Climate Change
A Global Threat to Cardiopulmonary Health

Mary B. Rice[1,2], George D. Thurston[3], John R. Balmes[4,5], and Kent E. Pinkerton[6]

[1]Pulmonary and Critical Care Unit, Massachusetts General Hospital, Boston, Massachusetts; [2]Cardiovascular Epidemiology Research Unit, Beth Israel Deaconess Medical Center, Harvard Medical School, Boston, Massachusetts; [3]Department of Environmental Medicine, New York University School of Medicine, New York, New York; [4]Division of Environmental Health Sciences, Department of Medicine, University of California, San Francisco, California; [5]Division of Environmental Health Sciences, School of Public Health, University of California, Berkeley, California; and [6]Center for Health and the Environment and the John Muir Institute of the Environment, University of California Davis, Davis, California

Abstract

Recent changes in the global climate system have resulted in excess mortality and morbidity, particularly among susceptible individuals with preexisting cardiopulmonary disease. These weather patterns are projected to continue and intensify as a result of rising CO_2 levels, according to the most recent projections by climate scientists. In this Pulmonary Perspective, motivated by the American Thoracic Society Committees on Environmental Health Policy and International Health, we review the global human health consequences of projected changes in climate for which there is a high level of confidence and scientific evidence of health effects, with a focus on cardiopulmonary health. We discuss how many of the climate-related health effects will disproportionally affect people from economically disadvantaged parts of the world, who contribute relatively little to CO_2 emissions. Last, we discuss the financial implications of climate change solutions from a public health perspective and argue for a harmonized approach to clean air and climate change policies.

Keywords: climate change; air pollution; cardiovascular health; pulmonary health

In the past several decades, an accumulation of scientific evidence has shown that climate change is not only an environmental and economic problem but also a human health problem of enormous proportions. Some of the most well-described human health consequences of climate change are the exacerbation of preexisting cardiopulmonary disease. The American Thoracic Society, whose mission is to improve health worldwide by advancing research, clinical care, and public health in respiratory disease and critical illness, is concerned about the implications of climate change for global public health, especially cardiopulmonary health.

As early as 1896 it was found that carbon dioxide in the Earth's atmosphere causes an imbalance between infrared light–transmitting and –absorbing properties and an increased back-radiation effect in the atmosphere that elevates the temperature at the surface and in the lower atmosphere (1). Human activities that burn fossil fuels release additional CO_2 into the atmosphere. CO_2 levels have risen dramatically since industrialization and continue to rise at alarming rates (Figure 1). The 2013 Intergovernmental Panel on Climate Change (IPCC) report concluded that CO_2 concentrations have risen by 40% since preindustrial times, primarily due to fossil fuel emissions, and have reached levels "unprecedented in at least the last 800,000 years" (2). Other human activities release other greenhouse gases with similar effects, including methane, nitrous oxide, and sulfur dioxide, in addition to naturally occurring ozone and water vapor. Particulate black carbon is released from fossil fuel, biomass, and forest burning and directly absorbs solar radiation, which warms surface temperatures, and also deposits on snow and ice, which reduces the reflectivity of snow and further contributes to global warming (3).

There is no dispute among climate scientists that the Earth's climate system is warming. Figure 2 shows globally averaged surface and ocean temperatures since

(Received in original form October 30, 2013; accepted in final form January 2, 2014)

Supported by the National Institute of Environmental Health Sciences grant 1F32ES023352-01 (M.B.R.), the National Heart, Lung, and Blood Institute grant T32HL007374 (M.B.R.), the California Air Resources Board (J.R.B.), the New York University–National Institute of Environmental Health Sciences Center of Excellence Grant ES00260 (G.D.T.), the California National Primate Research Center grant P51 OD0011107 (K.E.P.), and the National Institute for Occupational Safety and Health grant U54 OH007550 (K.E.P.).

Correspondence and requests for reprints should be addressed to Mary B. Rice, M.D., Pulmonary and Critical Care Unit, Bulfinch 148, Massachusetts General Hospital, 55 Fruit Street, Boston, MA 02114. E-mail: mrice2@partners.org

Am J Respir Crit Care Med Vol 189, Iss 5, pp 512–519, Mar 1, 2014

Originally Published in Press as DOI: 10.1164/rccm.201310-1924PP on January 8, 2014
Internet address: www.atsjournals.org

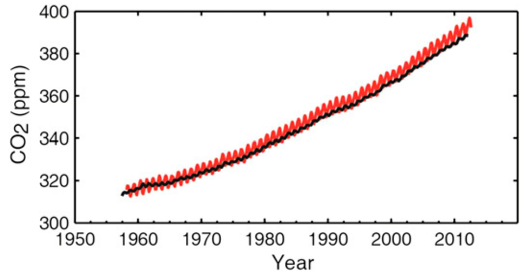

Figure 1. Atmospheric CO_2 from Mauna Loa, Hawaii (*red*) and South Pole (*black*) since 1958. Reprinted by permission from Reference 2.

