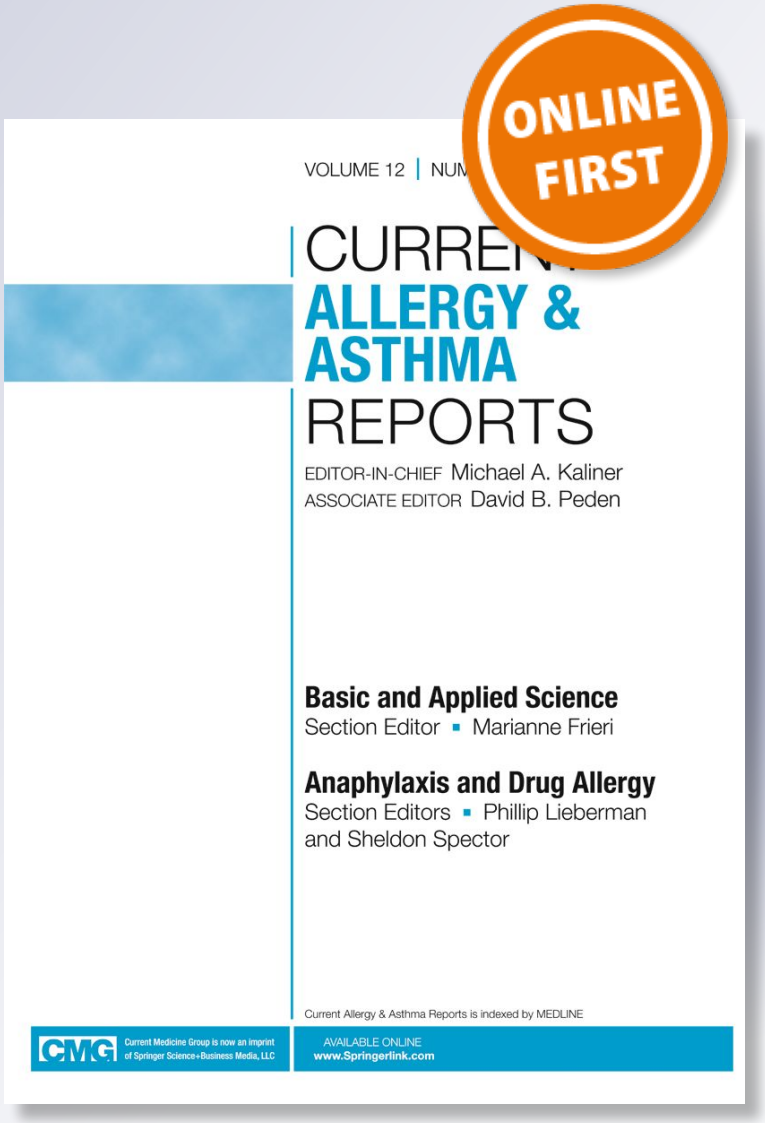
# *Climate Change and Allergic Disease*

**Leonard Bielory, Kevin Lyons & Robert Goldberg**

**Current Allergy and Asthma Reports**

ISSN 1529-7322

Curr Allergy Asthma Rep
DOI 10.1007/s11882-012-0314-z




Springer

Your article is protected by copyright and all rights are held exclusively by Springer Science +Business Media New York. This e-offprint is for personal use only and shall not be self-archived in electronic repositories. If you wish to self-archive your work, please use the accepted author's version for posting to your own website or your institution's repository. You may further deposit the accepted author's version on a funder's repository at a funder's request, provided it is not made publicly available until 12 months after publication.

Springer

Author's personal copy

Curr Allergy Asthma Rep
DOI 10.1007/s11882-012-0314-z

HOT TOPIC

# Climate Change and Allergic Disease

**Leonard Bielory · Kevin Lyons · Robert Goldberg**

© Springer Science+Business Media New York 2012

**Abstract** Allergies are prevalent throughout the United States and impose a substantial quality of life and economic burden. The potential effect of climate change has an impact on allergic disorders through variability of aeroallergens, food allergens and insect-based allergic venoms. Data suggest allergies (ocular and nasal allergies, allergic asthma and sinusitis) have increased in the United States and that there are changes in allergies to stinging insect populations (vespids, apids and fire ants). The cause of this upward trend is unknown, but any climate change may induce augmentation of this trend; the subspecialty of allergy and immunology needs to be keenly aware of potential issues that are projected for the near and not so distant future.

**Keywords** Climate change · Allergies · Allergic disease · Asthma · Rhinitis · Sinusitis · Food allergy · Cost of Illness · Economics

## Introduction

The skin, conjunctiva, respiratory and digestive tracts compose a large immunologically active surface that primarily interacts with the external environment. An allergen often triggers an allergic response at multiple sites and is associated with an atopic march in which the allergic response progresses to include multiple allergens and multiple responses. Allergic diseases, including asthma, hay fever, rhinitis, and atopic dermatitis, impact approximately one-third of the population in the U.S. (~100 million individuals) and are associated with significant health care costs and lost productivity that range from over-treatments to significant utilization of health care resources within the medical system. These include urgent care, emergency room visits, and hospitalizations [1, 2]. Data from National Center for Health Statistics/NHANES studies indicate that the prevalence of allergic disease has increased over the past 30−40 years [3], including food allergies [4]. Although the underlying causes of the rising trend of allergic disease are not clear, links have been made to various climate factors (e.g., temperature, precipitation, rising $CO_2$ concentrations) and their impact on the production and distribution of aerobiological allergens (pollen and mold) [5, 6]. Regardless of the cause, the economic impacts of allergies, including allergic respiratory disorders, and the impact on quality of life are already a well-recognized health care burden; thus, any additional burden generated by climate change needs to be included in future impact assessments (Fig. 1).

