Climate change and respiratory diseases: a 2020 perspective

Manish Joshi[a,b], Harmeen Goraya[a], Anita Joshi, and Thaddeus Bartter[a,b]

Purpose of review

To present an overview of the impact of climate change upon human respiratory health.

Recent findings

Climate change involves two major types of change. First, there is overall progressive warming. Second, there is increased variability/unpredictability in weather patterns. Both types of change impact negatively upon human respiratory health. Worsening air quality and increased allergens can worsen existing disease. Climate-related changes in allergens and in vectors for infection can cause new disease. Redundant sophisticated studies have projected marked increases in respiratory morbidity and mortality throughout the world as a direct result of climate change. This article summarizes some of those studies.

Summary

The clarity of our vision with respect to the dramatic impact of climate change upon human respiratory health approaches 20/20. The data represent a mandate for change. Change needs to include international, national, and individual efforts.

Keywords

climate change, global warming, pulmonary diseases, respiratory health

INTRODUCTION

Earth's climate is changing. Each year is breaking the record of the preceding year when it comes to average surface temperature on planet earth; September 2019 tied as second hottest on record for the United States [1,2▪▪,3]. Europe had an unprecedented heat wave in 2019 [4,5]. Large wildfires in Siberia and Alaska made global headlines in 2019 [6,7]. Dorian was an unprecedented category 5 hurricane in the Bahamas and eastern coastal United States [8]. Severe drought is affecting many African countries and taking a toll not only on millions of human beings but on wildlife as well, with over 50 elephants reported dead within 2 months in Zimbabwe in October 2019 [9]. The United States National weather service issued its first-ever 'extreme red flag warning' for Los Angeles in October, 2019 [10]. For those whose opinions are based upon evidence and data, there is now ample evidence both that climate is changing at an unprecedented pace and that climate change is primarily due to human activities [1,2▪▪,11,12▪▪]. The fourth national climate assessment report concluded (based on extensive evidence) that, 'it is extremely likely that human activities, especially emissions of greenhouse gases, are the dominant cause of the observed warming since the mid-20th century [1,2▪▪,11]' (https://www.globalchange.gov/climate-change).

RESPIRATORY HEALTH EFFECTS DUE TO CLIMATE CHANGE

Climate change presents substantial challenges to overall human health and to respiratory health in particular. A discussion of impact on overall health is beyond the scope of this article; we will focus on the impact of climate change on respiratory health. Before delving into specific details, an overview of the impact of human activity on climate is warranted. This is illustrated in Fig. 1. The burning of fossil fuel for energy production, deforestation,

[a]University of Arkansas for Medical Sciences and Central Arkansas and [b]Veterans Healthcare System, Little Rock, Arkansas, USA

Correspondence to Manish Joshi, MD, FCCP, Associate Professor of Medicine, Pulmonary and Critical Care Division, University of Arkansas for Medical Sciences, 4301W. Markham, Slot #555, Little Rock, AR 72205, USA. Tel: +1 501 686 5525; fax: +1 501 686 7893; e-mail: mjoshi@uams.edu

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KEY POINTS

- Earth's climate is changing at an unprecedented pace, mainly due to anthropogenic causes.
- Climate change impacts negatively upon human respiratory health via a plethora of mechanisms which range from direct pulmonary toxicity due to greenhouse gasses to ecosystem changes with deleterious effects.
- We need to reduce greenhouse gases emissions on an emergent basis to mitigate the impact of climate change on human health.

large-scale concentrated animal feeding organizations (CAFOs), and the use of aerosols for cooling are the predominant causes of accelerated global warming [1,2••,11,12••]. These activities have led to increased production of greenhouse gases – mainly carbon dioxide, nitrogen dioxide, and methane gas – the predominant cause of earth's increasing temperature over the last century. This is in turn is the cause of frequent extreme weather patterns/events such as prolonged heat waves, melting of permafrost, rising sea levels, storms, flooding, and droughts causing wildfires [1,12••]. Each of these extreme events has independent direct and indirect effects on respiratory health (Fig. 1). Ironically, the burning of fossil fuels, the cornerstone of the industrial revolution, presents a multifaceted threat to human health both via the formation of greenhouse gasses and via air pollution, which itself has direct and independent adverse impacts on respiratory health [13,14••,15••].

Climate change and air quality

A substantial body of epidemiologic research describes how increasing atmospheric temperatures associated with climate change are worsening ambient air quality at local, regional, and global levels [1,12••]. Climate change is directly impacting air quality by increasing pollutant levels such as ozone and particulate matter and by influencing the dispersion and transport of pollutants and their precursors via changes in atmospheric ventilation and in precipitation, both of which affect the removal of air pollutants [1,2••,11,12••]. Ground-level (tropospheric) ozone (O_3) is formed by photochemical reactions between its precursors – including nitrogen oxides (NOX), methane (CH4), volatile organic compounds (VOCs), and carbon monoxide (CO). This happens when these precursor-pollutants chemically react in the presence of sunlight [16,17]. Major human contributions come from automobile exhaust, power plants, industrial boilers, refineries, chemical plants, and CAFOs [16,17]. The rate of O_3 formation is temperature-dependent; increasing earth's temperatures and increased sunlight favor more rapid formation. Thus increases in temperature, more and longer droughts, and less precipitation are all conducive to higher ground-level O_3 concentrations [16,17]. On the contrary, increasing temperatures due to climate change also increase the emission of natural VOCs, further increasing the anthropogenic contribution to ground-level ozone concentrations [17].