1850 (relative to 1961–1990 levels) and illustrates the global warming trend since the 1950s. The 2013 IPCC report concluded that global warming is "unequivocal" and that with 95 to 100% certainty, the observed warming since the 1950s is primarily due to human activity (2). Global temperatures rose 0.6 to 0.7°C from 1951 to 2010, of which 0.5 to 1.3°C is attributed to greenhouse gases, −0.6 to 0.1°C from other human emissions including the cooling effect of aerosols, −0.1 to 0.1°C from natural forcings, and −0.1 to 0.1°C from internal variability (2).

Disruption of the global climate promotes extreme weather patterns that harm human health. These include heat waves, droughts, thunderstorms and heavier precipitation, and hurricanes and tropical cyclones. Secondary consequences of these changes include worsening air quality (due to high temperatures, forest fires, and dust storms), floods, and desertification.

Environmental Air Pollution and Climate Change

The primary outdoor air pollutants associated with climate change that are of particular relevance to cardiopulmonary health are black carbon, ozone, and particulate matter. Black carbon is released from fossil fuel combustion (including diesel, coal, and fuel), cooking with biomass fuels (which is widespread in the developing world), and the burning of forest and crop residue for agricultural purposes. Black carbon has been identified as an important climate-forcing emission along with CO_2 (3), and has climate-forcing effects that last for decades (compared with centuries for CO_2). In addition to its effects on climate, black carbon is an air pollutant (a constituent of fine particulate matter) with well-described respiratory and cardiovascular health effects at increased concentrations, including worsening of preexisting cardiovascular disease (4), worsening lung function (5), and increases in chronic obstructive pulmonary disease (COPD) hospitalization and mortality (6) and total and cardiovascular mortality (7). Household air pollution, consisting of black carbon smoke from indoor cooking particularly in the developing world, has been ranked as the third largest contributor to the global burden of disease, largely because of its associations with childhood respiratory infections, COPD in women, and cardiovascular disease in men (8).

Ground-level ozone is an air pollutant that is formed through atmospheric reactions of nitrogen oxides and volatile organic compounds (both emitted by motor vehicles and fossil fuel burning) in the presence of sunlight. Ozone formation increases on sunny, cloudless days and at higher temperatures (9). The frequency and intensity of ozone episodes during summer months are projected to increase as a result of rising temperatures (10, 11). Some recent heat waves have been associated with ozone levels that exceeded air quality standards (12).

Short-term elevations in ozone have been associated with increases in all-cause mortality in relatively polluted Latin American cities (13) and in less-polluted cities in Western Europe and North America (14). The deadly heat wave of 2003 in Europe was associated with high levels of ozone that are believed to have contributed to excess mortality in addition to the mortality caused by the heat itself (12, 15). Ozone has also been found to exacerbate preexisting respiratory diseases in both children and adults. Because ozone is a respiratory irritant that causes bronchial inflammation and hyperresponsiveness (16, 17), people with preexisting obstructive lung disease are particularly susceptible to adverse

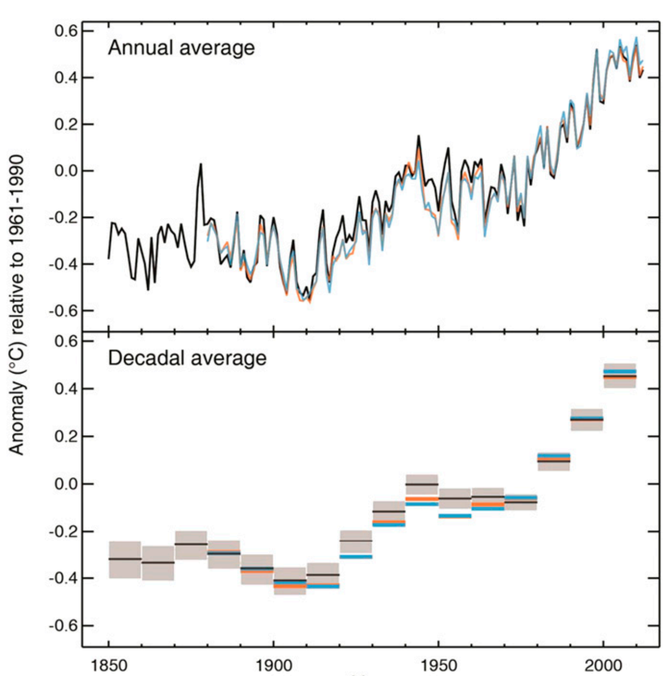

Figure 2. Observed globally averaged combined land and ocean surface temperature anomaly from 1850 to 2012 from three datasets used by the Intergovernmental Panel on Climate Change. *Bottom panel*: decadal mean values including the estimate of uncertainty for one dataset (*black*). Reprinted by permission from Reference 2.