## Climate Change

### Definition

One of the major issues regarding climate change is understanding the terms being used, There appears to be confusion among the public, government and scientific communities with regard to differences in the meaning of the terminology [7]. By using a statistical analogy, the term "climate" represents the 'mean' and "weather" represents the 'variation around the mean'. *Climate change* reflects

L. Bielory (✉)
Robert Wood Johnson University Hospital, Rutgers University, New Brunswick, NJ, USA
e-mail: bielory@rutgers.edu

K. Lyons
Rutgers University School of Business, Piscataway, NJ, USA

R. Goldberg
Center for Medicine in the Public Interest, New York, NY, USA

Published online: 13 October 2012

Author's personal copy



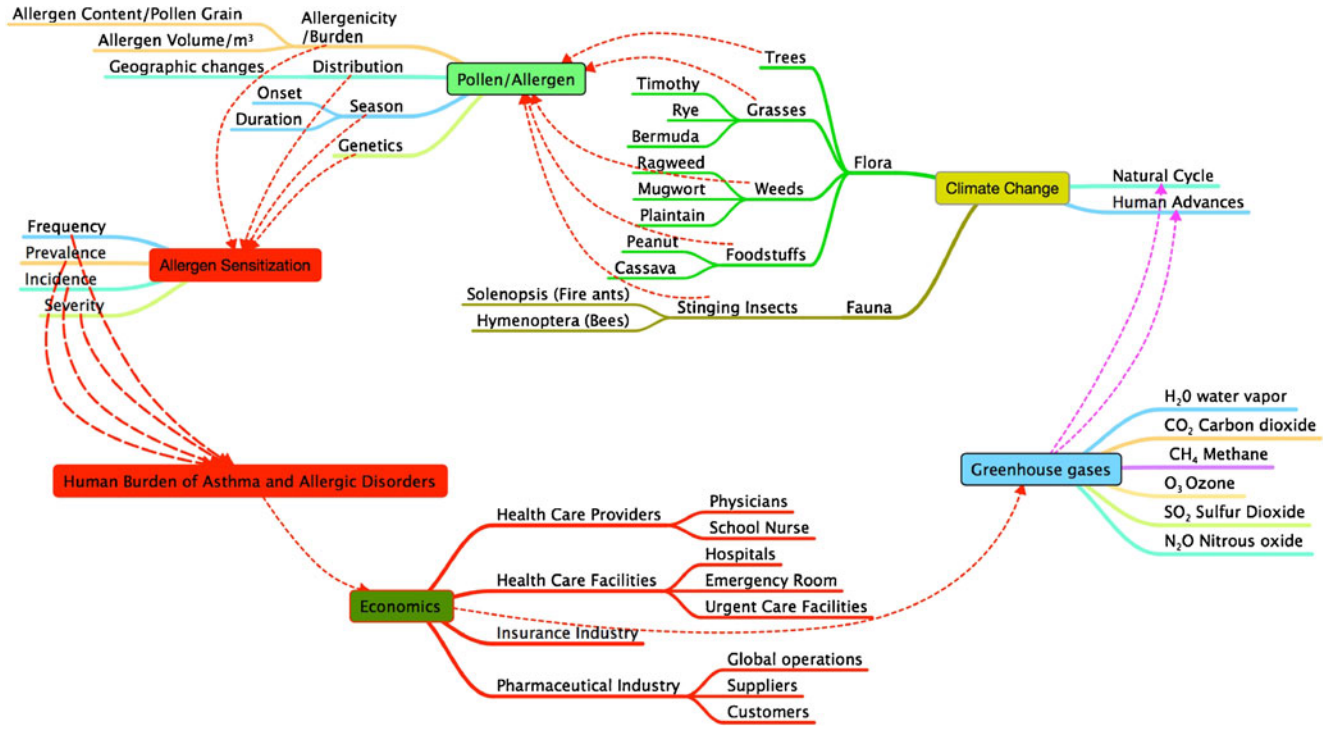



**Fig. 1** The cycle of climate and allergic disease. The generation of greenhouse gases, whether due to the nature's own cycle or in combination with man-made sources, generates conditions that promote changes in the climate that affect the flora and fauna associated with allergic disorders. These include alterations in habitats and allergen content of stinging insects to the impact on flora seasonal variations, geographic distribution, and allergen burden (concentration of allergen per grain of pollen or the actual amount of pollen produced per plant), as well as the potential changes in genetics of plants that may lead to the uncovering of novel allergens. Clinically, the exposure would lead to increased allergen sensitization with subsequent increases in frequency, prevalence, incidence, and severity of allergic disorders, including asthma. The end of the cycle is the impact that this would have on cost of illness (economics) through the various participants, including the health care providers and facilities, and pharmaceutical and insurance industries that would also leave a footprint in generating additional greenhouse gases

alterations in weather conditions over time (decades, centuries, millennia) while *weather* represents the day-to-day or *season-to-season* changes that include temperature (increase or decrease), precipitation (rain and snow), wind currents and multiple other meteorological variables.

## Intergovernmental Panel on Climate Change (IPCC)

There is increasing agreement among the world's scientists that alterations in greenhouse gas emissions into the lower atmosphere including carbon dioxide are now contributing substantially to the ongoing warming of the earth's surface. It is assumed that these changes have resulted from human activities that are superimposed on ongoing natural variations in the climate. The Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), a collaboration of more than 2000 scientists from 100 countries, noted that, since 1950, the temperature increase has been, with over 90 % certainty, due to primarily human activity—temperatures have increased 0.7 °C over the 100 years, and it is projected that they will increase by 1.8 to 4.0 °C from 1999 to 2099 [8]. Of note, recent measurements have shown that 2010 has been the hottest year globally in the instrumental record (i.e. since 1860) by the US-based Goddard Institute for Space Studies (NASA), the National Climatic Data Center (US National Oceanic and Atmospheric Administration). The IPCC report concluded that there was "good evidence" that the impact on temperatures and greenhouse gases has affected the timing of the onset of allergenic pollen production, which may influence pollen abundance and/or potency. These factors in turn are likely to increase the frequency of allergies and related respiratory disorders such as asthma [9]

## Preliminary Data on the Impact of Pollen Production

The impact that allergenic pollen would have on the development of allergies includes the annual volume of pollen, duration of exposure (onset, closure), intensity of exposure (daily amount), and allergenicity of pollen. In general, it has been appreciated that, for the greatest annual production of aeroallergens, tree pollen is the most abundant, followed by weeds and grasses. Climate change does impact the phenology [the study of plant (and animal) life cycle events that are

