Climate Change and Respiratory Health

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Current Evidence and Knowledge Gaps

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Abstract and Introduction

Abstract

Climate change is a key driver of the accelerating environmental change affecting populations around the world. Many of these changes and our response to them can affect respiratory health. This is an expert opinion review of recent peer-reviewed literature, focused on more recent medical journals and climate-health relevant modeling results from non-biomedical journals pertaining to climate interactions with air pollution. Global health impacts in low resource countries and migration precipitated by environmental change are addressed. The major findings are of respiratory health effects related to heat, air pollution, shifts in infectious diseases and allergens, flooding, water, food security and migration. The review concludes with knowledge gaps and research need that will support the evidence-base required to address the challenges ahead.

Introduction

Whether the term used is climate change, environmental change, global warming or increase in extreme weather events, the global environment is undergoing profound change and many of these changes can affect respiratory health. Temperature increases are associated with increases in air pollutants, wildfires cardio-respiratory disease. Extreme storm events and sea-level rise increase opportunities for flooding.[1,2] A strong majority of scientists now agree that Greenhouse gas (GHG) production by humans is the primary cause of these changes.[3,4] Though the most profound temperature increases and environmental changes are in the far north with dramatic reductions in sea ice,[3] the most significant effects at the population level are occurring where large urban areas are vulnerable to the direct and indirect effects of climate change.[5]

Direct health effects include heat related illness and related exacerbation of underlying cardio-vascular disease, COPD and asthma, increases in hazardous air pollution days from ozone and particulate matter (including forest fires and desertification) and mortality and morbidity from extreme weather events.[6–8] Indirect effects include shifts in vector borne illness, allergen load, malnutrition, reduced freshwater resources, flooding and forced migration with accompanying societal disruptions and their 'downstream' effects.[3,6,9] The WHO conservatively estimated over a decade ago in 2000, that more than 150,000 deaths per year from climate change related causes along with over five million disability affected life-years lost per year over the previous three decades.[10,11]

This paper reviews the latest scientific studies on climate change and respiratory health including global health impacts in low resource countries. It concludes with an outline of knowledge gaps and research needs in respiratory health that will support the evidence-base needed to address both mitigation and adaptation challenges.

Methods

We conducted an expert opinion review of some of the recent literature, especially papers published in peer-reviewed academic journals within the last five years, on topics relevant to climate change and respiratory health including those of the UN sponsored International Panel on Climate Change (IPCC). We searched the PubMed biomedical database using the terms "climate change and respiratory health" and selected the most highly-relevant papers to review. We also reviewed recent research on climate-health relevant modeling results from non-biomedical journals that frequently publish on climate change's effects on air pollution; these include, for example, *Atmospheric Environment*, *Journal of Geophysical Research*, and *Climatic Change* among others. Journals publishing papers that describe human health effects associated with climate-atmospheric chemistry modeling include *Environmental Health Perspectives*, *American Journal of Preventive Medicine*, and others, as well as federal and state environmental and health agency regulatory documents.

We summarized some of the latest research findings on how climate change can affect respiratory disease prevalence, mostly from studies in the USA, but with some recent work from elsewhere in North America, Europe, and Asia included. Given the evidence, that the environmental health effects of climate change are underway and projected to increase in future, one can expect the body of scientific literature on climate change and respiratory health to grow rapidly.

Known Climate Related Impacts to Respiratory Health

A substantial body of epidemiological research describes how rising atmospheric temperatures associated with climate change are linked to changing distributions of respiratory disease and mortality.[2,4,8,12] Extreme weather events in recent years have highlighted some of the significant health consequences of these events on respiratory health. Below, we highlight a few health outcomes with clear association to climate change related hazards. The listing is meant to be illustrative, not exhaustive.

Wildfires

Heat and drought conditions prevailed across much of the USA in the summers of 2011 and 2012, and contributed to wildfire risks. The 2012 wildfire season had the third highest total burn area in records dating back to 1960 more than 9.1 million acres as of 30 November 2012—and the average fire size was the highest on record.[13] Fire frequency has increased in western US states in recent decades, partially in response to warmer spring and summer temperatures, reduced precipitation and snowpack, earlier snowmelt in spring, and prolonged summer fire seasons at higher elevations, trends projected to continue as climate change continues.[14] Smoke emissions can travel hundreds of kilometers downwind of fire areas, exposing people to a complex mixture of fine particles, ozone precursors, and other health-harming compounds.[15–20] One recent worldwide estimate is that 339,000 deaths annually may be attributable to landscape fire smoke.[17] Respiratory and cardiovascular hospital admissions and emergency room visits increase in response to wildfire smoke exposures, strongly associated with PM levels.[15,21] These health threats could increase in future as climate change exacerbates wildfire risks in many regions.[22]

Changes in Pollen Releases (Asthma & Allergic Rhinitis)

