalynology examines the fossil pollen record, whereas analysis of peat and lake sediments provides information spanning the more distant past up into the most recent decades.^{6,9,10} Records of aeroallergen sampling give insights of ongoing responses from the more recent past into the present.^{11,12} Both pollen abundance and diversity can give clues to shifts in plant dominance. Weng and colleagues⁹ examined the pollen fossil record in 4 different altitudinal vegetation belts: sub-Andean forest, Andean forest, subparamo, and grass paramo (high treeless plateau). Plant and pollen diversity decreased with altitude, and under

Table 1
Effect of environment on allergenic plants and pollen

Plant/pollen type	Reference	Environmental variable	Region	Effect
385 plant species	15	Increased temperature	United Kingdom	Onset flowering advanced a mean of 4.5 days during decade; approximately 65 species advanced 15 days
Grass	17	Increased temperature	Switzerland	Increased counts
Birch	29	Increased temperature	Spain	Delayed onset, shorter season, lower counts
	16, 19		Western Europe	Increased pollen counts, earlier season onset, higher peak level
	17, 20		Switzerland	Increased counts
	18		Denmark	Increased counts
Hazel	22	Increased temperature	Italy	Increased counts
	17		Switzerland	Increased counts
Oak	11	Increased temperature	Spain	Earlier season onset
Alder	30	Increased temperature	Spain	Delayed onset 2–8 days
Olive	21	Increased temperature	Spain	Earlier season onset, longer season, higher total counts
	22		Italy	
Japanese cedar	28	Increased temperature	Japan	Longer season
Cypress	22	Increased temperature	Italy	Earlier season onset, longer season, higher total counts
Longleaf pine	33	Increased carbon dioxide	United States	Increased biomass
<i>Parietaria</i> sp	22	Increased temperature	Italy	Earlier season onset, longer season, higher total counts
Ragweed <i>Ambrosia</i> sp	23	Increased temperature	Canada	Increased counts, earlier onset, longer season,
	24	Increased carbon dioxide	United States	increased range
	27		Poland	Increased biomass, increased pollen production
	34, 35, 36, 39		United States	
<i>Artemisia</i> sp	12	Increased temperature	Poland	Earlier season onset
	32	Increased carbon dioxide	United States	Increased biomass, increased ground cover
Poison ivy <i>Toxicodendron radicans</i>	31	Increased carbon dioxide	United States	Increased biomass, increased antigen

warmer climatic conditions, more species-diverse vegetation moved upslope and vice versa with cooling conditions.

Altitude is a surrogate for temperature decrease and northerly latitude. For every 1,000-ft increase in height, there is a 3°F decrease in temperature, the equivalent of moving 600 miles farther north.¹³ Floristic zones define the type of native vegetation found in a region and are in turn defined by several factors affecting high and low temperatures and mean precipitation. A major factor is the hardiness zone, which is characterized by the mean annual minimum temperature. In the North American continent there are 12 such zones stretching from the tundra of the Northwest Territories (−60°F) to the Mexican tropics (>40°F). Shifts in global temperatures will cause migration of these zones north or south and will therefore affect the type of vegetation found at any latitude in a given region. This shift has been shown in the North Atlantic fossil pollen record, with southern encroachment of boreal trees, such as fir, larch, and alder with cooling and replacement with oak and white pine with subsequent warming.⁶ Global warming has caused a shift of the zones northward, requiring a 2006 revision of the 1990 US Department of Agriculture Plant Hardiness Zone Map.¹⁴ Some areas within the United States have experienced a 2-zone shift in the 16 years between maps.