Ozone is a direct respiratory irritant. It causes airway inflammation and damages lung tissues [14••,15••,18]. Ozone exposure has been implicated in diminishing lung function and increased mortality, especially in children and the elderly [14••,15••,18,19]. Ozone exposure can cause or exacerbate obstructive lung diseases such as chronic obstructive pulmonary disease (COPD) and bronchial asthma [14••,15••]. Orru *et al.* [20] investigated the magnitude of the impact of climate-change-induced changes in ground-level ozone concentration on the total rate of respiratory hospitalizations and the total all-cause mortality in Europe using emission scenarios, models, and epidemiological data. Comparing the then current situation (1990–2009) with the baseline period (1961–1990), the largest increase in ozone-associated mortality and morbidity due to climate change (4–5%) was predicted for Belgium, Ireland, the Netherlands, and the United Kingdom. They also compared the baseline period and the future periods (2021–2050 and 2041–2060) and projected much larger increases in ozone-related mortality and morbidity for Belgium, France, Spain, and Portugal.

Inhalable particulate matter is defined as particles small enough to be deposited in the lungs. Particulate matter is broken into two size categories; particulate matter with an aerodynamic diameter of 10 μm or less (PM_{10}), at which size they can deposit in the airways, and those with an aerodynamic diameter of 2.5 μm or less ($PM_{2.5}$), at which size they can be deposited in alveoli. The main sources of $PM_{2.5}$ include motor vehicles (especially diesel-powered), power plants, heating systems for buildings, wildfires, and, in arid regions, wind-blown dust [14••,15••]. Climate change is increasing concentration of particulate matter via several pathways which include increased production due to extreme events such as wildfires and the storms, and decreased clearance due to less large-scale precipitation over land [1,2••,12••,21]. Particulate matter has significant adverse impact on respiratory health and mortality [13,14••,15••]. Liu *et al.* [22•] evaluated the association of particulate matter with respiratory mortality and all-cause mortality in 652 studies around the globe. This time-series analysis study showed a positive association between short-term

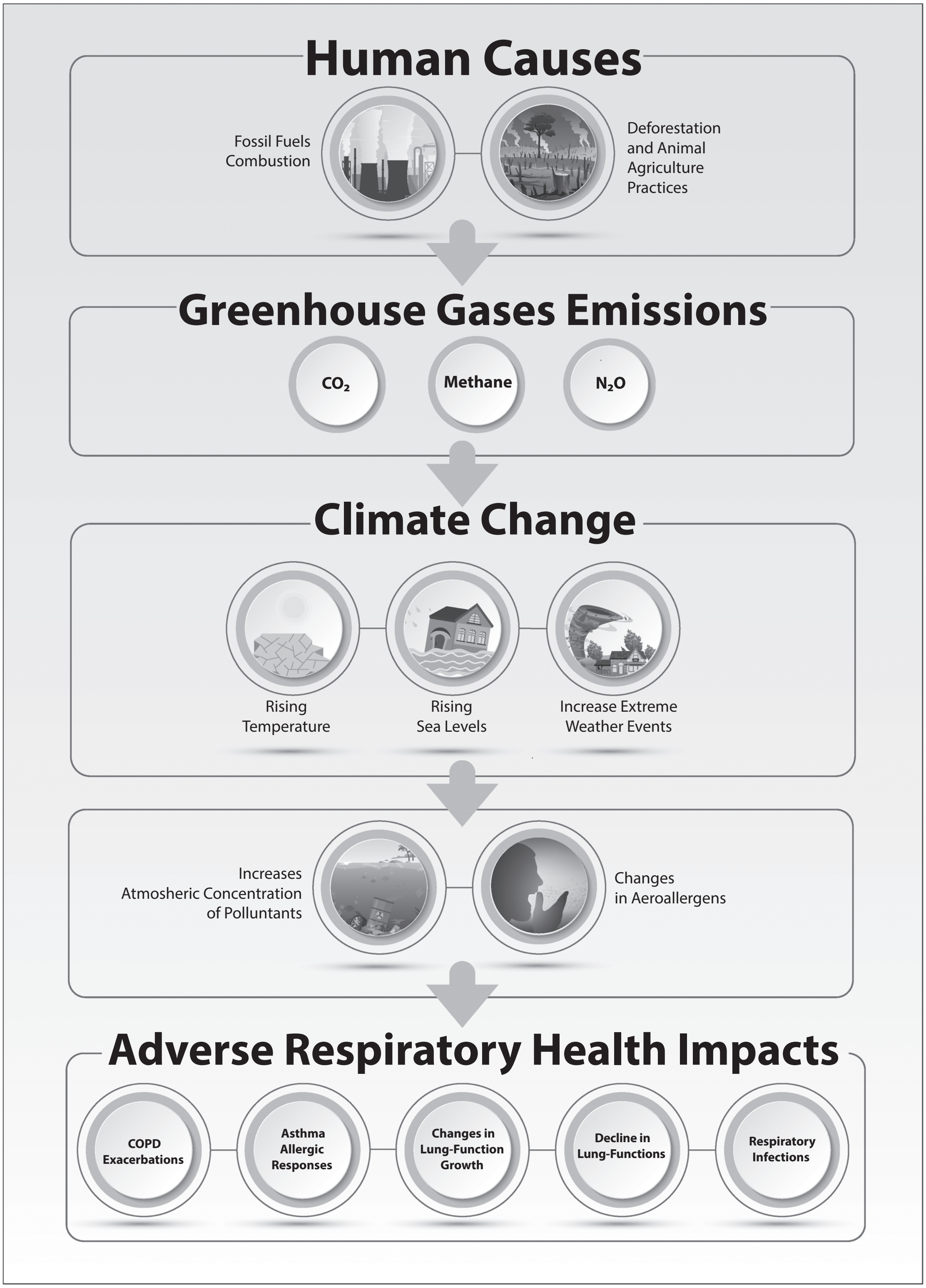

FIGURE 1. Overview figure summarizing the anthropogenic causes of climate change and their impact on respiratory health.

