The Role of Extreme Weather and Climate-Related Events on Asthma Outcomes

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KEYWORDS

• Asthma • Thunderstorm asthma • Flooding • Hurricane • Drought • Wildfire • Mold • Pollen

KEY POINTS

- Thunderstorms during pollen season have the potential to elicit asthma exacerbation epidemics.
- As prolonged heat waves and droughts become more frequent, the risk of large wildfires will likely increase resulting in poor air quality and worsening asthma control.
- A significant number of homes in the United States are currently affected by mold and dampness, which may aggravate existing asthma or provoke the development of asthma.
- Heavy rainfall events causing freshwater flooding, sea level rise, and increased tropical storm activity are likely to damage living structures and worsen indoor air quality.

INTRODUCTION

It has been well established that climate change is not only occurring but accelerating[1–4] The most significant driver of this change is raising atmospheric carbon dioxide (CO_2) concentration. Over the past 250 years there has undoubtedly been an increase in atmospheric CO_2 concentration and two-thirds of that increase has occurred within the past 50 years alone. There has also been a measurable increase in other greenhouse gases, methane and nitrous oxide, which have played an additive role.[2,5] The effects of these quantitative changes in greenhouse gases has been associated with witnessed glacier recession, artic ice thinning, sea levels rising, dispersal of plant and animal geographic range, longer and more abundant pollen seasons, and increased extreme weather events among others.[2,5] It has now been more than a decade since *Lancet* published their 2009 report on the health effects of climate change and stated “climate change is potentially the biggest global health threat in the 21st century.”[1]

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Climate change reflects any significant change in temperature, wind patterns, precipitation over extended periods of time, usually decades. Over the past several hundred years, there has been an observed 1°C temperature rise. The Paris Agreement has created a target to keep the increase well below 2°C to prevent the "tipping point," which could result in more catastrophic consequences. Ideally the goal would be less than 1.5°C, but to accomplish this it has been reported that global emissions would need to be reduced in half by 2030 and reach net-zero by 2050.[3,4,6] The purpose of this review is to draw attention to asthma-related outcomes attributed to extreme weather and climate change–related events to ultimately allow anticipation and planning for current and future needs with identification of vulnerable populations including those with asthma. There have been already more than 200 extreme weather and climate events since 1980 that have each been associated with greater than $200 billion in damages.[7] These events can include flooding rains, prolonged wet periods, prolonged heat waves, drought, wildfires, hurricanes, severe thunderstorms, tornadoes, storm surge, and coastal flooding.

The Global Initiative for Asthma (GINA) describes asthma as a heterogeneous disease associated with chronic inflammation and hyperresponsiveness of the airways. This is a common disease affecting up to 300 million people worldwide making it a global health problem. There is a rising prevalence in developing countries and rising treatment costs worldwide.[8] In the United States alone, asthma affects an estimated 26 million people.[8] Weather can affect airway hyperresponsiveness directly (eg, cold air) or indirectly by augmenting aeroallergen production and worsening air pollution. One of the hallmarks of asthma is variable airflow obstruction, which can be triggered by multiple factors: humid air, cold air, respiratory irritants (eg, smoke), aeroallergens (eg, pollens, dust mites, dander cockroach, and mold spores), exercise, infections and medications.[8,9] As the frequency and severity of extreme weather and climate-related events occur it will increase exposure to these exacerbating stimuli and directly impact asthma outcomes.

SEVERE THUNDERSTORMS AND TORNADOES

Thunderstorm asthma (TA) is a phenomenon of an observed increase in acute asthma attacks that occur following thunderstorms. Thunderstorm-related asthma attacks are associated with unusual weather occurrences with wind and torrential rain paired with high pollen counts. Although these occurrences are rare in the literature, they are likely underreported. A challenge to studying this phenomenon is tracking small, yet significant increases in asthma exacerbations following thunderstorms. An observational study of more than 215,000 asthma-related emergency department (ED) visits in Atlanta, Georgia, between 1993 and 2004 found an associated increase in emergency room (ER) visits on days with a thunderstorm ($P>.001$).[10] Although the study showed an increase in asthma exacerbations, it notably did not account for pollen levels or the time of year particular pollens would be expected present in an air sample. Between 1990 and 1994, Newson and colleagues[11,12] reported 38 occurrences with excess asthma-related hospital admissions and correlated 12 (38%) with thunderstorms. Similar descriptions of increased ED visits have also been reported in Canada, Australia, and England.[13–16]