Pollen and Climate Change

Bud set and flowering are intimately linked to accumulated warmth over time for many herbaceous and woody plants. Global warming would therefore speed flower development, resulting in earlier blooming. In 2002, Fitter and Fitter¹⁵ reported that of 385 British plant species examined, the mean first flowering had advanced by 4.5 days during the previous decade. A sixth of species had a marked advancement of 15 days, whereas 10 species (3%) had delayed flowering. Spring-flowering plants were the most affected and were especially sensitive to temperature in the preceding month. Entomophilous plants were more affected than anemophilous ones. Despite that observation, many wind-pollinated aeroallergenic types of pollen have demonstrated altered seasons (Table 1). European pollen monitoring has shown increases during 30 years in hazel, birch, and grass counts in Switzerland and Denmark.^{16–18} Emberlin and coworkers¹⁹ evaluated birch pollination across Europe and found earlier onset in London, England, Brussels, Belgium, Zurich, Switzerland, and Vienna, Austria, but a variable effect in Turkey, Finland, and later onset in Kevo, Finland. Frei and Gassner²⁰ reviewed 38 years of pollen data (1969–2006) from Basel, Switzerland, showing that the start of birch flowering had advanced 15 days, and there were trends for increased total annual birch pollen amounts and highest daily mean pollen concentrations. Use of a thermal forecasting model was validated for European olive (*Olea europaea*) in Spain, and observations from 1982 to 2001 showed earlier onset of pollination.²¹ The onset of olive pollen anthesis was expected to advance by 1 to 3 weeks throughout the century. The same group of researchers similarly demonstrated earlier flowering of oak (*Quercus*) associated with increased temperatures in the preflowering periods during the past 50 years.¹¹ Higher oak pollen counts were found in Mediterranean sites. Assuming a doubling of carbon dioxide levels for the end of the 21st century, *Quercus* will start a month earlier, and concentrations will be 50% higher. Ariano and colleagues²² showed that throughout 27 years in Liguria, Italy, earlier onset, longer season, and increased total pollen counts for *Parietaria*, cypress, and olive and total counts for birch were increased but without a change in the season.

Similar trends have been seen for late summer weeds, such as *Artemisia* (mugwort) and *Ambrosia* (ragweed) in Poland and Canada, respectively.^{12,23} The explosive expansion of ragweed (primarily short ragweed, *Ambrosia artemisiifolia*) in central Europe has been linked to its predilection to the warm continental climate, and it is suggested that its extension northward will be facilitated by

increasing temperatures.^{24,25} Ragweed sampling data collected from almost a dozen sites across the Midwest United States and southern Canada from 1995 to 2009 revealed an increase of the ragweed pollen season of 13 to 27 days, which correlated with delay of first frost.²⁶ Three woody perennial shrubs in the northeastern United States (lilac, apple, and grape) monitored from 1965 to 2001 showed earlier first leaf and first flower dates, with advances of 2 to 8 days.²⁷

Earlier onset with warmer temperature is not a universal finding. Japanese cedar counts in Japan from 1987 to 1998 showed a longer season due to increased pollination in the autumn but no increase in count amplitude or earlier spring onset.²⁸ In contrast to findings in Switzerland, grass counts in Galicia, Spain, during the past 15 years showed a downward trend in annual grass counts, lower peaks, fewer days with elevated counts, and delayed onset with a decreased duration of the season when compared with counts during the past 30 years.^{17,29}

Boreal hardwoods require a fixed cumulative amount of chilling temperatures to break dormancy, followed by subsequent accumulation of heat to initiate flowering. Warmer winters may result in a delay in achieving the necessary length of chill. *Alnus* (alder) is such a winter-pollinating northern tree. Trend analysis of onset of pollination of *Alnus* in Spain has shown a gradual delay of between 2 and 8 days.³⁰

There are several studies evaluating the effects of increased carbon dioxide and temperature on allergenic and toxic plants. Mohan and colleagues³¹ assessed the 6-year effect of carbon dioxide, which increased 200 $\mu\text{L/L}$ over ambient levels (370 to 570 $\mu\text{L/L}$) on growth of poison ivy in loblolly pine stands. During the study, in the increased carbon dioxide plots the poison ivy showed increased photosynthesis, water use efficiency, and population biomass. In addition, the carbon dioxide-enriched plants produced a greater percentage of unsaturated urushiol, which is more antigenic. The mat-forming, short, perennial shrub-fringed sage, *Artemisia frigida*, is the most widespread and abundant *Artemisia* species in the world. Doubling carbon dioxide levels over ambient levels on Colorado shortgrass steppe plots revealed a 40-fold biomass increase in *A frigida* during 5 years.³² The percentage of ground cover of *A frigida* increased 20-fold. Plots of longleaf pine, *Pinus palustris*, show increased growth with carbon dioxide enrichment, whereas sand post oak, *Quercus margetta*, was unaffected, and several grasses and weeds were negatively affected.³³ These studies reinforce the theory that elevated carbon dioxide levels will be attended by shifts in various plant communities.