exposure to PM_{10} and $PM_{2.5}$, respiratory mortality, and all-cause mortality after adjustment for gaseous pollutants. Another study by Silva *et al.* [23] using multiple global chemistry-climate models showed that premature mortality will increase from changes in air pollution attributable to climate change. Their study showed that increases in $PM_{2.5}$ due to climate change are estimated to result in 55 600 deaths/year in 2030 and 215 000 deaths/year in 2100. Estimates of $PM_{2.5}$-related mortality increase in 2100 in all regions except Africa, with the greatest predicted increases in mortality in India (80 200 deaths/year, 40 deaths/year/million people), the Middle East (50 400 deaths/year, 45 deaths/year/million people) and East Asia (47 200 deaths/year/, 43 deaths/year/million people). The former Soviet Union is predicted to have the highest per capita mortality in 2100 (57 deaths/year/million people) [23]. Another recent study by Analitis *et al.* [24▪] showed increased mortality due to synergy between temperatures and air pollution.

Climate change and respiratory allergic responses

Warmer temperatures from climate change are affecting aero-allergenic plant pollen production worldwide [25▪]. Increased amounts of carbon dioxide as well as warmer temperatures are causing increased growth of allergenic plants [26]. Both the increased growth and extension of pollen seasons with warmer springs and delays in first fall-frost can lead to increased production of pollen [27–29]. A conforming real-world experimental study was conducted by growing ragweed plots concomitantly in urban and rural environments. The study results showed that the ragweed grew faster, flowered earlier, and produced significantly greater above-ground biomass and ragweed pollen in the urban environment, where carbon dioxide concentrations were 30% higher than in the rural environment [27]. Another confirming study by Ziska *et al.* [28] showed a clear association between recent warming and an increase in the duration of ragweed pollen season (up to 27 days) in midwestern North America. Similar studies in Europe have shown trends toward earlier starts of birch pollen seasons in London, Brussels, Zurich, and Vienna [29].

It is interesting that global warming is not only increasing the concentration of pollen in the air, but it is also increasing the 'allergenic potency' of airborne allergens [30,31]. In a study that examined the impact of urbanization on the proteome of birch pollen and its chemotactic activity on human granulocytes, researchers reported that extracts from pollen collected in urban areas had higher chemotactic activity for human neutrophils than did pollen from rural sites [30]. Another interesting study by Beck *et al.* found ozone exposure to be an important factor that enhanced the allergenicity of birch pollen in susceptible individuals. The authors concluded that ozone can impact human respiratory health not only as a direct pollutant but also by increasing allergic symptoms via its impact on allergenicity [31].

Climate change can also cause some allergen-producing plants to move into new areas, and winds can carry pollen long distances from the site of origin [32]. Both the increases in aeroallergens and the causative link between climate change and these increases cited above have been endorsed by a recent report submitted by the American Academy of Allergy, Asthma & Immunology Working Group [33▪]. The longer pollen seasons (and increased concentrations of pollen in ambient air) increase the duration of human exposure to aeroallergens and thus increase allergic sensitization. Exposure to more and more allergenic pollen may make people that do not currently have allergies develop allergic symptoms; in people with allergic diseases, it has a potential of increasing the severity and duration of symptoms [32,33▪,34]. There have been increases in emergency department visits and hospital admissions for asthma and allergic rhinitis, in the number of physician visits, and in the sale of over-the-counter allergy medications [35–37].

Climate change and its impact on respiratory infections

The classic model of causation in infectious disease, also known as the epidemiologic triad, consists of host, an infectious agent (including transmitting vector), and the environment (Fig. 2). This simple model can explain how respiratory infections may impact human health due to change in environment attributable to climate change, as we live in ecosystems which involve complex interactions between organisms and the environment. Climate change may impact the incidence of bacterial, viral, fungal, and tick-borne respiratory infections [38]. There is quite a bit of seasonal as well as year-to-year

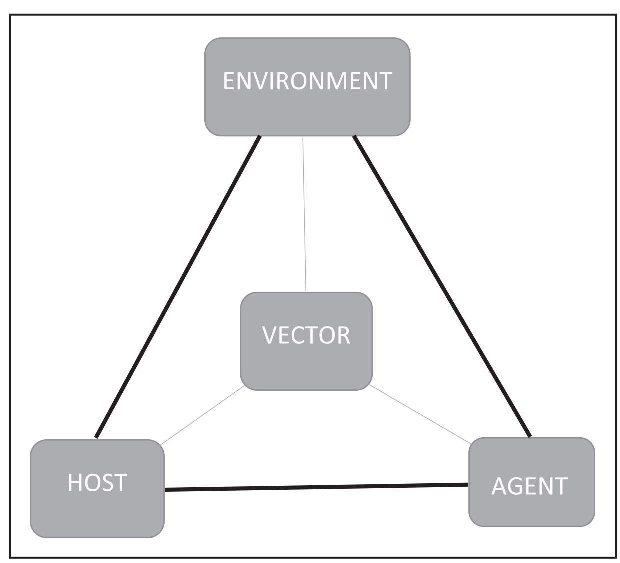

FIGURE 2. The epidemiology triad.

unpredictability in common respiratory viral epidemics (such as influenza and respiratory syncytial virus) and associated bacterial pneumonias [39,40]. Climate change may add more unpredictability in terms of incidence, total duration, and severity of these infectious epidemics [41]. Respiratory infections such as influenza-like illness (ILI) have a higher incidence during the winter months in areas with temperate climate [42]. Caini *et al.* [43▪] looked at the incidence of ILI in the Netherlands over the interval 1970–2016. Their findings showed that ILI incidence declined from 1970 and reached a minimum in the season 2002–2003, but then started to increase in 2003. Lower humidity and temperature in a given week were associated with higher ILI incidence the following week. Their study conclusions suggest that changes in climatic parameters may have played a role in shaping the long-term trends of ILI rates in the Netherlands [43▪].