Aero-allergenic plant pollen production is also affected by climate change. Laboratory and field studies in Europe, North America, Australia and Asia have shown that allergenic tree, grass, and weed pollen production increases several-fold under the influence of higher carbon dioxide (CO_2) concentrations.[23,24] The combination of earlier spring onset and warmer summer temperatures that delay the first fall frost can extend pollen production seasons; in midwestern North America, ragweed-pollen production increased up to 27 days between 1995 to 2009, associated with rising temperatures.[25] Increases in ambient pollen concentrations are associated with higher rates of allergic sensitization, higher numbers of emergency department (ED) visits and hospital admissions for asthma and allergic rhinitis, as well as higher numbers of physician visits, and large increases in over-the-counter allergy medication sales.[7,8,26–31]

Heat Waves (COPD, CVD)

Over the last 50 years, average annual temperatures in the USA have increased more than 1°C.[4] From 1987 to 2005 in 43 large US cities, mortality increased 3.74% [95% PI 2.29–5.22%] during heat waves, compared with non-heat wave days.[32] During multi-day heat wave periods, excess deaths can range into the tens of thousands, as in the 2003 European and 2010 Russian heat waves, among other notable recent heat wave events. Extreme heat increases short-term premature mortality and morbidity from a variety of causes, including those directly heat-related (heat stroke, heat syncope, heat edema, etc.) and a range of cardiovascular, respiratory, kidney and other illnesses.[33–35] Increased temperature variability can also increase mortality among the elderly.[36]

Air Pollution (Asthma & COPD)

A substantial body of research describes how increasing atmospheric temperatures, along with changes in vertical mixing height in the atmosphere, local weather patterns, wind speed and direction can worsen ground-level pollution, notably ozone.[7,37–39] Ground-level ozone exposures diminish lung function and increase acute premature mortality, asthma-related hospitalizations and emergency department visits.[7,37,40–42] For people with COPD, CVD, and diabetes, chronic ozone exposures also increase morality risks.[43] Temperatures have been projected to continue to rise through the end of this century, the extent depending upon the emissions scenario: by an additional 2–3.6C for a lower-emissions (B1) scenario, up to 4–6C for a current emissions growth, (A2) scenario (Figure 1).[4] This raises concerns about the ability to meet health-based air quality standards in the future. Recent studies suggest that by the year 2050, as many as 2,500 summertime deaths may be attributable to premature ozone-related mortality associated with climate change under a high-emissions (A1) scenario, absent other limits on ozone precursors.[44] Climate change can also lead to higher atmospheric concentrations fine particulates ($PM_{2.5}$), although the effect of rising temperatures is more complex for the different chemical constituents of $PM_{2.5}$.[45,46]