There is no exact definition for TA and the precise mechanism remains debated. There appears to be an interaction when specific meteorologic and aerobiology factors mesh to produce a "perfect storm." One of the earliest observations was published in *Lancet* in 1983.[17] This report described a 10-fold increase in asthma exacerbations requiring hospital admission following a July 6 thunderstorm in Birmingham, UK. On that particular day, air pollution was low and pollen counts were high.[17] Since that episode there have been additional reports in the UK, Australia, Canada, Italy, Iran, United States, and Saudi Arabia of TA.[18] In many of these episodes there was such a spike in resources needed to treat asthma exacerbations that it overwhelmed the local health systems.

The most notable TA epidemic occurred in Melbourne, Australia, on November 21, 2016. This particular event followed a thunderstorm with high wind, torrential rain, and high pollen counts. Over the course of the evening and the following day, more than 8500 patients required treatment for asthma exacerbations and 10 deaths were reported. This rapid influx of patients with asthma severely stressed the local emergency services.[11,19] Similar reports of local health services being pushed to the limit occurred in England in 1994 during a TA event. At that time a sixfold increase in ER asthma visits was reported. More concerning was that 5 of 11 local emergency departments exhausted nebulizer face masks, 8 of 11 ran out of steroid tablets, 6 of 11 short-acting bronchodilator inhalers and 4 of 11 $beta_2$-agonist nebules.[20]

There continues to be debate about the mechanism of TA. The most agreed on explanation involves high levels of aeroallergens accumulating at ground level. These intact pollens are larger than 10 μm in diameter allowing them to reach the upper respiratory tract but are rarely capable of penetrating the bronchial regions. The most common appears to be grass pollen grains (30–40 μm) with additional evidence suggesting fungal spores may also be involved.[11,18,21] As thunderstorms develop warm updrafts of air rapidly ascend into the atmosphere. This air current pulls along the concentrated whole pollens until they reach the high humidity environment of the cloud base. Due to the wet conditions and through a process of osmotic rupture the pollen releases allergenic starch granules that are smaller than the 5 μm required reaching the lower airways. These allergens are then returned to ground level by storm downdrafts or potentially via rain droplets and released on evaporation.[22]

To date, grass pollen appears to have the most data to support it as the antigenic stimulus for bronchospasm in TA. Other pollen such as olive has been implicated in at least one episode of TA and fungal spores have been suspected in others.[19,23] There is, however, a strong association with grass pollen season and the reported episodes of TA in both the Northern and Southern hemispheres. Is this association simply because most thunderstorms tend to occur in late Spring and early Summer which happens to be grass pollen season or is there more of clear causative role of grass pollen? Marks and colleagues[24] reported a considerable increase in the concentration of ruptured grass pollen grains following a thunderstorm. This particular thunderstorm event resulted in increased asthma hospital admissions and was associated with a fourfold increase in intact grass pollen grains and a sevenfold increase in ruptured grass grains compared with 1 hour before the storm's outflow.[24] The ruptured grass pollens are capable of releasing large amounts of allergen-bearing starch granules. These particles were found to contain major grass pollen allergens and induced bronchospasm following bronchial challenge in sensitized patients.[25–27] Venables and colleagues[20] reported that before 1994 TA event grass pollen counts were at a 6-year high and mold spores were at a typical level. After the storm 16 patients who suffered asthma exacerbations were tested for specific IgE to grass pollen and mold mix by CAP (Pharmacia). Twelve of the patients had very high specific IgE to pollen (Class 4–6), and 3 had low or moderate IgE to mold (Class 1–2). Of the 16 patients, only 2 did not have specific IgE pollen, whereas 13 were negative to mold.[20] Marks and colleagues[24] proposed the following criteria for identification of TA outbreaks: (1) the occurrence of asthma outbreaks closely linked to thunderstorm outflows; (2) thunderstorm outflow events limited to late spring and summer when there are high levels of airborne grass pollen; (3) individuals with grass pollen allergy are most likely to be affected; (4) there is a close temporal association between the arrival of the thunderstorm outflow and a major rise in the concentration of intact and ruptured pollen grains.[24]