Climate change is causing global warming as well as influencing short-term (e.g., diurnal) and long-term (e.g., intraseasonal) temperature variability [1,2▪▪]. Sun *et al.* [44▪] in their prospective study assessed the association of intraseasonal temperature variability with respiratory disease hospitalizations among a cohort of elderly Chinese individuals in Hong Kong. The study data demonstrated a positive association between increased variability in wintertime temperatures and risk of incident respiratory diseases. The hazard ratios for total respiratory diseases, pneumonia and COPD per 1 °C increase in wintertime temperature variability were 1.20 (95% confidence interval 1.08–1.32), 1.15 (1.01–1.31), and 1.41 (1.15–1.71), respectively [44▪]. Temperature variability is expected to increase with climate change [1,2▪▪]. The diurnal temperature range, defined as the difference between maximal and minimal temperatures within 1 day, and the temperature change between 2 neighboring days, have both been reported to impact childhood pneumonias and respiratory disease mortality [45,46]. In the resource-limited tropical and subtropical areas of Asia and Africa, climate change could potentially increase the incidence of childhood pneumonias through several different mechanisms; altered precipitation with periods of heavy rainfall leading to increased time indoors and indoor crowding, increased indoor exposure to biomass fuel smoke, and immune system variability due to vitamin D level variability caused by variability in sun exposure [38,34].

Climate change may cause an increase in the overall incidence and geographical spread of infectious diseases with different modes of transmission. Vector-borne diseases like malaria and dengue are on rise in the Africa and Asia due to alterations in vectorial capacity (a measure of the capacity for vectors to transmit a pathogen to a host) [47▪▪]. Climatic changes have increased overall vectorial capacity for dengue virus in the 2010s compared with the 1950s; increases of 7.8% for A aegypti and 9.6% for A albopictus have been documented [47▪▪]. Similarly, the transmission of Plasmodium falciparum and Plasmodium vivax, the two dominant parasites causing malaria worldwide, have been on the rise due to increasing suitability for its transmission attributable to climate change [47▪▪]. Overall, there is limited research with respect to how climate change will alter disease vectors. Extreme weather events such as hurricanes can have implications for a multitude of diseases, and our understanding of long-term effects on respiratory infectious diseases is limited [48▪].

The endemic mycoses found in North America, namely blastomycosis, coccidioidomycosis, and histoplasmosis, are caused by thermally dimorphic fungi and cause infections (mainly respiratory) in areas to which these fungi are geographically restricted, also referred to as mycosis-endemic areas [49]. Several studies suggest that these so-called endemic areas are expanding, likely due to climate change and human land use [49,50▪–52▪].

CLIMATE CHANGE CAUSING EXTREME WEATHER EVENTS AND ITS IMPACT ON RESPIRATORY HEALTH

Extreme events such as wildfires and prolonged heat-waves and drought are causing increase in pollutants such as particulate matter and ground-level ozone, often to dangerous levels [1,2▪▪,12▪▪]. There are now studies from all over the world demonstrating that such events are associated with dangerous level of pollutants and impact respiratory health [21,53–56].

Heat waves

Several time-series and case crossover studies have found a strong synergistic association between heat waves and air pollution [57▪–60▪]. Johansson investigated how the extreme summer of 2018 affected the ground-level ozone concentrations compared to the summer periods of 2013–2017 in four different sites in southwest Sweden [57▪]. The study demonstrated that all sites experienced higher average ozone concentrations during 2018 than the period 2013–2017; the important contributing factors were heat waves, high insolation, low humidity, and high vapor pressure deficit [57▪]. Lin *et al.* [58▪] studied the impact of extreme meteorological events including heat wave, atmospheric stagnation, and temperature inversion in the Pearl River delta region of China in each summer season (April–October) from 2006 to 2017. They concluded that atmospheric stagnation had the largest impact on O_3 concentrations over the region, resulting in a 58% increase compared with normal days; heat waves and temperature inversion led to increases of 28 and 14%, respectively [58▪]. Utembe *et al.* [59▪] used the WRF-Chem model to simulate mixing ratios of atmospheric pollutants in greater Sydney during the January, 2013 extreme heat episodes that broke previously long-held temperature records. The results from their modeling study not only confirmed the relative and combined impacts of temperature and biogenic emissions on air quality but also showed that relative impacts of temperature and biogenic emissions were additive [59▪]. Kalisa *et al.* [60▪] performed regression analysis of the relationship between O_3, PM_{10}, nitrogen dioxide (NO_2), and temperatures in urban and rural areas of Birmingham and found that during heatwaves, all pollutant levels rose at each site, with the maximum temperature coinciding with the peak levels of O_3 and PM_{10}. Levels of ozone were found to increase by more than 50% with increases in temperature [60▪].