Author's personal copy



influenced by seasonal and annual variations in climate] of allergenic plants through alterations in pollen allergenicity, season, distribution, and amount [10–13] (see Table 1). One of the major considerations is that greenhouse gases (e.g., atmospheric $CO_2$) will absorb energy in the form of heat, which will result in increased surface temperatures and wider fluctuations in weather [11], with changes in plant biomass and pollen production [6] such as short ragweed (*Ambrosia artemisiifolia*) increasing by as much as 60 % [14, 15]. In addition, study associated with the growth of ragweed using different CO2 concentrations suggested that, although the total pollen protein that was harvested from the plants remained unchanged, the AMB a 1 concentrations increased as a function of CO2 concentrations. Relative to pollen grown at current CO2 concentrations (i.e., 370 μmol/mol), pollen grown at futuristic levels such as 700 μmol/mol of CO2 contained 1.6 times more AMB a 1 allergen ($p<0.01$) [16]. Ragweed has one of the longest seasons of aeroallergens and is commonly believed to have the most common prevalence among allergic patients due to increased exposure [17]. In a recent analysis of the National Health and Nutrition Examination Survey, ragweed was the most common allergen, to which 70 % of the United Stated population had sensitivity (unpublished observation by author). Other allergenic plants that have demonstrated climate-induced changes include mugwort, grasses, and trees (including Japanese cedar [18, 19], olive, hazel, longleaf pine, cedar, birch, and alder) [20, 21] . In addition to projected changes in pollen, allergenic fungal spore growth and sporulation (e.g., *Alternaria alternata* [22]) are increased [23]. However, other studies have demonstrated an inverse relationship to allergenicity to increased spore production of *Alternaria* [20, 24]. In general, temperature is a more important variable for spring and early summer pollination of allergenic trees and grasses, while photoperiods (duration of sunlight) are more important for late summer and fall allergenic plants. The impact on pollen will involve dispersion and/or transport, as deposition of ragweed pollen appears to be more local than tree pollen. However, just as some areas will demonstrate increased pollen concentrations, others will show a decrease, such as that noted in European studies between the decreased "hay fever" prevalence (after 1992−1993) and reduced pollen counts [25], and decreased grass (Poaceae) pollen counts [26], coinciding with reduced precipitation. Overall, pollen concentrations have been noted by the International Phenological Gardens in Europe over the past 30 years, with earlier flowering by almost a week since the early 1960s [27] as it relates to grass pollen [28], birch pollen [29], mugwort/*Artemisia* species [11], and *Olea europaea* (olive tree) [30]. The grass pollen season in the northeast United States typically begins in April and ends in October, thus actually having two clear seasonal peaks. An earlier start of the grass pollen season was previously reported [28] in the New York/ New Jersey metropolitan area. Earlier and prolonged release of ragweed pollen season in a transect from Texas northward to Canada found a significant increase in length by 2−4 weeks since 1995 [31]. This has been consistent with the finding from an earlier meta-analysis that suggested a phenologic advance of 5 days per decade for multiple species of plants [32].

There is also the possibility that new aeroallergens may be introduced by intercontinental dispersion of pollen [33] such as ragweed to Europe [34]. Studies into the modeling of many of these allergenic species are presently part of ongoing research, entitled the Global Change Research Program (http://www.epa.gov/ncer/science/globalclimate/) Science to Achieve Results (STAR) initiated by the United States Environmental Protection Agency.

## Modeling

Bayesian modeling has incorporated variable selection−parameterization−evaluation−prediction to generate a climate change model and its potential impact on multiple pollen "indices" such as annual production, onset, peak date, and peak value [35]. Three IPCC scenarios representing regionally oriented economic development , rapid economic growth, and a balanced emphasis on all energy sources, and global environmental sustainability with different projections of global annual average $CO_2$ concentrations [853, 709, and 533 ppm] and temperature (17.7, 17.0, and 16.1 °C) in 2100 were used to generate future pollen indices to assess the risk of human-induced climate change. The predicted averages of annual production and peak value from 2020 to 2100 are 1.1~7.7 times versus the corresponding mean 2000−2009 values, with the onset and peak day advancing by 1~2 weeks (abstract accepted for presentation, ACAAI 2012).

## Climate Change Impact on Allergies and Asthma

### Allergies

Allergic diseases are the result of an interaction between the immune system and the interplay between genetics and the environment, primarily at the mucosal surfaces, and include rhinitis, conjunctivitis, sinusitis, asthma, urticaria, atopic and contact dermatitis, and gastrointestinal disorders such as food allergy, but also insect sting hypersensitivity [36].

#### *Allergen Sensitization*

As a result of climate change, allergen sensitization augmented by increased pollen production, increased duration

Author's personal copy



**Table 1** Significant correlation found between $CO_2$ concentrations and allergenic pollen concentrations in various countries