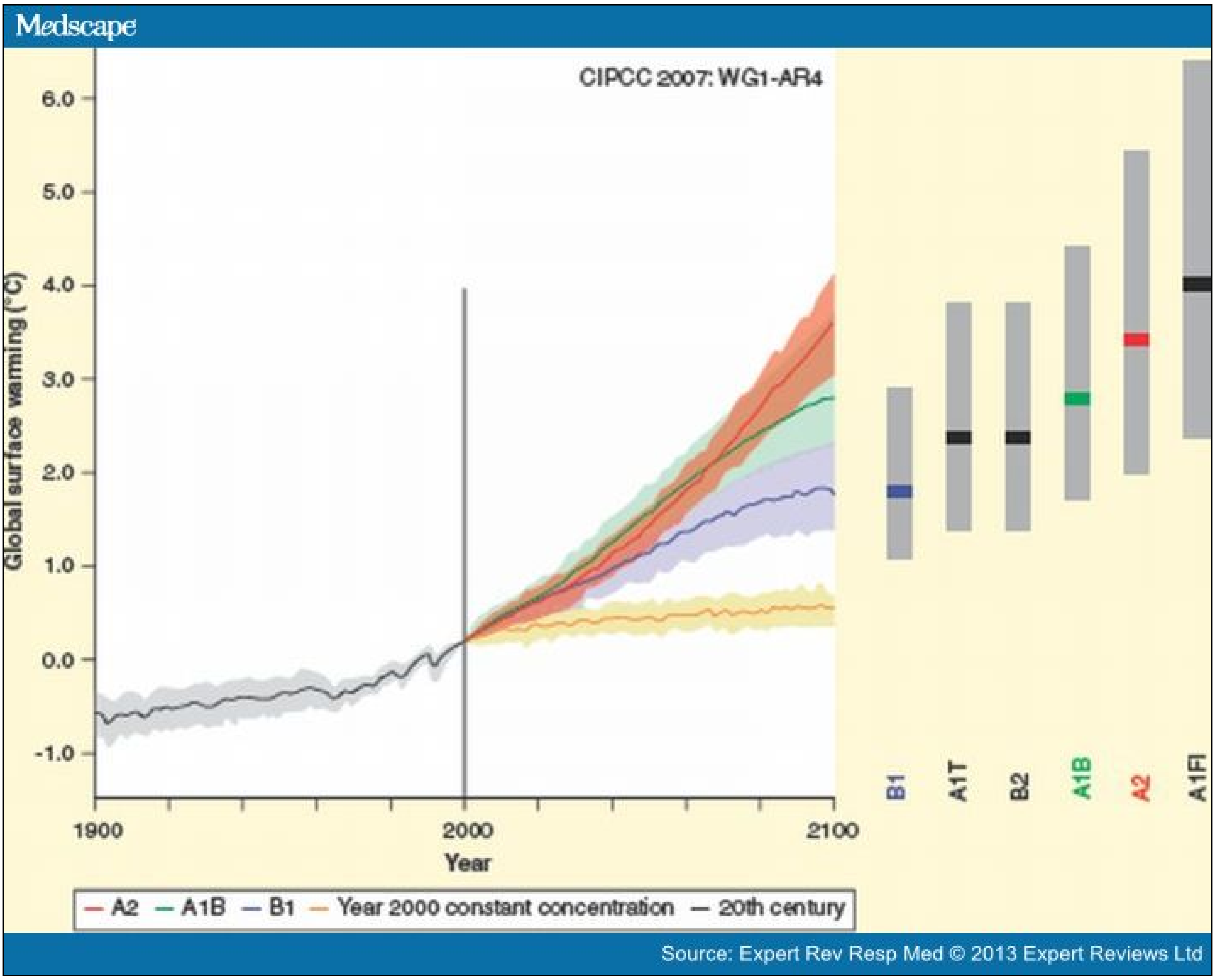

Figure 1.

Multi-model averages and assessed ranges for surface warming. Legend: Solid color lines are multi-model global averages of surface warming (relative to 1980–1999) for the scenarios A2, A1B and B1, shown as red, green, and blue (respectively), which are continuations of the 20th century simulations. Shading denotes the ±1 standard deviation range of individual model annual averages. The lower orange line is for the experiment where concentrations were held constant at year 2000 values. The grey bars at right indicate the best estimate (solid line within each bar) and the likely range assessed for the six SRES marker scenarios. The assessment of the best estimate and likely ranges in the grey bars includes the AOGCMs in the left part of the figure, as well as results from a hierarchy of independent models and observational constraints. Taken from Climate Change 2007: The Physical Science Basis. Working Group I Contribution to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Figure SPM 5, Cambridge University Press.

Desertification & Associated Increase in Particulate Matter

Summer drought in the USA in 2012 brought home to many people how far-reaching the effects of climate change can be. Drought conditions create multiple health challenges: in dry conditions, more pollen, dust, particulates, and when present, wildfire smoke which can irritate respiratory epithelium, exacerbate chronic respiratory illnesses, asthma, and increase risks for acute respiratory infection. Drought conditions may enhance risks of transmission of some infectious illnesses, including coccidioidomycosis (Valley Fever), with the fungal spores inhaled from disrupted soils, and *Naegleria fowleri*, a pathogen found in untreated surface waters that has caused lethal cerebral infections in recreational swimmers when water temperatures increase as water body levels drop.[47] As water supplies become scarce during drought, decreased hand washing practices may increase infectious illness risks further.[12]

Potential Climate Related Impacts to Respiratory Health

In this section, we will discuss respiratory health effects, which may be impacted by climate change, though the precise link to a climate related hazard is poorly understood or is indirect. For example, pneumonia is a common illness that affects approximately 450 million people per year and is a major cause of death in all parts of the world. It is rarely mentioned in the context of climate change,[48] but clear seasonal variation is noted suggesting climate related effects.

Infections

The incidence of respiratory infections varies on a seasonal basis. Lower respiratory tract infections have a higher incidence during the winter in temperate areas, but in tropical areas, the incidence of infection is usually higher during the annual rainy season.[49] A retrospective analysis in Hong Kong showed that the magnitude of summer peaks of influenza. A infections have been increasing over the past decade.[50] A recent study in China found that multi-day increases in temperature (i.e., lack of cooling at night) were associated with increase emergency department utilization for respiratory tract infections.[51] Climate change could potentially increase the incidence of childhood pneumonia in tropical settings through several different mechanisms. Increased time indoors because of heavier rainfall could increase crowding and exposure to biomass fuel smoke, and decrease exposure to sunlight (i.e., reduced vitamin D). Population displacement due to drought and famine could further increase the rate of transmission of infections.[49] Malnutrition due to drought as a result of climate change is likely to increase pneumonia deaths, since a substantial proportion of pneumonia deaths in children under 5 years are attributed to this factor.[52]

Flooding, Storms & Mold Exposure

In addition to increased rainfall in tropical areas, climate change is predicted to increase the intensity of storm events that will lead to flooding.[53] Flooding threatens health infrastructure even in wealthy countries. Patients requiring mechanical ventilation and intensive care are particularly vulnerable due to the challenges posed by evacuation and power outages.[54] Resource poor facilities are likely to be even more vulnerable to extreme weather threats. Additionally, asthma exacerbations have been associated with thunderstorm activity in North America, Europe and Australia.[55,56] With increased intensity of storms this hazard may increase.