Wildfires

Wildfire activity has been increasing over the past several decades in the Western United States and in many other parts of the world, with the increases attributed to global climate change [61–64]. Anthropogenic contributions to climate change are estimated to have led to a doubling of the total area burned by forest-fires in the Western United States between 1984 in 2015 [61]. A comprehensive review article by Reid and Maestas [65▪▪] concluded that as climate change progresses, the probability of wildfires is likely to increase in many places, impacting respiratory health. Wildfire smoke is a complex mixture of thousands of compounds, primarily $PM_{2.5}$, carbon dioxide, hydrocarbons, and nitrogen oxides which contribute to increase air pollution locally and regionally, at times to dangerous levels as seen over the past several summer seasons in California [63,64,65▪▪,66▪]. Recent data have confirmed associations between wildfire smoke exposures and exacerbations of obstructive lung diseases such as asthma and COPD [66▪]. Several studies have redundantly demonstrated an association between wildfire smoke exposure and all respiratory health outcomes including outpatient visits, emergency department visits, and hospitalizations [67▪,68,69▪▪,70,71▪,72,73]. Although immediate respiratory health effects from wildfire smoke exposure are well studied, there is a paucity of data on the long-term respiratory impact of wildfire smoke [74,75▪,76,77].

Flooding and severe storms

The frequency and intensity of severe hurricanes and storms is on rise in the United States, and climate change is predicted to further increase the intensity of these extreme events [1,2▪▪,12▪▪]. There has been an alarming increase in sea levels, threatening coastal cities with flooding. Several studies have demonstrated associations between bronchial asthma and thunderstorm activities [21,78]. Post-flooding dampness is also associated with increases in aero-allergenic mold levels, causing exacerbations of asthma and allergic rhinitis [21,78]. Following hurricanes Katrina and Rita, there were high indoor mold exposures for several months in the storm-affected areas, with the potential of causing upper and lower respiratory symptoms [79].

CONCLUSION

The impacts of climate change reviewed in this chapter represent only a fraction of the impact of climate change upon us and our world. One trying to find a word to describe the breadth and implications of climate change must struggle for words. Words of magnitude such as ‘colossal,’ ‘monumental,’ ‘prodigious’ do not suffice, and one is left reaching for words such as ‘apocalyptic,’ a word which has connotations of a religious vision of the end of the world or of a science fiction thriller in which we must defeat an extraterrestrial enemy to save the earth. In this true story, ‘the enemy is us.’ We as a species may be outsurvived by the ant and the armadillo, but in this era we are the masters of the earth. With tools, machines, and ingenuity man has managed to broach and conquer every corner of our planet. Sadly, we have not matched mastery with stewardship, and now the waste products from our success in changing the planet are changing us.

We see and understand with increasing clarity how climate change will affect us. But 20/20 vision is of no avail without action. Almost every country and society on this planet is planning to tackle climate change and its impacts; the Paris agreement a prime example of uniformity of intent [80]. Those of us in ‘developed’ economies play a greater role in generating greenhouse gasses and must play a greater role in mitigation. We represent about 10% of the world’s population and yet consume approximately one-third of the world’s total energy production [81]. We have the privilege of being able to make choices and the duty to do so. Personal decisions matter. A change to a more plant-based diet as suggested by a recent WHO report can lead to a decrease in animal farming, protect land and water, and mitigate climate change [82,83]. Collectively, the sacrifice of little conveniences such as excessive cooling or heating of our homes and workplaces can have far-reaching positive effects. Our path will determine the future of generations to come. We do need to reduce greenhouse gases emissions. We need to do it now. It's an emergency.

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REFERENCES AND RECOMMENDED READING

Papers of particular interest, published within the annual period of review, have been highlighted as:
▪ of special interest
▪▪ of outstanding interest

1. US global change research program. Available at: https://www.globalchange.gov/climate-change. [Accessed 25 September 2019]
2. ▪▪ Fourth National Climate Assessment, vol. II: impacts, risks, and adaptation in the United States (2018). Available at: https://nca2018.globalchange.gov/. [Accessed 25 September 2019]

The Fourth National Climate Assessment, completed in November 2018, is a comprehensive and authoritative report on climate change and its impacts in the United States.

3. September 2019 tied as 2nd hottest on record for U.S. NOAA. Available at: https://www.noaa.gov/news/september-2019-tied-as-2nd-hottest-on-record-for-us. [Accessed 12 November 2019]
4. Europe heat wave shattered all-time records in Germany, Belgium, Luxembourg, the Netherlands, the U.K. and Paris. Available at: https://weather.com/safety/heat/news/2019-07-22-europe-heat-wave-forecast-france-germany-netherlands-belgium. [Accessed 12 November 2019]
5. The 2019 western European heatwaves. ECMWF. Available at: https://www.ecmwf.int/en/newsletter/161/news/2019-western-european-heatwaves. [Accessed 20 November 2019]
6. An Alaska wildfire is the nation's most expensive so far this season. Available at: https://www.adn.com/alaska-news/2019/09/19/an-alaskan-wildfire-is-the-nations-most-expensive-so-far-this-season/. [Accessed 12 November 2019]
7. Huge wildfires in Russia's Siberian Province continue. Available at: https://www.nasa.gov/image-feature/goddard/2019/huge-wildfires-in-russias-siberian-province-continue. [Accessed 12 November 2019]
8. Hurricane Dorian – September 6, 2019. Weather.gov. Available at: https://www.weather.gov/mhx/Dorian2019. [Accessed 12 November 2019]
9. More than 50 elephants starve to death amid severe drought in Zimbabwe. Independent. Available at: https://www.independent.co.uk/news/world/africa/elephants-dead-zimbabwe-drought-starve-water-number-a9165681.html. [Accessed 12 November 2019].
10. Why the 'extreme red flag' winds hitting L.A. region are especially dangerous. Available at: https://www.latimes.com/california/story/2019-10-29/extreme-red-flag-winds-hitting-la-region-dangerous-historic. [Accessed 12 November 2019]
11. Wuebbles DJ, Fahey DW, Hibbard KA; USGCRP. Climate science special report: fourth national climate assessment, volume I. Washington, DC: US Global Change Research Program; 2017 ; 470. Available at: https://science2017.globalchange.gov/. [Accessed 25 September 2019]
12. ▪▪ The Intergovernmental Panel on Climate Change. Available at: https://www.ipcc.ch/. [Accessed 25 October 2019]

The Intergovernmental Panel on Climate Change (IPCC) is the United Nations body for assessing the science related to climate change. The IPCC prepares comprehensive assessment reports about the state of scientific, technical, and socioeconomic knowledge on climate change, its impacts and future risks, and options for reducing the rate at which climate change is taking place.