| Common name [Ref.] | Variables | Phenology | Scientific name | Location/method |
|---|---|---|---|---|
| Peanut and grain sorghum [66] | Temp<br>32/22, 36/26, 40/30, and 44/34 °C<br>$CO_2$<br>350 and 700 ppm | Elevated temperature decreased germination in both species and elevated $CO_2$ did not alter pollen longevity | *Arachis hypogaea; Sorghum bicolor* | Controlled laboratory facility in Gainesville, FL, USA.<br>SPAR chamber with natural sunlight |
| Cowpea [67] | Temp<br>30/22 and 38/30 °C<br>$CO_2$<br>360 and 720 ppm | Elevated $CO_2$ did not protect pollen from damage by elevated UV/temperature | *Vigna unguiculata* | Controlled laboratory facility in Mississippi, USA<br>SPAR chamber with natural sunlight |
| Loblolly Pine [68] | Temp<br>ambient summer, not controlled<br>$CO_2$<br>ambient and ambient plus 200 ppm | Elevated $CO_2$ resulted in increased pollen production and pollen production at younger ages and smaller tree sizes | *Pinus taeda* L. | Outdoor plantation plots in North Carolina, USA with vertical $CO_2$ delivery pipes on plot |
| grain-sorghum [69] | Temp<br>32/22, 36/26, 40/30 or 44/34 °C<br>$CO_2$<br>350 and 700 ppm | Temperature effects on reproductive processes is more severe at elevated $CO_2$ concentrations | *Sorghum bicolor* (L.) Moench | Controlled laboratory facility in Gainesville, FL, USA.<br>SPAR chamber with natural sunlight |
| soybean [70] | Temp<br>30/22 and 38/30 °C<br>$CO_2$<br>360 and 720 ppm | Elevated $CO_2$ did not protect against damaging effects of increased UV-B and | *Glycine max* L. | Controlled laboratory facility in Mississippi, USA<br>SPAR chamber with natural sunlight |
| Ragweed [16] | | Allergen content increases with elevated $CO_2$ | *Ambrosia artemisiifolia* | |
| Ragweed [14] | Temp<br>constant 26/21 °C.<br>$CO_2$<br>~380 (ambient) and 700 ppm | Elevated $CO_2$ increased pollen production, biomass, and flowered earlier | *Ambrosia artemisiifolia* | Glasshouse with controls for $CO_2$, temperature, and lighting (6 h per day supplemental light) |
| Ragweed [31] | Temp<br>ambient<br>$CO_2$<br>ambient | Increased duration | *Ambrosia artemisiifolia* | Transect that ran from Texas to Canada/ambient observations |
| Ragweed [71] | Temp<br>ambient<br>$CO_2$<br>ambient | Increased duration | *Ambrosia artemisiifolia* | Central Croatia/ambient measurements of pollen levels |
| Ragweed [72] | Temp<br>ambient<br>$CO_2$<br>ambient | Increased concentration | *Ambrosia artemisiifolia* | Northeastern Croatia/ambient measurements of pollen levels |
| Ragweed [73] | Temp<br>ambient<br>$CO_2$<br>ambient | Increased concentration | *Ambrosia artemisiifolia* | Slovakia/ambient measurements of pollen levels |
| Fireweed [74]; (also called Willowherb) | Temp<br>ambient<br>$CO_2$<br>350 and 650 ppm | No effect on pollen tube growth but significant effect on pollen germination probability. Some families increased and others decreased. | *Epilobium angustifolium* | Polyethylene chamber within greenhouse with ambient sunlight and temperature. Also varied nutrient loading in soil and sunlight was supplemented by artificial lighting. Greenhouse located in France or Switzerland. |

Author's personal copy



**Table 1** (continued)

| Common name [Ref.] | Variables | Phenology | Scientific name | Location/method |
|---|---|---|---|---|
| Garden Nasturtium [75]; also called Indian Cress or Monks Cress | Temp constant 22/16 °C<br>$CO_2$ ~380 and 760 ppm | Elevated $CO_2$ increased nectar secretion rate but did not affect time to flowering, total number of flowers produced, pollen to ovule ratio | *Tropaeolum majus* | Growth cabinets with artificial lighting located in Australia |
| Rice [76] (cv IR72) | Temp ambient and ambient plus 4 °C<br>$CO_2$ Ambient and ambient plus 300 ppm | Increased temperature and $CO_2$ resulted in sterility among pollen grains (less germination) | *Oryza sativa* | Open-top chambers Los Banos, Philippines |
| Field bean [77] | | Increased $CO_2$ increased number of flowers by 25 %; these flowers remained for 17 % longer time compared to controls | *Vicia faba* L | Open |
| Japanese cedar [18, 19] | Temp ambient<br>$CO_2$ ambient | Increased concentration | *Cryptomeria japonica* | Japan/epidemiological study that assessed correlation of temporal trends with patient visits |
| Birch [78] | Temp ambient<br>$CO_2$ ambient | Increased concentration | *Betula* | Northwestern Poland/ambient measurements of pollen levels |
| Birch [79] | Temp ambient<br>$CO_2$ ambient | Earlier flowering | | Switzerland/ambient observations |
| Grass [80] | Temp ambient<br>$CO_2$ ambient | Increased concentration | | Australia/ambient measurements of pollen levels |
| Mugwort [81] | Temp ambient<br>$CO_2$ ambient | Increased concentration | *Artemisia* spp. | Central Croatia/ambient measurements of pollen levels |
| Alder [82] | Temp ambient<br>$CO_2$ ambient | Increased concentration | *Alnus glutinosa* | Northwestern Spain/ambient measurements of pollen levels coupled with observations |
| Cedar [83] | Temp ambient<br>$CO_2$ ambient | | Cupressaceae | Southern Spain/ambient measurements of pollen levels |
| Alder [84] | Temp ambient<br>$CO_2$ ambient | Increased duration | *Alnus* | Worcester, United Kingdom; Poznań, Poland/ambient measurements of pollen levels coupled with observations |

(Adapted from Blando et al. [21])

of exposure, potential increase in allergenicity and pollutant exposure can act synergistically to stimulate the various genes to generate changes in biomarkers, thus altering the physiology of cells and tissues to generate an atopic disease state [37]. Thus, they can increase the prevalence and enhance allergic response, leading to more severe allergic disorders, including asthma, in the upcoming twenty-first century [38]. Over the past 40 years, allergic rhinitis in the

Author's personal copy



United States has increased in a continuum from 10 % in 1970 (Bousquet et al. 2008) to 16 % in the 1976−1980 survey (the NHANES II study) (Gergen, Turkeltaub and Kovar 1987 [39]) to 28 % in the 1988−1994 survey (NHANES III) [3] to 30 % in 2000 [40]. Similar rankings were found in Canada, although with a higher prevalence that ranged from 45 to 52 % of the population (Boulet et al. 1997), suggesting that further increases in sensitivity of the population are likely (i.e., more than 50 % prevalence).

*Rhinitis*

Over the past 30 years, allergic rhinitis prevalence in the US population has increased from 10 % in 1970 to 30 % in 2000 [41], which correlates with the recognition that skin testing positivity prevalence over the same period of time appears to have also increased [3, 39]. Pollen is not the only factor that may play a role in the increasing prevalence of rhinitis, as temperature and humidity also contribute to appropriate nasal function such as eosinophilic infiltration during the late-phase allergic responses [42]. Furthermore, warmer temperatures positively correlate with physician-diagnosed allergic rhinitis [43]. It has been predicted that the number of hay fever sufferers in Japan will increase by 40 % by 2050 because Tokyo's average yearly temperature has already increased by 3 °C since 1890 and is projected to further increase by 3.5 °C by the end of the century [44]. Overall, there have been several indicators that point to climate change as a possible factor in the increase in allergic rhinitis prevalence [44].