Floods can also cause persistent dampness in homes that is associated with microbial growth, especially fungal (molds). The molds that grow in buildings in a post-flood environment can be different and the levels much higher than what is common when flooding has not occurred. High indoor/outdoor mold ratios were observed in the months immediately following Hurricanes Katrina and Rita, indicating the potential for high indoor exposures.[57] Respiratory illness associated with mold exposure is generally non-infectious in immune-competent individuals. Individuals who are sensitized to fungal allergens are at risk for exacerbations of allergic rhinitis and asthma with high indoor exposures.[58] Aero-allergenic mold levels may increase under climate change through several mechanisms: 1) elevated carbon dioxide concentrations augmenting growth, indoor dampness and conditions in building materials that encourage toxic mold growth indoors, and rising temperatures that support growth.[57,59–61]

Greenhouse Gas Mitigation & Adaptation Co-benefits for Publichealth

To improve the likelihood of minimizing the adverse effects of climate change, we must reduce the anthropogenic causes, (i.e., GHG production, and at the same time prepare society to adapt to changes that cannot be stopped due to the momentum already in the climate system). Policy changes are beginning to impact GHG production in many parts of the world. Even the USA has seen recent reductions in fossil fuel use linked to improved fuel-efficiency standards for vehicles.[62] European nations have been significantly reducing GHG production over the past decade. These efforts are crucial for reducing future impacts, but because over-all global emissions continue to raise, adaptation to the impacts of future climate variability will also be required. Adaptation will take many forms. Those related to respiratory health are briefly reviewed below.

As noted in the above section on heat related illness, the magnitude of predicted temperature increase and effects stemming from this depends largely upon society's ability to reduce GHG emissions. Figure 1 shows the commonly modeled scenarios developed over the past 20years of research by the IPCC. Any reduction beyond the A2 scenario (close to our current trajectory) will require optimizing economic, technologic and population growth in a sustainable fashion, along with massive education and behavior change on an historic scale to reduce individual and collective emissions. If we are unable to achieve these goals then by mid-century, we will likely go beyond the 2^{o}C increase in temperature as a target not to be exceeded, agreed upon in the UN's Copenhagen meeting in 2009.[63] This target temperature is rejected by many African and island states as unacceptably high; half of this increase is believed to represent the limits of many ecosystems.[64]

As exhibited by the error bars in Figure 1, there is significant uncertainty in the range of projected average surface temperatures for each scenario. This uncertainty increases with efforts to predict changes more locally and with other parameters of climate change such as precipitation. The personal and collective efforts required to reach meaningful GHG reduction targets are significant. However, the benefits to health are also significant via reduction in health-harming co-pollutants emitted along with GHGs and can be immediate and more tangible than the reduction in GHGs. The improvements in health are noted in sectors where emissions are being reduced in Europe to meet GHG reduction targets; household energy use, urban land transport, electricity generation and food production and agriculture.[65] Technologies that lead to reduced GHG production also have additional spin-off improvements in all of these sectors, such as reduced air pollution, increased physical activity, more efficient and available food production and improved over-all quality of urban living. Thus, as nicely outlined in a special issue of *The Lancet*, "The news is not all bad".[66]

> *"The threat of climate change has generated a global flood of policy documents, suggested technical fixes, and lifestyle recommendations. One widely held view is that their implementation would, almost without exception, prove socially uncomfortable and economically painful. But as a series of new studies shows, in one domain at least—public health—such a view is ill-founded. If properly chosen, action to combat climate change can, of itself, lead to improvements in health"*.[66]
>
> *–Lancet Editorial Board 2010*.

Urban Planning, Exercise & Energy Consumption

A well-tested strategy in cities where the combined health effects of heat and air pollution are often compounded is heat and pollution early warning systems.[67] A more long term strategy involves mitigating the urban heat-island effect, the tendency for buildings and pavement to absorb more heat during the day and radiate heat at night. The heat-island reduces physiologically important cooling overnight and further stresses energy intensive air conditioning. In Asia, urban heat island effects have been linked to increases in respiratory hospital admissions.[68] In the USA., the rate of increase in number of extreme heat events was more than double in the most sprawling urban regions than in the most compact cities.[69] More work is needed to evaluate the health-adaptive opportunities that planned urban design affords.