13. Berger RE, Ramaswami R, Solomon CG, *et al.* Air pollution still kills. N Engl J Med 2017; 376:2591–2592.
14. ▪▪ Schraufnagel DE, Balmes J, Cowl CT, *et al.* Air pollution and noncommunicable diseases: a review by the forum of international respiratory societies' environmental committee. Part 1: The damaging effects of air pollution. Chest 2019; 155:409–416.

A comprehensive article on air pollution-related morbidity and mortality.

15. ▪▪ Schraufnagel DE, Balmes J, Cowl CT, *et al.* Air pollution and noncommunicable diseases: a review by the forum of international respiratory societies' environmental committee. Part 2: Air pollution and organ systems. Chest 2019; 155:417–426.

A comprehensive article on air pollution-related morbidity and mortality.

16. Ground-level ozone pollution. United States Environmental Protection Agency (US EPA). Available at: https://www.epa.gov/ground-level-ozone-pollution/ground-level-ozone-basics#formation. [Accessed 25 October 2019]
17. US EPA – USEP Agency. Assessment of the impacts of global change on regional US air quality: a synthesis of climate change impacts on ground-level ozone. Washington, DC: US EPA – USEP Agency; 2009 ; Available at: https://cfpub.epa.gov/si/si_public_record_report.cfm?Lab=NCEA&dirEntryId=203459. [Accessed 25 October 2019]
18. Jerrett M, Burnett RT, Pope CA 3rd, *et al.* Long-term ozone exposure and mortality. N Engl J Med 2009; 360:1085–1095.
19. Gauderman WJ, Urman R, Avol E, *et al.* Association of improved air quality with lung development in children. N Engl J Med 2015; 372:905–913.
20. Orru H, Andersson C, Ebi KL, *et al.* Impact of climate change on ozone-related mortality and morbidity in Europe. Eur Respir J 2013; 41:285–294.
21. De Sario M, Katsouyanni K, Michelozzi P. Climate change, extreme weather events, air pollution and respiratory health in Europe. Eur Respir J 2013; 42:826–843.
22. ▪ Liu C, Chen R, Sera F, *et al.* Ambient particulate air pollution and daily mortality in 652 cities. N Engl J Med 2019; 381:705–715.

This is a large study which included almost 60 million deaths from 652 cities in 24 countries addressing global ambient air pollution related mortality.

23. Silva RA, West J, Lamarque J, *et al.* Future global mortality from changes in air pollution attributable to climate change nature 2017. Nat Clim Change 2017; 7:647–651.
24. ▪ Analitis A, de' Donato F, Scortichini M, *et al.* Synergistic effects of ambient temperature and air pollution on health in Europe: results from the PHASE project. Int J Environ Res Public Health 2018; 15:1856.

The PHASE project was one of the first multicity projects to examine potential synergistic effects on mortality between meteorology and air pollution. The study results found significant interaction between apparent temperatures, temperature, and ozone concentrations for their effects on the total daily number of deaths for all ages.

25. ▪ Barnes CS. Impact of climate change on pollen and respiratory disease. Curr Allergy Asthma Rep 2018; 18:59.

A comprehensive review article on climate change and its impact on respiratory allergic diseases.

26. 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; 88:279–282.
27. Ziska LH, Gebhard DE, Frenz DA, *et al.* Cities as harbingers of climate change: common ragweed, urbanization, and public health. J Allergy Clin Immunol 2003; 111:290–295.
28. 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; 108:4248–4251.
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; 46:159–170.
30. Bryce M, Drews O, Schenk MF, *et al.* Impact of urbanization on the proteome of birch pollen and its chemotactic activity on human granulocytes. Int Arch Allergy Immunol 2010; 151:46–55.
31. Beck I, Jochner S, Gilles S, *et al.* High environmental ozone levels lead to enhanced allergenicity of birch pollen. PLoS One 2013; 8:e80147.
32. Lake IR, Jones NR, Agnew M, *et al.* Climate change and future pollen allergy in Europe. Environ Health Perspect 2017; 125:3.
33. ▪ Poole JA, Barnes CS, Demain JG, *et al.* Impact of weather and climate change with indoor and outdoor air quality in asthma: a Work Group Report of the AAAAI Environmental Exposure and Respiratory Health Committee. J Allergy Clin Immunol 2019; 143:1702–1710.

A comprehensive report of the American Academy of Allergy, Asthma & Immunology environmental exposure and respiratory health committee on climate change in its impact on air quality and asthma.

34. Takaro TK, Knowlton K, Balmes JR. Climate change and respiratory health: current evidence and knowledge gaps. Expert Rev Respir Med 2013; 7:349–361.