*Sinusitis*

Sinusitis commonly complicates the development of rhinitis, but there have been limited studies focusing on this condition (although an increase would be expected [45], as was noted in an observation performed by the New England Society of Allergy assessment of the clinical impact of an El Nino event) [46]. Some climates are worse than others for individuals with chronic sinusitis due to a variety of environmental factors that appear to be similar to those that would affect allergic rhinitis. Additionally, atmospheric inversions and drops in barometric pressure seem to cause sinus difficulties [47] apart from any effect they may exert on air pollution or allergen concentration such as that seen in extreme weather changes (e.g., those occurring before a rainstorm).

*Conjunctivitis*

Few studies have noted that pollutants have increased demands for outpatient care for nonspecific conjunctivitis. One study coupled national heath insurance data and those from the environmental protection administration in Taiwan [48]. Unlike other organ systems that are targeted by pollution, the effect on the eye is immediate. Ozone and nitrogen dioxide produced the strongest effects, along with large diameter particulate matter PM10 (not fine particulate matter), with a 2.5 % increase [95 % confidence interval (CI), 0.9−4.1] for a 16.4-ppb (parts per billion) concentration rise in $O_3$ and a 2.3 % increase (95 % CI, 0.7−3.9) for a 11.47-ppb concentration rise in $NO_2$. Poor air quality with increasing greenhouse gases along with a projected increase in pollen will increase the prevalence of allergic and potentially dry eye disease, thus expanding the geographic coverage and amount of people affected by the urban eye allergy syndrome [49–51].

*Asthma*

Scientific evidence supports the "united airway" concept that rhinitis, sinusitis and asthma are expressions of the same inflammatory process that appears in different sites of the respiratory tract at different times and thus increases the severity of the allergic disease process, including asthma [52]. As a result of climate change, increased allergen and pollutant exposures such as diesel exhaust particles increase the primary incidence of allergen sensitization in atopic individuals [37], enhance allergic response, and then increase allergic respiratory disease in the subsequent years [38]. Another climate change variable, temperature, has been reported to be associated with an increase in asthma prevalence. In a New Zealand study, an increase in mean temperature of 1 °C was associated with an increase in asthma prevalence of almost 1 % [53]. In a study comparing a Mediterranean climate versus a subcontinental northern Italian one, the prevalence of asthma increased when the reported annual mean temperature increased along with a decrease in the range of temperature. The report also noted that one of the greenhouse gases, $NO_2$, was associated with increasing the risk for allergic rhinitis while being exposed to high stable temperatures [54]; similar coastal effects related to increased annual temperatures were noted in another Italian study when compared to subcontinental portions of Italy [55]. Exercise-induced asthma has been reported to be aggravated in birch pollen allergic asthmatics versus non-birch pollen allergic asthmatics because of the warmer and more humid weather in the pollen season in spring [56]. When considering the concept of "one airway–one disease," it should be expected that when the upper respiratory tract would be affected by climate change that an effect would also be seen in the lower airways, leading to increased health care utilization [13, 21].

Author's personal copy



*Food Allergy*

The link between global climate change and plant food allergens, such as peanut, and the increase in associated food allergic diseases warrants further investigation [4, 57–59]. Increased $CO_2$ and temperatures are associated with increased aboveground biomass (similar to poison ivy). However, with several tuber-based foodstuffs, there is a decrease in the underground biomass such as that seen with Cassava (*Manihot esculenta*), the third largest global staple food [60], while the net effects of higher $CO_2$ may have been slightly positive for rice and soybean.[61].

*Contact Dermatitis*

More than 100 plant species can induce contact dermatitis, and the development of plant induced dermatitis may also change, as it has been demonstrated that uroshiol potency and content increase when the (poison ivy) plants are exposed to increasing concentrations of atmospheric carbon dioxide. Currently, sensitivity to urushiol occurs in about two in every three people, and amounts as small as 1 ng are sufficient to induce a rash, but previous work done in controlled growth chambers demonstrated that other vines exhibit large growth enhancements from elevated CO(2). While using an intact forest ecosystem to grow poison ivy, photosynthesis, water use efficiency, growth, and population biomass all increased. This suggests that the *Toxicodendron* taxa has the potential to become more abundant and perhaps more "toxic" in the future with the changes associated with climate change [62].

*Insect Sting Hypersensitivity*

An insect sting hypersensitivity increase has been reported in Alaska based on the analysis of medical insurance datasets that demonstrated statistical significance that appears dependent on increases in annual and winter temperatures, which correlate with stinging insect habitat geographic expansion [63]. The allergic impact of fire ants (*Solenopsis invicta*) may also have climate change implications, as it has been demonstrated that the phospholipase A content of venom is increased in the early summer, corresponding to higher prevalence of anaphylactic events as well as the potential increase in the sting attack rate [64].

*Cost of Allergic Disease*

A preliminary prediction of cost-of-illness (COI) based on the construct of a new patient value-driven supply chain system indicates that direct and indirect economic costs (and patient care inefficiencies) for allergic and asthma disease will rise significantly, while the quality and delivery of immediate care may suffer. Cost-of-illness research frequently measures the potential economic impacts and burdens of a disease as it attempts to estimate the maximum amount that could potentially be saved or gained if the disease were to be significantly reduced or eradicated. If COI is utilized with cost-effectiveness, cost-benefit analyses combined with other economic analysis methods, the COI economic analysis tends to be more accurate. In addition, new types of COI studies have been introduced due to multiple questions regarding COI effectiveness. These new types of COI approaches include field research by using a bottom−up approach, which involves estimating the quantities of services used for the illness by going prospectively or retrospectively through the patient's records [65]. In order to prepare and draw parallels and polarity between climate change and allergic disease impacts on future economic and supply chain value systems, we developed a simple Bayesian/supply chain economic model. This model provided preliminary results that show a potential 30 % rise within the next decade in medical expenditures related to allergic and asthma disease as climate change impacts continue to rise at the same rate. Additional factors to be included in the Bayesian model are the development of an open formulary or switching to over-the-counter forms of various common prescription medications such as oral antihistamines, ophthalmic agents, and intranasal treatments. Like most global industries with well-developed and optimized supply chains, there is a significant amount of research and development and supply chain optimization that firms conduct to meet consumer needs. To keep pace with the increased need to treat economic impact of asthma, the pharmaceutical industry must manage a complex networks of suppliers, customers and global operations; this will be one of the major management challenges of this century—a challenge shared by most global industries. However, this is a promising introduction to advanced value driven supply chain research that could prove to have major patient and industry operational and financial benefits.