Researchers have begun to model the air quality and health benefits from enhancing residents' ability to walk or bike to schools and workplaces via "active transportation" that substitutes these zero-carbon emissions trips for more vehicle-centric travel.[70] In one example from the urban transport sector, Woodcock and colleagues estimated that replacing current vehicles used on short trips in London with low emission vehicles, walking and cycling could reduce ischemic heart disease by almost 20% while significantly reducing GHG emissions.[71] A U.S. study that looked at the effect of substituting 50% of short (8 km round trip) car trips with bicycle trips estimated $8 billion/year in combined benefits from improved ozone and PM2.5 air quality, reduced health care costs, and improved physical fitness.[72] In lower-income countries as well, switching to cleaner fuel sources can yield impressive economic and health benefits.[73] Promising "triple-wins" can be achieved in increased personal fitness from more activity, improved respiratory health with lower co-pollutant emissions from less fossil fuel combustion, and simultaneous GHG reductions.[74,75]

Designing more walkability and green spaces into our cities enhances neighborhood cohesion, increases social capital, improves the quality of urban living[69,76] and may contribute to local food security,[77] while reducing emissions, the urban heat island and overall energy needs. Linked monitoring data on local and regional air quality, energy consumption, personal energy and transportation choices, and health outcomes could yield better understanding of how energy consumption and air pollution co-vary on hot summer days, and help further quantify more of the benefits to be gained from moving toward less-polluting energy sources.

Biomass Fuel Cooking/Heating Alternatives

Anthropogenic aerosol consists mainly of sulfate, nitrate, ammonium, black carbon (BC), and organic carbon (OC). These components interact with solar radiation in different ways depending on size and composition and contribute either a cooling or a warming forcing on climate.[78] BC absorbs solar radiation that causes a direct global warming effect,[79] and it also causes an additional warming effect after deposition onto snow and ice surfaces by reducing the reflectivity of snow.[80] Cooking with biomass fuels (wood, dung and crop waste) and open burning for agricultural purposes (deforestation and crop residue burning) are major sources of BC in the developing world. Fossil fuel combustion (diesel, oil and coal) is the primary source in developed countries. The strong warming due to the direct effect and snow-albedo effect of BC suggests that BC emission reductions could yield a short-term climate benefit. The Arctic may be particularly sensitive to the warming effects of BC.[81] The combustion sources that emit BC also emit other aerosol components that tend to cool climate, principally OC, so the net climate impact of emission controls is somewhat uncertain. A recent assessment, however, concluded that BC is the second-most important climate-forcing emission after CO_2 and suggested that even after accounting for co emissions, which cool the climate, reducing diesel and residential biomass emissions would have a mitigating effect on global warming.[82] That said, a strong case can be made for a strategy to control BC emissions from indoor cooking with biofuel because of the health co-benefits of reducing biomass smoke exposure (decreased risks of childhood pneumonia, COPD, and lung cancer among women, and children in developing countries as well as cardiovascular disease among men and women).[83,84]

Impacts on Low Resource Countries

Climate change represents the greatest environmental justice challenge of our times. Disproportionate consumption of fossil fuels by rich nations is largely responsible for our current levels of GHGs, with the poorest 15% of the world's people responsible for only 3% of the global carbon footprint in 2000.[85] Unfortunately, as North America and Europe reduce their emissions China, India and other rapidly developing nations have significantly increased their production continuing the global increase in emissions. Low-resource countries continue to suffer the greatest impacts because of their increased exposure to the effects of warming and their reduced ability to adapt to the changes. Indeed, the vast majority of the WHO's conservative estimate of 150,000 deaths per year are among those one billion poorest individuals.[74] In defining its research priorities,[5] the WHOhas been challenged to recognize this context and to clearly place their agenda in the "overall context of improving global health and health equity".[86] This focus is appropriate.

To buttress against the negative health impacts of climate change, societies must develop adaptive capacity. A key determinant of adaptive capacity is household social and economic capital.[87] The impacts of climate change will be felt more acutely by those whose choices are constrained by social and financial capital, even though their contribution to the problem of GHG production is miniscule. Building adaptive capacity for the populations of low-resource nations is recognized as a moral and ethical imperative by the participants in the UN's Framework Convention on Climate Change (UNFCCC). To this end they have established the Green Climate Fund (GCF) with pledges of up to $100 Billion (USD) annually by 2020 for adaptation and mitigation that moves countries to a more sustainable development path.[63] Managing the fund will be a significant challenge in itself.[88]

Effectively improving adaptive capacity in low-resource countries is not just altruistic. The UN Environment Program has carefully assessed the environmental capital available in the earth's ecological systems[89] and concluded that concluded that social stability in addition to human wellbeing, health and survival are now at destabilizing levels. Crucial resources including food[90–92] and water[93,94] are frequently in limited supply during stressful climate driven conditions. Though uncertain the threat of armed conflict remains a distinct possibility and further threat to health.[9]

An example of what progress can be made to combat the challenge of food and water insecurity in a low resource setting is demonstrated by Jennifer Burney and others at Stanford's Center on Food Security and Environment in their efforts to map aquifers in Africa's dry regions and develop cheap, efficient drip irrigation systems to improve crop yields and reduce GHG emissions from agriculture.[95]

Key Knowledge & Data Gaps

Gaps in Epidemiology

A substantial body of epidemiological research describes how rising atmospheric temperatures and alterations in weather patterns from climate change, are linked to changes in the distribution of respiratory disease and respiratory-related mortality and morbidity.[7,8,30,42,96–99]