respiratory effects of ozone. A substantial body of evidence has shown that modest short-term increases in ground-level ozone increase risk of acute care visits and hospitalization for asthma (18–21) and COPD (22, 23). Ozone exposure has been associated with deterioration in asthma control in studies in the United States and Europe, resulting in increased medication use and missed school and work days (24–26). There is emerging evidence that obesity may increase susceptibility to respiratory effects of ozone exposure, which is concerning given the increasing prevalence of obesity in many parts of the world (27, 28).

Climate change is expected to contribute to dangerous elevations in particulate matter by fostering conditions favorable to forest fires and, in some arid parts of the world, promoting sand storms. Climate models indicate that with 1°C of warming, wildland fire risk may increase two- to sixfold over the 1950 to 2003 baseline in most of the continental United States west of the Mississippi (29). Although forest fires may ignite in only certain regions, their smoke plumes may extend over great distances. During the Russian heat wave of 2010, for instance, smoke from more than 500 wildfires stretched across more than 1,800 miles—roughly the distance from San Francisco to Chicago (30). Studies in the United States, Europe, and Australia have associated exposure to wildland fire smoke with asthma and COPD exacerbations and hospitalizations (31, 32), congestive heart failure events (33), and overall mortality (34).

Rising temperatures and increasing frequency of droughts are projected to increase desertification in areas with dry climates (35). Desertification and droughts promote dust storms (36), which are public health hazards, particularly for people with pulmonary disease. Desert dust particles contain quartz, which has been found to cause airway inflammation in animal studies (37, 38). Exposure to airborne dust particles transported from regional deserts (in some cases more than 4,000 km away) has been associated with increases in cardiovascular and respiratory mortality (39), cardiopulmonary emergency room visits (40), stroke (41), and admissions for asthma (42) and pneumonia (43) in studies from Spain, Taiwan, and California.

Particulate matter emissions tend to increase during heat waves in regions where electricity is supplied by coal-fired power plants, as a consequence of increased electrical energy use for cooling. There is evidence that high temperatures and particulate matter interact to cause greater mortality than would be expected for the same level of particulate matter at cooler temperatures, even in developed countries where particulate levels are relatively low (44–46). Particulate matter concentrations have declined substantially in the developed world in recent decades as a result of air quality regulations and tightening emissions standards. Even if average particulate matter concentrations continue to decrease in the future, the relative toxicity of particulate matter may rise during higher temperature periods because of this interaction.

Aeroallergen (Pollen) and Climate Change

Higher levels of CO_2 and a warming climate are likely to worsen the global burden of allergic disease, which has been increasing in prevalence in the industrialized world for more than 50 years (47). Worldwide, between 10 and 30% of people suffer periodically from allergic rhinitis, and up to 40% are sensitized (by the presence of IgE antibodies) to environmental proteins (47). Warmer temperatures lengthen the pollen season in temperate climates because plants bloom earlier in the spring. Between 1995 and 2009, the pollen season lengthened 13 to 27 days above 44 degrees north in the United States (48). Higher levels of CO_2 in the atmosphere have been found to increase pollen productivity and the allergic potency (relative allergen protein content) of pollen (49, 50). Extreme weather events involving high winds, heavy precipitation, and thunderstorms, which may increase in incidence over mid-latitudes due to climate change (2), may also contribute to large sudden bursts of allergen release (51, 52).

Higher pollen concentrations have been associated with increased prevalence of allergic sensitization (53) and increased healthcare use for allergic disease, measured in terms of over-the-counter allergy medication use (54), and emergency department (ED) and physician office visits for allergic disease (55, 56). Longer, more potent allergy seasons are likely to be especially detrimental to people with asthma. Experimental studies have found reduced lung function and increased pulmonary inflammation in subjects with asthma exposed to pollen (57, 58). Numerous studies in temperate climates have found increases in asthma and wheeze-related ED visits in association with high pollen concentrations (59–62). Some studies have linked asthma outbreaks to thunderstorms with peaks in allergen release (51, 52, 63). There may be adverse synergistic effects of increases in both air pollution and pollen for people with allergy and/or allergic asthma. Higher levels of particulate matter and ozone lower the bronchoconstrictive threshold to environmental allergens such as pollen and increase the subsequent production of IgE and cytokines, which may promote allergic respiratory disease (16, 64–66).