## Conclusions

It is the opinion of experts that, even with mitigating programs, the effects of the present concentrations of greenhouses gases and fluorocarbons (even if we were to reduce them to zero) will exert an impact such that the present course will remain for the remainder of the twenty-first century and beyond. The influence of climate change on allergy is unpredictable, as there are various items on both sides of the scale. However, preliminary suspicions by clinical experts indicate that the scale is tipped toward increasing allergies and allergic airway disease, but depending on regions as climate change will have different effects in

Author's personal copy



different regions. As the impact of climate change on allergic diseases emerges, there is and will be increased exposure and sensitization to various allergenic plants that will potentially promote the "allergic march" with increases in the prevalence and sensitivity of the "one airway–one disease", particularly affecting the pediatric population while increasing the persistence of symptoms or the development of new allergies later in the geriatric population. The cost of climate change due to increased severity and number of patients will require advanced modeling to properly mitigate, but more importantly adapt to the needs of the allergic population.

**Disclosure** Dr. Bielory is supported in part by STAR grant no. RD834547 (Observational, Laboratory, and Modeling Studies of the Impacts of Climate Change on Allergic Airway Disease; primary investigator: Leonard Bielory, MD, Rutgers University Center for Environmental Prediction).

Drs. Lyons and Goldberg reported no potential conflicts of interest relevant to this article.

## References

1. Ivanova JI, Bergman R, Birnbaum HG, et al. Effect of asthma exacerbations on health care costs among asthmatic patients with moderate and severe persistent asthma. J Allergy Clin Immunol. 2012;129:1229–35.
2. AAAAI. American Academy of Allergy, Asthma and Immunology - Allergy Statistics (1996-2006). AAAAI Website 2008; 2008.
3. Arbes Jr SJ, Gergen PJ, Elliott L, Zeldin DC. Prevalences of positive skin test responses to 10 common allergens in the US population: results from the third National Health and Nutrition Examination Survey. J Allergy Clin Immunol. 2005;116: 377–83.
4. Beggs PJ. Plant food allergens: another climate change-public health link. Environ Health Perspect. 2009;117:A191.
5. Shea KM. Climate change: public health crisis or opportunity. J Publ Health Manag Pract JPHMP. 2008;14:415–7.
6. Shea KM, Truckner RT, Weber RW, Peden DB. Climate change and allergic disease. J Allergy Clin Immunol. 2008;122:443–53. quiz 454-445.
7. Weber EU, Stern PC. Public understanding of climate change in the United States. Am Psychol. 2011;66:315–28.
8. IPCC. Climate Change 2007: Synthesis Report. In: Intergovernmental Panel on Climate Change. 2007.
9. Solomon S, Qin D, Manning M et al. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. In: Solomon S, Qin D, Manning M et al., editors. Intergovernmental Panel on Climate Change; 2007. p. 996.
10. Beggs PJ. Impacts of climate change on aeroallergens: past and future. Clin Exp Allergy. 2004;34:1507–13.
11. Stach A, Garcia-Mozo H, Prieto-Baena JC, et al. Prevalence of Artemisia species pollinosis in western Poland: impact of climate change on aerobiological trends, 1995-2004. J Investig Allergol Clin Immunol. 2007;17:39–47.
12. Beggs PJ. Adaptation to Impacts of Climate Change on Aeroallergens and Allergic Respiratory Diseases. Int J Environ Res Public Health. 2010;7:3006–21.
13. Beggs PJ, Bambrick HJ. Is the global rise of asthma an early impact of anthropogenic climate change? Environ Health Perspect. 2005;113:915–9.
14. Rogers CA, Wayne PM, Macklin EA, et al. Interaction of the onset of spring and elevated atmospheric CO2 on ragweed (Ambrosia artemisiifolia L.) pollen production. Environ Health Perspect. 2006;114:865–9.
15. Wayne P, Foster S, Connolly J, et al. Production of allergenic pollen by ragweed ( Ambrosia artemisiifolia L.) is increased in CO 2 -enriched atmospheres. Ann Allergy Asthma Immunol. 2002;88:279–82.
16. Singer BD, Ziska LH, Frenz DA, et al. Increasing Amb a 1 content in common ragweed (Ambrosia artemisiifolia) pollen as a function of rising atmospheric CO2 concentration. Funct Plant Biol. 2005;32:667–70.
17. Dervaderics M, Fust G, Otos M, et al. Differences in the sensitisation to ragweed pollen and occurrence of late summer allergic symptoms between native and immigrant workers of the nuclear power plant of Hungary. Immunol Investig. 2002;31:29–40.
18. Teranishi H, Katoh T, Kenda K, Hayashi S. Global warming and the earlier start of the Japansese-cedar (Cryptomeria japonica) pollen season in Toyama, Japan. Aerobiologia. 2006;22:90–4.
19. Nakagawa H, Ohashi N, Omura A, et al. Clinical manifestations of Japanese cedar pollinosis: an epidemiological study. Rhinology. 1996;34:201–5.
20. Weber RW. Impact of climate change on aeroallergens. An Allergy Asthma Immunol. 2012;108:294–9. Official publication of the American College of Allergy, Asthma, & Immunology.
21. Blando J, Bielory L, Nguyen V, et al. Anthropogenic Climate Change and Allergic Diseases. Atmosphere. 2012;3:200–12.
22. Epstein PR. Climate change and human health. N Engl J Med. 2005;353:1433–6.
23. Corden JM, Millington WM. The long-term trends and seasonal variation of the aeroallergen Alternaria in Derby, UK. Aerobiologia. 2001;17:127–36.
24. Wolf J, O'Neill NR, Rogers CA, et al. Elevated atmospheric carbon dioxide concentrations amplify Alternaria alternata sporulation and total antigen production. Environ Health Perspect. 2010;118:1223–8.
25. Frei T, Gassner E. Climate change and its impact on birch pollen quantities and the start of the pollen season an example from Switzerland for the period 1969-2006. Int J Biometeorol. 2008;52:667–74.
26. Jato V, Rodriguez-Rajo FJ, Seijo MC, Aira MJ. Poaceae pollen in Galicia (N.W. Spain): characterisation and recent trends in atmospheric pollen season. Int J Biometeorol 2009.
27. Menzel A, Fabian P. Growing season extended in Europe. Nature. 1999;397:695.
28. Burr ML. Grass pollen: trends and predictions. Clin Exp Allergy. 1999;29:735–8.
29. Emberlin J, Detandt M, Gehrig R, et al. Responses in the start of Betula (birch) pollen seasons to recent changes in spring temperatures across Europe. Int J Biometeorol. 2002;46: 159–70.
30. Avolio E, Pasqualoni L, Federico S, et al. Correlation between large-scale atmospheric fields and the olive pollen season in Central Italy. Int J Biometeorol. 2008;52:787–96.
31. Ziska L, Knowlton K, Rogers C et al. Recent warming by latitude associated with increased length of ragweed pollen season in central North America. Proc Natl Acad Sci U S A. 2011.
32. Root TL, Price JT, Hall KR, et al. Fingerprints of global warming on wild animals and plants. Nature. 2003;421:57–60.
33. Beltrani VS, Barsanti FA, Bielory L. Effects of glucocorticosteroids on the skin and eye. Immunol Allergy Clin N Am. 2005;25:557–80.