Changes in the frequency, intensity, and areal extent of extreme weather events, including heat waves, drought, extreme precipitation, and coastal flooding, are exacerbated by climate change and they in turn affect the distribution and incidence of respiratory diseases. There are, however, remaining challenges in attributing specific changes in the patterns of disease incidence to the local and regional effects of climate change, and more accurate predictive models are needed.[100] There are disparities in the temporal and spatial scales at which air pollution monitoring and health tracking data are collected, administrative barriers to sharing and linking environmental-health data sets, and a general paucity of such monitoring data (even in the USA) that might otherwise allow questions about changing trends in prevalence of climate-sensitive respiratory conditions to be assessed in the recent past or approaching near-real time. Residential housing characteristics, air-conditioning availability and use, individual activity patterns, and individual and community-level temperature and air pollutant exposures all factor into a thorough assessment of climate-health effects.[69,101,102]

Other questions to be investigated concern the degree to which populations may adapt over time to ozone exposures, or if mortality displacement may occur, similar to heat responses.[103] This refers to a short-term increase in mortality rates, often in response to temperature or air pollution events, which can be followed in subsequent weeks by a decrease in overall mortality. The exposure effectively advances or "displaces" the date of death to an earlier day for those most vulnerable in a population, leading to fewer deaths after the event. There have been relatively few assessments thus far of the proximal and distal effects of wildfire smoke on respiratory health. Monitoring networks are needed that can link satellite data of smoke plumes to near-ground monitoring of emissions, ambient downwind concentrations, and associated health effects, in order to provide a foundation for creating early-warning systems in areas downwind of fires where respiratory health could be threatened.

Beyond laboratory and field studies of how rising temperatures and atmospheric CO2 can influence the timing, production, and allergenicity of pollen,[23,31] questions remain about allergy/asthma-relevant threshold levels of pollen concentrations in the air, how those concentrations may vary locally, and what local modifying effects co-exposures to other climate change-sensitive air pollutants like ground-level ozone may have. Furthermore, do local carbon dioxide sources have local effects on pollen production? Our ability to address these research questions will be enhanced by establishing a more finely-resolved national network of daily pollen monitoring sites, linked at comparable temporal and spatial scales to reporting networks for near real-time health tracking of allergy and asthma health effects, linked with carbon dioxide emission source data, and other health-relevant air pollutant monitoring.

A better understanding is needed of the precise biophysical mechanisms underlying heat waves impacts on respiratory mortality;[42] the effects of increasing minimum nighttime temperatures on internal biophysical set-points, relative to cardiovascular, respiratory or other morbidity thresholds; and the degree to which increasing temperature variability associated with a changing climate could increase both respiratory morbidity and mortality in the future.[36,102]

Gaps in Exposure Assessment

Air pollutants and their precursors can affect climate, and, in turn, the distributions of air pollutants are highly dependent upon regional climate.[78] When considering strategies to abate air pollution and mitigate anthropogenic climate warming, policymakers face tradeoffs and synergies. For example, sulfate is a major component of $PM_{2.5}$ pollution in many regions, but reducing sulfate for health reasons could lead to a rapid rise in surface temperatures as the atmospheric cooling effect of sulfates diminishes.[104] In the absence of emission changes, a warming climate may increase air pollution in many polluted regions, an impact that has been referred to as "a climate change penalty" on air quality.

A wide range of model estimates exists for regional air quality both at present and for future projections. Increasing the length of time over which relationships between relevant meteorological variables and air quality have been observed can provide useful information for evaluating models. Further study of the observed relationships may help to improve our understanding of the links between air quality and climate.

Gaps in mechanistic understanding limit confidence in projecting future air quality in a changing climate. For example, how ozone (O_3) levels will be impacted by climate change is strongly dependent on how organic nitrates ($RONO_2$) are considered,[37,104] and there is major variability in how models treat the impact of $RONO_2$ on oxides of nitrogen (NO_X) availability as an O_3 sink.[105] Uncertainties remain about biogenic volatile organic compound oxidation and subsequent secondary aerosol formation.[106] Aerosol-oxidant interactions also require further study as they may determine particulate matter (PM) air quality in some regions.[107]

Human interactions with the biosphere are crucial to understand because vegetation acts as both a source and a sink for many air pollutants. The attribution of O_3 and PM air pollution to "anthropogenic" versus "biogenic" sources is complicated by atmospheric chemistry that involves both anthropogenic and biogenic precursors and by land-use changes, which alter biogenic sources.[108] Sources from agriculture and livestock sectors are generally difficult to model, but non-negligible, particularly for methane and ammonia (NH_3). Human-driven changes in land-use and land cover, such as urbanization or shifts between forests and agriculture, could dramatically alter future O_3 and aerosol precursor emissions.[78]

Climate-driven changes in PM could be large, but there are major uncertainties in the model projections.[78] Aerosolized particulate concentrations are particularly sensitive to precipitation changes and are expected to decrease in regions with increased rainfall. Large contributions are possible from "natural" aerosol sources, such as carbonaceous aerosols from wildfires, mineral dust, and biogenic precursors to secondary organic aerosol. As noted earlier, in regions experiencing a warmer and dryer climate, wildfires are expected to increase. Seasonal dust storms will likely increase and lead to hazardous levels of $PM_{2.5}$ in regions downwind of major desert source regions, and in some cases, leading to long-range transport across oceans.