According to the National Oceanic and Atmospheric Administration (NOAA), there are an estimated 16 million thunderstorms worldwide each year and 100,000 in the United States. Approximately, 10% of these are considered to be severe thunderstorms, which must include hail 1 inch or larger, wind speed greater than 57.5 mph, or a tornado. As a result of anthropogenic climate change there has been an alteration of multiple environmental variables, which are predicted to cause an increase in the frequency and severity of severe thunderstorms throughout the United States, Europe, and Australia.[28–30] The most severe thunderstorms, those producing tornadoes, have also been affected by climate change. Although tornadoes can occur in all months, there has been a trend in the United States of “tornado season” occurring earlier each year.[30,31] There has also been an interesting trend dating back to the 1970s showing a decrease in the number of days per year with tornadoes but an increase in the days of “tornado outbreaks.” These are defined as days with more than 30 tornadoes. In the 1950s and 1960s this was rarely reported, but by 2000 there was approximately 20 of these days and by the end of the decade the number had increased to nearly 60.[30,32]

Severe thunderstorms are the type most associated with TA and the projected increase in severe thunderstorm activity raises particular concern for widespread asthma outbreaks. A second requirement for TA appears to be high pollen counts, particularly grass pollen, and this too has been augmented by climate change. Grass pollen is one of the leading aeroallergens worldwide, as up to 20% of the land surface is covered by grassland.[33,34] There are multiple weather variables that influence pollen production including mean daily temperature, maximum temperature, minimum temperature, average wind speed, atmospheric CO_2, relative humidity, accumulated sunshine hours and rainfall.[21,35] There have been reports throughout the world (eg, United States, Canada, Poland, Italy) demonstrating increased duration of pollen season, peak pollen concentration, total season pollen load, and pollen allergenicity.[36–41]

HEAT WAVES, DROUGHTS, AND WILDFIRES

It is predicted that the world will continue to experience more frequent and warmer hot days/nights, more frequent and longer lasting heat waves, fewer days with frost, more heavy rain events with flooding, and paradoxically more periods of drought.[2,35] NOAA describes 3 different classes of drought: (1) meteorologic drought results from precipitation deficit, (2) agricultural drought due to soil moisture deficit, and (3) hydrological drought occurs from runoff deficit. The United States has experienced several significant droughts since 2011 in the Great Plains/Midwest and California.[42] Although there is no evidence to suggest global meteorologic drought trends, there are regions of the world where anthropometric climate change appears to be driving drought. It has been projected that future higher temperatures will likely contribute to increased drought frequency and magnitude in the continental United States.[42] These warmer temperatures paired with rising CO_2 levels will amplify pollen production to impact allergic diseases including asthma.[5]

Over the past several years, there have been serious wildfires throughout the world in Australia, Chile, and California among others.[35] Over the past few decades there has been a significant increase in wildfires in the western United States and Alaska.[43–45] Multiple factors are associated with the development of large wildfires including temperature, soil moisture, relative humidity and vegetation.[42] A large portion of the increase in wildfires in the western United States has been attributed to warmer and drier conditions and a clear link between drought and increased fire risk exists.[43–45] Wildfires can include forest fires, grass fires, bush fires and vegetation fires. These fires can be stoked naturally, accidently or implemented during deforestation practices.

Due to multiple climate driven factors a significant increase in wildfires is projected and years without extremely large wildfires will become extremely rare.[46,47] These changes will bring about an increase in natural air pollution with more fine particulate matter ($PM_{2.5}$), carbon monoxide (CO), polycyclic aromatic hydrocarbons, aldehyde, semi-volatile and volatile organic compounds.[48,49] The molecules have the capability of irritating the respiratory epithelium causing chronic inflammatory/oxidative stress, acute bronchospasm and subsequently asthma exacerbations.[50,51] Fine particulate matter has an aerodynamic diameter less than 2.5 μm allowing for deposition into lower airways. It is also a major component of wildfire smoke and has the ability to widely disperse up to 1000 miles away and last for several weeks.[52]