Author's personal copy




34. Csontos P, Vitalos M, Barina Z, Kiss L. Early distribution and spread of <i> Ambrosia artemisiifolia in Central and Eastern Europe. Botanica Helvetica. 2010;120:75–8.
35. Zhang Y, Isukapalli S, Bielory L, Georgopoulos P. Bayesian Analysis of Climate Change Effects on Observed and Projected Airborne Levels of Birch Pollen. Atmos Environ. 2012.
36. Dapul-Hidalgo G, Bielory L. Climate change and allergic diseases. Ann Allergy Asthma Immunol. 2012;109:166–72. Official publication of the American College of Allergy, Asthma, & Immunology.
37. Riedl MA. The effect of air pollution on asthma and allergy. Curr Allergy Asthm R. 2008;8:139–46.
38. Gilmour MI, Jaakkola MS, London SJ, et al. How exposure to environmental tobacco smoke, outdoor air pollutants, and increased pollen burdens influences the incidence of asthma. Environ Health Perspect. 2006;114:627–33.
39. Gergen PJ, Turkeltaub PC, Kovar MG. The prevalence of allergic skin test reactivity to eight common aeroallergens in the U.S. population: results from the second National Health and Nutrition Examination Survey. J Allergy Clin Immunol. 1987;80:669–79.
40. Bousquet J. Strategies to treat allergic disease. Drugs Today (Barc). 2008;44(Suppl B):25–7.
41. Bousquet J, Khaltaev N, Cruz AA, et al. Allergic Rhinitis and its Impact on Asthma (ARIA) 2008 update (in collaboration with the World Health Organization, GA(2)LEN and AllerGen). Allergy. 2008;63 Suppl 86:8–160.
42. Assanasen P, Baroody FM, Naureckas E, Naclerio RM. Hot, humid air increases cellular influx during the late-phase response to nasal challenge with antigen. Clin Exp Allergy. 2001;31:1913–22.
43. Lee YL, Shaw CK, Su HJ, et al. Climate, traffic-related air pollutants and allergic rhinitis prevalence in middle-school children in Taiwan. Eur Respir J Off J Eur Soc Clin Respir Physiol. 2003;21:964–70.
44. Williams R. Climate change blamed for rise in hay fever. Nature. 2005;434:1059.
45. Kinkade JM. Climate in relation to nasal sinusitis. Eye Ear Nose Throat Monthly. 1957;36:223–9.
46. Freye HB, King J, Litwin CM. Variations of pollen and mold concentrations in 1998 during the strong El Nino event of 1997-1998 and their impact on clinical exacerbations of allergic rhinitis, asthma, and sinusitis. Allergy Asthma Pro Off J Reg State Allergy Soc. 2001;22:239–47.
47. Parris C, Frenkiel S. Effects and management of barometric change on cavities in the head and neck. J Otolaryngol. 1995;24:46–50.
48. Chang CJ, Yang HH, Chang CA, Tsai HY. Relationship between air pollution and outpatient visits for nonspecific conjunctivitis. Investig Ophthalmol Vis Sci. 2012;53:429–33.
49. Leonardi A, Lanier B. Urban eye allergy syndrome: a new clinical entity? Curr Med Res Opin. 2008;24:2295–302.
50. Bielory L. Ocular allergy and dry eye syndrome. Curr Opin Allergy Clin Immunol. 2004;4:421–4.
51. Hom MM, Nguyen AL, Bielory L. Allergic conjunctivitis and dry eye syndrome. Ann Allergy Asthma Immunol Off Publ Am Coll Allergy Asthma Immunol. 2012;108:163–6.
52. Bachert C, Claeys SE, Tomassen P, et al. Rhinosinusitis and asthma: a link for asthma severity. Curr Allergy Asthma Rep. 2010;10:194–201.
53. Hales S, Lewis S, Slater T, et al. Prevalence of adult asthma symptoms in relation to climate in New Zealand. Environ Health Perspect. 1998;106:607–10.
54. de Marco R, Poli A, Ferrari M, et al. The impact of climate and traffic-related NO2 on the prevalence of asthma and allergic rhinitis in Italy. Clin Exp Allergy. 2002;32:1405–12.
55. Zanolin ME, Pattaro C, Corsico A, et al. The role of climate on the geographic variability of asthma, allergic rhinitis and respiratory symptoms: results from the Italian study of asthma in young adults. Allergy. 2004;59:306–14.
56. Karjalainen J, Lindqvist A, Laitinen LA. Seasonal variability of exercise-induced asthma especially outdoors. Effect of birch pollen allergy. Clin Exp Allergy. 1989;19:273–8.
57. Beggs PJ, Walczyk NE. Impacts of climate change on plant food allergens: a previously unrecognized threat to human health. Air Qual Atmos Health. 2008;1:119–23.
58. Sicherer SH, Muñoz-Furlong A, Godbold JH, Sampson HA. US prevalence of self-reported peanut, tree nut, and sesame allergy: 11-year follow-up. J Allergy Clin Immunol. 2010;125:1322–6.
59. Beggs PJ. Climate change and plant food allergens. J Allergy Clin Immunol. 2009;123:271–2. author reply 272.
60. Gleadow RM, Evans JR, McCaffery S, Cavagnaro TR. Growth and nutritive value of cassava (Manihot esculenta Cranz.) are reduced when grown in elevated CO. Plant Biol (Stuttg). 2009;11 Suppl 1:76–82.
61. Lobell DB, Schlenker W, Costa-Roberts J. Climate trends and global crop production since 1980. Science. 2011;333:616–20.
62. Mohan JE, Ziska LH, Schlesinger WH, et al. Biomass and toxicity responses of poison ivy (Toxicodendron radicans) to elevated atmospheric CO2. Proc Natl Acad Sci U S A. 2006;103:9086–9.
63. Yang X, Dong M, Huang Z. Role of mucilage in the germination of Artemisia sphaerocephala (Asteraceae) achenes exposed to osmotic stress and salinity. Plant Physiol Biochem PPB Soc Fr Physiol Veg. 2010;48:131–5.
64. Hannan Jr CJ, Stafford CT, Rhoades RB, et al. Seasonal variation in antigens of the imported fire ant Solenopsis invicta. J Allergy Clin Immunol. 1986;78:331–6.
65. Tarricone R. Cost-of-illness analysis: What room in health economics? Health Policy. 2006;77:61–3.
66. Prasad PVV, Boote KJ, Allen LH. Longevity and temperature response of pollen as affected by elevated growth temperature and carbon dioxide in peanut and grain sorghum. Environ Exp Bot. 2011;70:51–7.
67. Singh SK, Kakani VG, Surabhi GK, Reddy KR. Cowpea (Vigna unguiculata [L.] Walp.) genotypes response to multiple abiotic stresses. Journal of photochemistry and photobiology. B. Biology. 2010;100:135–46.
68. Ladeau SL, Clark JS. Pollen production by Pinus taeda growing in elevated atmospheric CO2. Funct Ecol. 2006;20:541–7.
69. Prasad PVV, Boote KJ, Allen LH. Adverse high temperature effects on pollen viability, seed-set, seed yield and harvest index of grain-sorghum [Sorghum bicolor (L.) Moench] are more severe at elevated carbon dioxide due to higher tissue temperatures. Agric For Meteorol. 2006;139:237–51.
70. Koti S, Reddy KR, Reddy VR, et al. Interactive effects of carbon dioxide, temperature, and ultraviolet-B radiation on soybean (Glycine max L.) flower and pollen morphology, pollen production, germination, and tube lengths. J Exp Bot. 2005;56:725–36.
71. Peternel R, Culig J, Srnec L, et al. Variation in ragweed (Ambrosia artemisiifolia L.) pollen concentration in central Croatia, 2002-2003. Ann Agric Environ Med. 2005;12:11–6.
72. Stefanic E, Kovacevic V, Lazanin Z. Airborne ragweed pollen concentration in north-eastern Croatia and its relationship with meteorological parameters. Ann Agric Environ Med. 2005;12:75–9.
73. Bartková-Scevková J. The influence of temperature, relative humidity and rainfall on the occurrence of pollen allergens (Betula, Poaceae, Ambrosia artemisiifolia) in the atmosphere of Bratislava (Slovakia). Int J Biometeorol. 2003;48:1–5.
74. Lavigne C, Mignot A, Stocklin J. Genetic variation in the response of pollen germination to nutrient availability and elevated atmospheric co2 concentrations in epilobium angustifolium. Int J Plant Sci. 1999;160:109–15.
75. Lake J, Hughes L. Nectar production and floral characteristics of tropaeolum majus l. Grown in ambient and elevated carbon dioxide. Ann Bot. 1999;84:535–41.