Ziska and Caulfield³⁴ and Wayne and associates³⁵ reported increased *A artemisiifolia* (short ragweed) biomass and pollen production of 61% to 90% with increased ambient carbon dioxide. In an experiment manipulating both temperature and carbon dioxide, Rogers and coworkers³⁶ increased temperature simulating early spring and showed increased inflorescences and pollen compared with later-blooming ragweed plants. Greater biomass and pollen production was seen with increased carbon dioxide, which had a greater impact on later-growing cohorts. Because content of the ragweed major allergen Amb a 1 will vary in plants from site to site and even from year to year at the same site, the question can be raised of whether increased pollen production necessarily implies an increase in airborne allergenic load.^{37,38} This issue was addressed by Ziska and associates³⁹ collecting ragweed pollen along an urban transect in Maryland, using the urban environment as a surrogate for climate change. There was a gradient of both air temperature and carbon dioxide level through 4 sites: urban, suburban, semirural, and rural. The urban site averaged a 2°C higher temperature and a 30% higher carbon dioxide level than the rural site. As expected, the urban ragweed had a greater above ground biomass, grew faster and flowered earlier, and produced more pollen than the rural site. There was an almost 2-fold greater con-

Table 2
Effect of environment on fungi

Fungal type	Reference	Environmental variable	Effect
Mycorrhiza	44–46	Increased carbon dioxide Decreased soil nitrogen	Increased biomass Decreased biomass
Powdery mildew <i>Erysiphe</i> sp	47	Increased carbon dioxide	Increased infectivity of thale cress
Autumnal-fruiting mushrooms	48	Increased temperature	Delayed/compressed fruiting season
Spring-fruiting mushrooms	49	Increased temperature previous winter	Fruiting season advanced 18 days
<i>Alternaria</i> sp	50	Increased carbon dioxide	100% increased airborne spores
<i>Cladosporium</i> sp	51	Increased carbon dioxide	Decreased biomass Decreased bacterial counts
<i>Alternaria alternata</i> <i>Cladosporium phlei</i>	52	Increased carbon dioxide	3-fold increased spore biomass Decreased Alt a 1 concentration per spore but 2-fold increase overall production due to biomass increase Increased spore biomass

centration of Amb a 1 per microgram of protein in the rural vs the other sites. However, there was a larger than 7-fold increased production of pollen from the urban sites compared with the rural site, supporting the increased airborne allergenic burden.

Interaction of Climatic Factors

The close link between elevating carbon dioxide and temperature levels and the effect on plants is evident; however, other physical factors will have augmenting or modulating effects as well. Soil moisture content is important. UV radiation in conjunction with increased temperature or carbon dioxide had varying effects on flowering and pollen production in soybean strains.⁴⁰ Either increased temperature or UV-B irradiation resulted in smaller flowers, less and misshapen pollen, and poor germination, which could not be overcome by increased carbon dioxide. When the effects of increased carbon dioxide are separated from increased temperature, the effect on plants is variable. Wu and colleagues⁴¹ studied the effect of temperature, precipitation, and atmospheric carbon dioxide concentrations on tree-line elevation in tropical Africa based on pollen data from the last glacial maximum. They found that lowering of the tree line during the last glacial maximum was primarily triggered by regional drying, especially at higher elevations, but amplified by decreases in carbon dioxide concentration and possibly temperature. This was, they believed, in contrast to events in the Holocene and future climates, where increases in tree-line elevation would be dominated by temperature. The importance of water availability in the response of plants to carbon dioxide concentration and temperature has also been reinforced by the studies of Lecain and coworkers,⁴² who demonstrated that the effect of elevated carbon dioxide levels on photosynthesis of grasses in a semiarid ecosystem is blunted by decreased soil water content.⁴²

Fungi and Climate Change

Growth of fungi can likewise be affected by climate change (Table 2). As reviewed by Gilmour and colleagues,⁴³ **increased rainfall and coastal flooding will increase indoor wetness and thereby augment mold growth.** They state that increased temperature with resultant increased use of air-conditioning with “inevitable mismanagement will likely result in more cases of inappropriate moisture conditions in buildings.”