A severe and long-lasting wildfire occurred in Victoria, Australia in 2006 to 2007, and during that event there were 2047 emergency department encounters for asthma. Hikerwal and colleagues[53] reported an increase in asthma exacerbations with a positive association with wildfire-related $PM_{2.5}$. This association was found to be the strongest on the same day of smoke exposure and other lag day periods did not demonstrate a significant association. The strongest association for wildfire-related $PM_{2.5}$ and asthma-related ED visit was adult women.[53] Interestingly, there have been several reports of adult women being at increased risk for wildfire-related asthma exacerbation. A large southern California wildfire in 2003 resulted in an influx of cardiopulmonary associated hospital admissions. This wildfire produced a substantially large amount of smoke impairing air quality. During the fire the highest recorded 24-hour $PM_{2.5}$ was more than 240 $\mu g/m^3$. For comparison, the US National Ambient Air Quality Standard for 24-hour average $PM_{2.5}$ is 35 $\mu g/m^3$. During the period of wildfires, asthma admissions increased across all age groups by 4.8% (95% confidence interval [CI] 2.1%–7.6%) and a 26% increase in the period following the fires suggesting a delayed inflammatory response. During the wildfires there was an increased risk of asthma admission for female individuals ages 5 to 19 (49% $P<.02$) compared with male individuals and also women 20 to 64 years of age (41%, $P<.001$ compared with their male counterparts.[54] In June 2008, a lightning strike ignited a peatbog fire in North Carolina, and Rappold and colleagues[55] reported a significant increase in all asthma-related ED visits (odds ratio [OR] 1.65; CI 1.25–2.17). Another potential vulnerable asthma subgroup is obese children base upon observations from the 2003 southern California wildfires.[56] This study reported an increase in short-acting β2-agonist across all body mass index (BMI) groups, but the largest increase was in the obese (BMI >30) group ($P<.05$).[56] In addition, an 8-year study showed that poor air quality (>10 $\mu g/m^3$ increase in PM_{10}) was associated with a 5.02% increase in asthma admissions.[57]

Heat waves can be dangerous due to the physiologic stress that prolonged high temperatures can invoke and also their association with triggering wildfires.[58–62] An example is the 2010 prolonged heat wave in Moscow that triggered multiple wildfires in the forest and peat bogs surrounding the city. The estimated all-cause mortality for the heat wave of 2010 was approximately 55,000. Shaposhnikov and colleagues[60] reported excess mortality during this period in subjects with underlying respiratory disease (relative risk (RR): 2.05, CI 1.80 to 2.39). An extreme heat wave in Omaha, Nebraska occurred in 2012.[63] There were not any associated wildfires or unusually poor air quality associated with this event. Daily asthma admission was found to be higher during the heatwave compared to the same dates 1 year prior with more seasonable temperatures. The peak asthma admission rates coincided with the most consecutive days of intense heat and the apex was during the hottest time of day. Subjects who were children or African American were threefold more likely to be seen for an asthma exacerbation.[63] Kharin and colleagues[64] projected that heat waves that were historically once in a 20-year period will occur every 2 to 3 years throughout much of the United States by the second half of the century.

TROPICAL CYCLONES (HURRICANES/TYPHOONS), STORM SURGE, AND FRESHWATER FLOODING

Of the extreme weather and climate-related events, hurricanes are known to cause the most significant mortality.[7] The Intergovernmental Panel on Climate Change Fifth Assessment Report (IPCC AR5) consensus projects a global increase in tropical cyclone intensity, precipitation rates and frequency of very intense tropical cyclones. During the past century the global sea level rose by 8 inches in most areas of the world, which will aggravate storm surge from cyclones.[65] The US Midwest and Northeast have recently seen more flooding[42,65–67] and frequency of heavy downpours has increased globally.[68] The areas historically affected by flooding will also continue expand. The Federal Insurance and Mitigation Administration of the Federal Emergency Management Agency found that by the end of the twenty-first century the 1% annual chance floodplain area would increase in area by 30%.[69] The US Global Change Research Program has project with high confidence that the frequency and intensity of heavy precipitation events will continue to increase.[42]

Extreme precipitation can potentially damage buildings allowing for moisture to enter the living area. This provides an opportunity for mold growth and increased levels of other aeroallergens which can worsen air quality and may trigger asthma in sensitized individuals.[70] It has been estimated that up to 50% of homes in the United States have indoor dampness and/or mold. Home dampness can aggravate preexisting respiratory conditions and also may cause new onset asthma.[70,71] Targonski and colleagues[72] reported that multivariate analysis of asthma patients in Chicago, Illinois, were 2.16 times more likely to die when mold counts were greater than 1000 spores/m^3 compared with days with mold counts less than 1000 spores/m^3. There was a reported increase in asthma and asthma severity after the recent 2017 Hurricane Maria in Puerto Rico. The Associated Press attributed this to high mold counts, increased rodents/cockroaches in damaged dwellings and poor air quality associated with the use of diesel and/or gasoline powered generators.[38]