Author's personal copy



76. Matsui T, Namuco O, Ziska L, Horie T. Effects of high temperature and CO2 concentration on spikelet sterility in indica rice. Field Crop Res. 1997;51:213–9.
77. Osborne JL, Awmack CS, Clark SJ, et al. Nectar and flower production in Vicia faba L. (field bean) at ambient and elevated carbon dioxide. Apidologie. 1997;28:43–55.
78. Puc M, Wolski T. Betula and Populus pollen counts and meteorological conditions in Szczecin, Poland. Ann Agric Environ Med. 2002;9:65–9.
79. Schneiter D, Bernard B, Defila C, Gehrig R. [Effect of climatic changes on the phenology of plants and the presence of pollen in the air in Switzerland]. Allerg Immunol. 2002;34:113–6.
80. Green BJ, Dettmann M, Yli-Panula E, et al. Atmospheric Poaceae pollen frequencies and associations with meteorological parameters in Brisbane, Australia: a 5-year record, 1994-1999. Int J Biometeorol. 2004;48:172–8.
81. Peternel R, Hrga I, Culig J. Variations in mugwort (Artemisia spp.) airborne pollen concentrations at three sites in central Croatia, in period from 2002 to 2003. Coll Antropol. 2006;30:895–900.
82. Gonzalez Parrado Z, Valencia Barrera RM, Fuertes Rodriguez CR, et al. Alternative statistical methods for interpreting airborne Alder (Alnus glutimosa (L.) Gaertner) pollen concentrations. Int J Biometeorol. 2009;53:1–9.
83. Diaz de la Guardia C, Alba F, de Linares C, et al. Aerobiological and allergenic analysis of cupressaceae pollen in Granada (Southern Spain). J Investig Allergol Clin Immunol. 2006;16:24–33.
84. Smith M, Emberlin J, Stach A, et al. Regional importance of Alnus pollen as an aeroallergen: a comparative study of Alnus pollen counts from Worcester (UK) and Poznań (Poland). Ann Agric Environ Med. 2007;14:123–8.