Future PM levels will be a function of changes in both emissions and climate. Concentrations of PM are driven by local as well as regional anthropogenic emissions, depend on regional oxidant levels, and are complex to model. Changes in sulfate aerosol concentrations, however, generally follow changes in sulfur dioxide (SO_2) emissions. Changes in NO_X emissions influence nitrate aerosols to a lesser extent than the SO_2-sulfate relationship due to competition between sulfate and nitrate for ammonium, such that nitrate aerosol is inversely dependent on sulfate. Continued reductions in SO_2 emissions alongside rising NH_3 emission could lead to nitrate aerosol levels equivalent to or larger than sulfate aerosol levels in some regions over the 21st century.[109]

The impact of anthropogenic aerosol on clouds is more uncertain. There is an indirect cooling effect of aerosol, also known as the cloud albedo effect.[110] Very little is known on the contribution of different aerosol components to this effect. While several studies have tried to quantify the cloud albedo effect of BC-containing particles, the sign of the cloud effect (i.e., cooling or warming) is model-dependent and varies with the BC to OC mass ratio, the size of emitted particles, and the magnitude of the emission change.[111]

Other significant gaps in our understanding of human health risk in a changing climate are also of interest to pulmonologists. How do heat stress and air pollution interact in different geographical and social settings? What makes communities resilient to extreme heat and air pollution events? Can vulnerable populations (e.g., old, young, impoverished, with chronic cardio-respiratory conditions) be protected? What factors determine a community's adaptive capacity and can this capacity be 'grown' by efforts through the Green Climate Fund?

Understanding Combined Effects

Laboratory and epidemiologic studies have shown that air pollutants harm lung function in patients with allergic asthma; and that pollutant-induced damage to mucociliary clearance and airway inflammation can exacerbate the effects of inhaled aeroallergens.[112] The combined health effects of air pollutants like O_3, PM and pollens are challenging to study, in part because there are relatively few monitoring sites in the US at which daily measurements are made from stations with co-located sensors for pollen, ozone, and particulate matter,and associated health outcomes, on comparable time and spatial scales. Meteorological data and information on changes in land-use that can affect pollen production are also needed to fully understand climate-environment-health relationships. Efforts to model and understand these complex relationships will need to account for human vulnerability factors (age, pre-existing chronic disease, etc.); whether local communities have early warning systems, local monitoring networks, or preparedness plans in place; and whether health-relevant local pollen concentration thresholds exist.

Disease & Natural Cycles Research Needs

> *"Whoever wishes to investigate medicine properly, should proceed thus: in the first place to consider the seasons of the year, and what effects each of them produces, for they are not all alike, but differ much from themselves in regard to their changes"*
>
> – *Hippocrates*.[113]

Seasonality is a characteristic of many respiratory diseases, most frequently influenza epidemics.[114,115] Such diseases that vary seasonally demonstrate some form of climatic dependence and are most likely to be influenced by climate change and variability.[116–118] Furthermore, in depth understanding of past and current seasonal variation in illness incidence can provide a baseline for future studies to identify early impacts of climate change on health.[119] Our understanding of seasonal patterns in respiratory disease and even infections is rudimentary; however, and we have not parsed the role of temperature, humidity crowding, vector biology or ecology,[120] or much less the combination of these plus other environmental factors such as forest fire or drought-related increases in desert PM, O_3, pollen, mold, heat or other potentially climate related exposures. It is clear that infectious disease ranges are shifting with increasing temperatures into higher latitudes and elevation,[10] but the impacts on human health, given complex interactions with other dynamic social and biological systems, and the interventions that might be successful in mitigating these impacts, are largely unknown and a rich area for future research.

Human Migration

Estimates of the extent of human migration expected due to environmental change in the next 40–50 years vary from negligible to over 200 million depending largely on the definition of migration.[121] The drivers of human migration are multiple as people move to improve social and economic circumstances, to seek better opportunities for their children and to reunite with family members or in extreme circumstances to avoid violence or persecution. Though most recent research in this area tends to overlook environmental drivers of migration, climate change can clearly influence decisions to migrate.[121] It is rare to attribute migration to one reason. Instead, climate change is one factor that interacts with many others to drive population movement.[122] Much of the decision to move can be driven by vulnerability to specific climate change induced exposure and whether that exposure is viewed as permanent, as in the case of sea-level rise, or temporary (though likely recurrent) as after a riverine flood or hurricane.[123–126] These pressures are not new.[122] In the early 20th century rising sea levels on the Chesapeake Bay led many residents to abandon their homes,[127] and in the present day rising sea levels threaten to displace millions of people in Bangladesh and other heavily populated, low-lying countries[128] as well as small communities on the arctic coast.[129] It is likely that climate-forced changes in water and food security, extreme weather events and sea-level rise will impact established migration patterns as well as contribute to novel ones. Such large scale migrations would strain existing refugee resources and potentially serve as a mechanism for the increased movement of infectious diseases[130,131] and conflict or create new sources of conflict.[9]