A review by the Institute of Medicine concluded that there was sufficient evidence of an association with a damp indoor environment and/or presence of mold and asthma.[35] A more recent report by the World Health Organization established a considerable number of childhood asthma is attributable to indoor dampness and mold.[70] Alternatively, removing mold and dampness from homes can improve asthma outcomes. This was demonstrated in a prospective, randomized, controlled trial of symptomatic asthmatic children where indoor mold and water damage was remediated in the experimental group. The follow-up period was 1 year and the remediation group had significantly fewer symptom days (P = .003) and fever asthma exacerbations (P = .003) as compared withto the non-remediation group.[73]

In 2005, New Orleans, Louisiana, was struck by 2 powerful storms, Hurricanes Katrina and Rita. These extreme weather events resulted in significant inland flooding and storm surge. Several post-hurricane studies reported heavy indoor fungi growth with high levels of mold spores, endotoxins, and fungal glucans.[74–76] Likewise, New Jersey was ravaged by Hurricane Irene in 2011 and Hurricane Sandy in 2012, which caused significant flooding and structural damage. Saporta and Hurst[77] reported that post-hurricane, patients had 34.6 times (P = .0001) more positive intradermal skin tests to molds than before the hurricanes, and 95% of patients tested had at least one mold sensitization compared with 62% (P = .0001) before the hurricane. In another study involving 3835 individuals surveyed who were involved in the reconstruction efforts post-Sandy, more than one-third (34.4%) reported worsening lower respiratory tract symptoms (wheeze, persistent cough, shortness of breath).[78]

Bangkok, Thailand, is located in a lowland area near the Chao Phraya River delta and is prone to flooding. In 2011, a severe flood, described as the worst flooding in Thailand history, lasted 175 days and killed 815 people. In addition to the loss of life there was considerable destruction to homes, including mold damage. After the floods, sensitization determined by skin prick testing showed a significant increase in *Alternaria* sensitization among children with asthma and allergic rhinitis.[79] The Hawaiian island of Kawaii was struck by class III/IV Hurricane Iniki in September 1992. In the post-Iniki period, physician visits for asthma significantly increased (RR 2.81; 95% CI 1.93–4.09) and asthma hospital admissions were 3 times higher.[80] As climate change continues to alter ocean levels, produce increased inland flooding from heavy precipitation, and coastal flooding from storm surge, indoor mold problems can be expected to worsen.[35]

CLINICAL CARE POINTS

- Thunderstorms during pollen season have the potential to elicit asthma exacerbation epidemics.[18] Staying indoors with the windows closed can prevent TA in sensitized patients.[35]
- As prolonged heat waves and droughts become more frequent, the risk of large wildfires will likely increase resulting in poor air quality and worsening asthma control.[46–48,50–52]
- A significant number of homes in the United States are currently affected by mold and dampness, which may aggravate existing asthma or provoke the development of asthma.[70,71] Mold remediation efforts can significantly improve asthma control.[75]
- Heavy rainfall events causing freshwater flooding, continued sea level rise and increased tropical storm activity are likely to damage living structures and worsen indoor air quality.[42,74–76] If working in an area with significant mold exposure wearing an elastomeric respirator is more effective at reducing exposure to endotoxins and mold than N95 respirators.[75]

Data from Refs.[18,35,42,46–48,50–52,70,71,74–76]

DISCUSSION

It should be recognized that climate change is not solely an environmental concern, but these changes are unmistakably interconnected to our health. The effects of climate change will significantly impact those with underlying allergic and asthma disease. Asthma is a heterogenous disease with multiple environmental factors that have been associated with pathogenesis, exacerbations and mortality. GINA estimates that up to 18% of the world's population has asthma making it a global health concern. As summarized here, high pollen burden linked with TA, robust indoor and outdoor mold spore levels associated with tropical storms, heavy precipitation events or poor air quality during wildfires attributed to drought conditions, impacts allergic and asthmatic diseases. To slow climate change it will take a united effort though all sectors of society. Interestingly, the long-term effect of the current unprecedented decline in carbon emissions and air pollution observed from intensive quarantine practices in response to the worldwide coronavirus pandemic of 2019 to 2020 is yet unknown.

In conclusion, the allergy and asthma community of scientists and clinicians should be proactive in research and clinical efforts to assure the safety and health of our patient population to include long-term and emergency preparedness resulting from climate-related events.

DISCLOSURE

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