A great deal of research has been directed toward the effect of elevated carbon dioxide on the symbiotic relationship between mycorrhizal fungi and plants. Arbuscular mycorrhiza invade the cells of plant roots and act intracellularly, whereas ectomycorrhizal fungi remain extracellular. In both cases, the plants (frequently trees) provide carbohydrates to sustain the fungi, and the mycorrhiza capture phosphorus, sulfur, nitrogen, and other micronutrients that are made available to the plant. Increased carbon dioxide enhances growth of fungal mycorrhizal associations with trees.⁴⁴

Although biomass is initially increased for the symbiotes, the process is limited by the soil availability of nitrogen.^{45,46}

Increased plant biomass may also result in increased saprobic fungi. Aggressiveness of powdery mildew (*Erysiphe cichoracearum*) infection of thale cress (*Arabidopsis thaliana*) is increased with elevated carbon dioxide levels.⁴⁷ The effect on fungal sporulation may not be straightforward. Although earlier mushroom fruiting with a later end of season was previously reported in England, a Norwegian study⁴⁸ of 83 mushroom species revealed a delayed and compressed autumnal fruiting season. These authors⁴⁹ further reported, however, that in both the United Kingdom and Norway, 34 spring fruiting fungi advanced their fruiting by a mean of 18 days and that early fruiting correlated with the high temperatures of the preceding winter.

Little research has been published on the impact of carbon dioxide elevation or climate change on allergenic *Deuteromycetes*. Klironomos and coworkers⁵⁰ found a 100% increase in airborne *Alternaria* spores in chambers with aspen (*Populus tremuloides*) grown at double the ambient carbon dioxide. Contrary results were seen by Kelly and associates,⁵¹ who examined the microbial colonization of *P tremuloides*, *Salix alba*, and *Acer saccharum* leaf litter in a woodland stream at double ambient (720 ppm) carbon dioxide. In that study the only significant change was a decrease in *Cladosporium* species biomass and bacterial counts on the aspen leaves. Wolf and colleagues⁵² examined the effect of elevated carbon dioxide concentration on the growth of *Alternaria alternata* and *Cladosporium phlei* on timothy (*Phleum pratense*) leaf blades. Timothy plants were grown at carbon dioxide concentrations of 300, 400, 500, and 600 micromol/mol. The leaf carbon-nitrogen ratio was greater at 500 and 600 micromol/mol, and leaf biomass was greater at 600 micromol/mol. The leaf carbon-nitrogen ratio was positively correlated with *A alternata* spore production and negatively correlated with antigenic protein content per spore (polyclonal enzyme-linked immunosorbent assay measuring more than Alt a 1). However, spore biomass at the higher 2 concentrations was 3 times greater than the lower concentrations, and antigenic protein was twice as high. *C phlei* spore production was likewise positively correlated with leaf carbon-nitrogen ratio, but spore counts were lower and did not show significant differences between the carbon dioxide levels.⁵²

Conclusion

Whether one chooses to believe that the present climate change is primarily due to human activity or that these changes represent another global cycle, as has occurred in the history of the earth, **the evidence that warming is occurring is uncontroversial.** As stated by Beggs,⁵³ **there is now a wealth of evidence that climate change has had and will have a further impact on a variety of allergenic plants.** In the face of adequate moisture, increased carbon dioxide generally increases plant biomass and pollen production. It is conceiv-

able that increases in airborne pollen numbers will increase the efficiency of windborne pollination, thereby increasing propagation of such plants. The expectation then is that there will be increasing amounts of robust allergenic plants and an increasing aeroallergen burden for those with inhalant allergy. Ariano and coworkers²² showed an increase in sensitization for *Parietaria*, birch, cypress, and olive, which paralleled the increases in total pollen counts. Although purely speculative at this time, it is interesting to consider the role that climate change, with the concomitant increase in certain aeroallergen exposures, may have in the increased prevalence of atopic disorders. Although the additional role of air pollutants in augmenting allergen sensitization and their interaction with aspects of climate change is beyond the scope of this review, 2 recent reviews have addressed this interplay.^{14,54}

It is obvious that an assortment of research approaches can provide useful insights into the impact of climate change on aeroallergens and resultant allergic disease. Considering the cascading effects of increased carbon dioxide and temperature, increased biomass, increased pollen and aeroallergen burden, increased sensitization, and finally atopic illness, further research can be directed to all of these levels. Monitoring of changes in pollen counts and plant phenology continues as a useful gauge of climate change. Additional studies of airborne characterized allergen levels will give greater precision in assessing aeroallergen burden. Expanded studies of other relevant aeroallergenic plants besides *Ambrosia* and *Artemisia* should be an area of further research. The paucity of published studies of the impact of carbon dioxide and other environmental variables on airborne allergenic fungi reinforces the need for research in this arena.

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