Conclusion

Human induced climate change has begun and is accelerating. Effects on respiratory health are being felt around the world, but are not evenly distributed. Populations in low-resource countries are experiencing greater impacts and have less capacity to adapt in the future. Respiratory effects range from direct heat and air pollution effects, to changes in the biological burden of allergens and shifting infectious disease patterns. Climate driven refugees are increasing and are often forced to live under conditions that promote respiratory infections. Mitigation of GHGs to reduce future impacts is crucial, but adaptation to the inevitable increases in temperature will also be required. Much of this activity has co-benefits for health beyond those directly related to climate change such as increased physical activity and shifts to cleaner fuels. Support for adaptation in low resource countries is a moral imperative to which wealthy nations have committed through the UN response to climate change. Such adaptation can lead to improvements in respiratory health and deserve support. The socio-political, ecological, ethical, technical and human health challenges posed by climate change will test our capabilities as a species for generations to come.

Expert Commentary

Human-induced climate change has begun and is accelerating. Effects on respiratory health are being felt around the world, but are not evenly distributed. Populations in low-resource countries are experiencing greater impacts and have less capacity to adapt in the future. Respiratory effects range from direct heat and air pollution effects, to particulates in wildfires, to changes in the biological burden of allergens and shifting infectious disease patterns. Climate-driven refugees are increasing and are often forced to live under conditions, which promote respiratory infections. Mitigation of GHGs to reduce future impacts is crucial, but adaptation to the inevitable increases in temperature will also be required. Much of this activity has co-benefits for health beyond those directly related to climate change such as increased physical activity and shifts to cleaner, less environmentally degrading fuels. Support for adaptation in low resource countries is a moral imperative to which wealthy nations have committed through the United Nations' response to climate change. Such adaptation can lead to improvements in respiratory health and deserve support. The socio-political, ecological, ethical, technical and human health challenges posed by climate change will test our capabilities as a species for generations to come.

Five-year View

Over the past five years since the IPCC report in 2007 stated in the clearest terms yet that anthropogenic warming is occurring, there has been little encouraging activity from governments participating in the UN Conference of the Parties (COP) annual meetings. Scientists and some government agencies have laid out multiple significant societal and ecological impacts of climate change, including clearly articulating that a rise in average global surface temperature greater that 2^{o} C will overwhelm the biological balance in many of the earth's fragile ecologies (58, 59). While these predictions are raising increasing alarm, they are not generating any indication of the massive international governance and energy policy shifts needed to reduce greenhouse gas production or begin increasing adaptive capacity for the most vulnerable nations. Globally, fossil fuel use continues to grow driven in part by the large rapidly growing economies of China and India. Arguments continue about the inequitable distribution of economic development and the relationship between this human need and the historic and future energy needs of developing countries. If the international community cannot reach agreement on binding reductions in GHGs in the next five years, we are very likely to exceed the biological capacity of many crucial ecosystems worsening the health effects outlined in this paper. Future generations will rightfully condemn our inability to reduce our fossil fuel consumption and better prepare them for their own future development.

Sidebar

Key Issues

- Human-induced climate change is underway, and is a key driver of accelerating environmental change.
- Climate change-associated effects on respiratory health are being globally observed, but are not evenly distributed. Populations in low-resource countries experience differentially greater impacts and have less capacity to adapt, now and in the future.
- Respiratory effects range from direct heat and air pollution effects, to particulates in wildfires, to changes in the biological burden of allergens and shifting infectious disease patterns. Numbers of climate-displaced people who are often forced to live under conditions that promote respiratory infections are increasing.
- Limiting Greenhouse gas (GHG) emissions to reduce future impacts is crucial, but adaptation (climate-health preparedness) must also simultaneously be supported. Many of these activities also provide benefits for health (co-benefits) beyond those directly related to climate change, such as increased physical activity and shifts to cleaner, less environmentally degrading fuels.
- Support for adaptation in low resource countries by wealthier nations is an historic environmental justice challenge. While the $100 billion (USD) pledged to the UN's Green Climate Fund annually by 2020 can be viewed as a "moral imperative" response, these adaptation investments also enhance global environmental and political stability and security.
- The socio-political, ecological, ethical human health challenges posed by climate change will test our theoretical, technical and planning capabilities as a species for generations to come.

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Papers of special note have been highlighted as:

* of interest

** of considerable interest

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