35. Darrow LA, Hess J, Rogers CA, *et al.* Ambient pollen concentrations and emergency department visits for asthma and wheeze. J Allergy Clin Immunol 2012; 130:630–638.e4.
36. Ito K, Weinberger KR, Robinson GS, *et al.* The associations between daily spring pollen counts, over-the-counter allergy medication sales, and asthma syndrome emergency department visits in New York City, 2002–2012. Environ Health 2015; 14:71.
37. Sheffield PE, Weinberger KR, Kinney PL. Climate change, aeroallergens, and pediatric allergic disease. Mt Sinai J Med 2011; 78:78–84.
38. Mirsaeidi M, Motahari H, Taghizadeh Khamesi M, *et al.* Climate change and respiratory infections. Ann Am Thorac Soc 2016; 13:1223–1230.
39. Meerhoff TJ, Paget JW, Kimpen JL, Schellevis F. Variation of respiratory syncytial virus and the relation with meteorological factors in different winter seasons. Pediatr Infect Dis J 2009; 28:860–866.
40. Weinberger DM, Klugman KP, Steiner CA, *et al.* Association between respiratory syncytial virus activity and pneumococcal disease in infants: a time series analysis of US hospitalization data. PLoS Med 2015; 12:e1001776.
41. Towers S, Chowell G, Hameed R, *et al.* Climate change and influenza: the likelihood of early and severe influenza seasons following warmer than average winters. PLoS Curr 2013; 5:5.
42. Tamerius JD, Shaman J, Alonso WJ, *et al.* Environmental predictors of seasonal influenza epidemics across temperate and tropical climates. PLoS Pathog 2013; 9:e1003194.
43. Caini S, Spreeuwenberg P, Donker G, *et al.* Climatic factors and long-term
▪ trends of influenza-like illness rates in the Netherlands, 1970–2016. Environ Res 2018; 167:307–313.

The study findings suggest that climate change likely played a role in the long-term trends of influenza-like illness incidence rates in the Netherlands.

44. Sun S, Laden F, Hart JE, *et al.* Seasonal temperature variability and emergency
▪ hospital admissions for respiratory diseases: a population-based cohort study. Thorax 2018; 73:951–958.

The study concluded that warmer climates worsened association of pneumonia mortality with air pollution in Hong Kong.

45. Xu Z, Hu W, Tong S. Temperature variability and childhood pneumonia: an ecological study. Environ Health 2014; 13:51.
46. Song G, Chen G, Jiang L, *et al.* Diurnal temperature range as a novel risk factor for COPD death. Respirology 2008; 13:1066–1069.
47. Watts N, Amann M, Arnell N, *et al.* The 2018 report of the Lancet Countdown
▪▪ on health and climate change: shaping the health of nations for centuries to come. Lancet 2018; 392:2479–2514.

The most comprehensive article tracking 41 indicators across five domains: climate change impacts, exposures, and vulnerability; adaptation, planning, and resilience for health; mitigation actions and health cobenefits; finance and economics; and public and political engagement.

48. Shukla MA, Woc-Colburn L, Weatherhead JE. Infectious diseases in the
▪ aftermath of hurricanes in the United States. Curr Trop Med Rep 2018; 5:217–223.

The descriptive study highlights the common infectious pathogens that affect evacuees, nonevacuees, and medical responders following hurricanes in the USA.

49. Benedict K, Thompson GR 3rd, Deresinski S, Chiller T. Mycotic infections acquired outside areas of known endemicity, United States. Emerg Infect Dis 2015; 21:1935–1941.
50. Brown EM, McTaggart LR, Dunn D, *et al.* Epidemiology and geographic
▪ distribution of blastomycosis, histoplasmosis, and coccidioidomycosis, Ontario, Canada, 1990–2015. Emerg Infect Dis 2018; 24:1257–1266.

The 26-year longitudinal study characterized the epidemiology of microbiologically confirmed cases of blastomycosis, histoplasmosis, and coccidioidomycosis in Ontario, Canada, confirming their endemicity.

51. Maiga AW, Deppen S, Scaffidi B, *et al.* Mapping histoplasma capsulatum
▪ exposure, United States. Emerg Infect Dis 2018; 24:1835–1839.

The study suggests that preferred soil environments for *Histoplasma* have migrated into the upper Missouri River basin likely due to changes in climate and human land use with increased cultivation.

52. Armstrong PA, Jackson BR, Haselow D, *et al.* Multistate epidemiology of
▪ histoplasmosis, United States, 2011–2014. Emerg Infect Dis 2018; 24:425–431.

The multistate comparison of histoplasmosis surveillance data suggests under detection and underrepresentation of histoplasmosis in the United States.

53. Tong S, Wang XY, FitzGerald G, *et al.* Development of health risk-based metrics for defining a heatwave: a time series study in Brisbane, Australia. BMC Public Health 2014; 14:435.
54. Analitis A, Michelozzi P, D'Ippoliti D, *et al.* Effects of heat waves on mortality. Epidemiology 2014; 25:15–22.
55. Gasparrini A, Guo Y, Hashizume M, *et al.* Mortality risk attributable to high and low ambient temperature: a multicountry observational study. Lancet 2015; 386:369–375.
56. Gabriel KMA, Endlicher WR. Urban and rural mortality rates during heat waves in Berlin and Brandenburg, Germany. Environ Pollut 2011; 159:2044–2050.
57. Tropospheric ozone during the 2018 heatwave in Southwest Sweden.
▪ Available at: https://bioenv.gu.se/digitalAssets/1739/1739945_julia-johansson-reviderad.pdf. [Accessed 5 October 2019]

A modeling study in Sweden confirming positive correlation between temperature and ozone formation.

58. Lin X, Yuan Z, Yang L, *et al.* Impact of extreme meteorological events on
▪ ozone in the Pearl River Delta, China. Aerosol Air Qual Res 2019; 19:1307–1324.

The study confirmed increased ozone formation during heat waves, atmospheric stagnation, and temperature inversion in large Chinese Province.

59. Utembe SR, Rayner PJ, Silver JD, *et al.* Hot summers: effect of
▪ extreme temperatures on ozone in Sydney, Australia. Atmosphere 2018; 9:466.

The results of this modeling study not only confirmed that relative impacts of temperature and biogenic emissions were additive.

60. Kalisa E, Fadlallah S, Amani M, *et al.* Temperature and air pollution relationship
▪ during heatwaves in Birmingham, UK. Sustainable Cities and Society 2018; 43:111–120.

The study results showed a positive linear relationship between temperature and air pollution during heatwaves in Birmingham, United Kingdom.

61. Abatzoglou JT, Williams AP. Impact of anthropogenic climate change on wildfire across western US forests. Proc Natl Acad Sci U S A 2016; 113:11770–11775.
62. Westerling ALR. Increasing western US forest wildfire activity: sensitivity to changes in the timing of spring. Philos Trans R Soc Lond B Biol Sci 2016; 371:20150178.
63. Williamson GJ, Bowman DMJS, Price OF, *et al.* A transdisciplinary approach to understanding the health effects of wildfire and prescribed fire smoke regimes. Environ Res Lett 2016; 11:125009.
64. Reid CE, Brauer M, Johnston FH, *et al.* Critical review of health impacts of wildfire smoke exposure. Environ Health Perspect 2016; 124: 1334–1343.
65. Reid CE, Maestas MM. Wildfire smoke exposure under climate change. Curr
▪▪ Opin Pulm Med 2019; 25:179–187.

It is one of the most comprehensive articles on wildfire smoke under climate change in its impact on human respiratory health.

66. Cascio WE. Wildland fire smoke and human health. Sci Total Environ 2018;
▪ 624:586–595.

A comprehensive review article on the impact of wildfires on human health from the National Health and Environmental Effects Research Laboratory, Office of Research and Development, US Environmental Protection Agency.

67. Hutchinson JA, Vargo J, Milet M, *et al.* The San Diego 2007 wildfires and
▪ Medi-Cal emergency department presentations, inpatient hospitalizations, and outpatient visits: an observational study of smoke exposure periods and a bidirectional case-crossover analysis. PLoS Med 2018; 15:e1002601.

The study examined outpatient visits, ED visits, and hospitalizations, and $PM_{2.5}$ attributed to wildfires within the Medi-Cal population of San Diego.

68. Salimi F, Henderson SB, Morgan GG, *et al.* Ambient particulate matter, landscape fire smoke, and emergency ambulance dispatches in Sydney, Australia. Environ Int 2017; 99:208–212.
69. Reid CE, Considine EM, Watson GL, *et al.* Associations between respiratory
▪▪ health and ozone and fine particulate matter during a wildfire event. Environ Int 2019; 129:291–298.

This is the first study to investigate the association between both $PM_{2.5}$ and O_3 during a wildfire, separately and in mutually adjusted models, and respiratory health.

70. Garcia-Olivé I, Radua J, Salvador R, Marin A. Association between forest fires, environmental temperature and cardiorespiratory admissions from 2005 to 2014. Arch Bronconeumol 2017; 53:471–534.
71. Deflorio-Barker S, Crooks J, Reyes J, Rappold AG. Cardiopulmonary effects
▪ of fine particulate matter exposure among older adults, during wildfire and nonwildfire periods, in the United States 2008–2010. Environ Health Perspect 2019; 127:37006.

The recent study found that asthma-related hospitalizations among elderly Americans were more sensitive to ambient $PM_{2.5}$ on smoke days than on nonsmoke days.

72. Liu JC, Wilson A, Mickley LJ, *et al.* Wildfire-specific fine particulate matter and risk of hospital admissions in urban and rural counties. Epidemiology 2017; 28:77–85.
73. Alman BL, Pfister G, Hao H, *et al.* The association of wildfire smoke with respiratory and cardiovascular emergency department visits in Colorado in 2012: a case crossover study. Environ Health 2016; 15:64.
74. Kim Y, Knowles S, Manley J, Radoias V. Long-run health consequences of air pollution: evidence from Indonesia's forest fires of 1997. Econ Hum Biol 2017; 26:186–198.
75. Lipner EM, O'Dell K, Brey SJ, *et al.* The associations between clinical
▪ respiratory outcomes and ambient wildfire smoke exposure among pediatric asthma patients at National Jewish Health, 2012–2015. GeoHealth 2019; 3:146–159.

The study observed only transient decline in forced expiratory volume in 1s older children with asthma who were to wildfire smoke.

76. Haikerwal A, Akram M, Sim MR, *et al.* Fine particulate matter (PM2.5) exposure during a prolonged wildfire period and emergency department visits for asthma. Respirology 2016; 21:88–94.
77. Black C, Gerriets JE, Fontaine JH, *et al.* Early life wildfire smoke exposure is associated with immune dysregulation and lung function decrements in adolescence. Am J Respir Cell Mol Biol 2017; 56:657–666.

78. D'Amato G, Cecchi L, Annesi-Maesano I. A trans-disciplinary overview of case reports of thunderstorm-related asthma outbreaks and relapse. Eur Respir Rev 2012; 21:82–87.

79. Rath B, Young EA, Harris A, *et al.* Adverse respiratory symptoms and environmental exposures among children and adolescents following Hurricane Katrina. Public Health Rep 2011; 126:853–860.

80. The Paris agreement. Available at: https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement. [Accessed 25 October 2019]

81. US EIA report. Available at: https://www.eia.gov/todayinenergy/detail.php?id=32912. [Accessed 20 November 2019]

82. Land is a critical resource, IPCC report says. Available at: https://www.ipcc.ch/2019/08/08/land-is-a-critical-resource_srccl/. [Accessed 20 November 2019]

83. How eating less meat could help protect the planet from climate change. Available at: https://time.com/5648082/un-climate-report-less-meat/. [Accessed 20 November 2019]