Increases in allergen exposure may also result in health effects beyond allergic disease. At least one study identified an increase in cardiovascular and respiratory mortality in association with higher pollen levels, a concerning finding that deserves further scientific investigation (67).

Extreme Weather

Climate change is likely to increase the frequency and intensity of a number of "extreme" weather events, including heat waves, hurricanes and tropical storms, and droughts. These changes have already been reported in recent decades (2). The 2013 IPCC report projects with 90 to 100% certainty that in the late 21st century there will an increase in heat waves over most land areas, an increase in the intensity and frequency of heavy precipitation over mid-latitudes and wet tropical areas, and an increase in the frequency and/or magnitude of extremely high sea levels (which may result in floods). The confidence levels for an increase in drought on a regional to global scale (66–100%) and increased tropical cyclone activity (>50–100%) in the late-21st century are lower (2).

Heat waves have well-documented adverse health effects. It is therefore highly concerning that climate models project up to a 50% increase in the frequency in the hottest (ie, the top 5th percentile based on historical records) days by midcentury (68, 69). Extreme heat increases all-cause mortality. The heat wave that hit western Europe in August 2003 resulted in an excess of 15,000 deaths in France alone (70). Studies have found that the elderly and those with chronic respiratory or cardiovascular disease are particularly susceptible to heat-related death (71, 72). Some of these deaths are due to a "harvesting effect," or short-term mortality displacement, wherein people who would have died within 1 to 2 months die a few weeks earlier. However, only 30 to 40% of the estimated deaths from recent heat waves in the United States have been attributed to a harvesting effect, and the remainder constitute actual life-years lost (73). A study of the 2003 heat wave mortality in France found no evidence of harvesting (70). As average temperatures increase, populations will adjust to a higher temperature range, but they will continue to be vulnerable at temperature extremes (74).

Extreme heat events are associated with exacerbations of respiratory and cardiovascular disease. Hot, humid days trigger asthma symptoms and have been shown to increase airway resistance, most likely by stimulating airway C-fiber nerves (75, 76). Studies in the United States have associated acute increases in temperature and humidity with increased ED visits and hospitalizations for asthma in children (77) and adults (78). A case-crossover study in England and Wales examining hourly temperature and incidence of myocardial infarction found that higher ambient temperatures above a threshold of 20°C were associated with an increased risk of myocardial infarction 1 to 6 hours after exposure (80). There is also evidence that extreme heat may trigger exacerbations of congestive heart failure (79).

Warming temperatures cause an intensification of the water cycle that increases the frequency of both droughts and floods and promotes storm formation. Hot temperatures increase the rate of evaporation of moisture in the soil, resulting in droughts. Warmer air also holds more moisture, leading to heavier precipitation and floods. Additionally, high sea surface temperatures increase wind velocities, which promotes storms. Tropical storms will only form in the presence of warm ocean waters of at least 26.5°C to a minimum depth of 50 m (81). The melting of sea ice and a rising sea level also increase the vulnerability of coastal areas to storm surges. The IPCC projects a rise in the sea level of 0.3 to 0.8 m by 2100 compared with 1986 to 2005 levels and a rise in sea surface temperatures by up to 2°C (2).

Although extreme weather events such as droughts, floods, and storms are low-probability events, the human health costs of any one event can be catastrophic. In 2011 in the United States, there were 14 weather-related disasters costing more than $1 billion in damages, which was a national record (82). Hurricane Katrina killed more than 1,300 people and displaced approximately 30,000 persons (83). Though the United States ranks first among the world's nations in terms of the frequency of coastal hurricanes, there are many regions of the world that are much less equipped to manage these natural disasters and suffer greater loss of life (81). In 1999, for example, 30,000 people died as a result of storms followed by floods and landslides in Venezuela (84). South Asia and Latin America have been identified as the most vulnerable areas to floods and tropical cyclones in terms of the human death toll and number of people affected (85). Studies of recent storms have identified drowning and severe injuries as the most common cause of death (85). The decreased sanitation and crowding after storms and floods promote the spread of infectious respiratory disease, and damage to the healthcare infrastructure, including disruption of electricity to clinics, hospitals, and intensive care units, impairs virtually every dimension of public health (81).

Desertification and droughts are a major public health concern for arid climates. Malnutrition is one of the top global health challenges, and climate change further threatens the ability of low-resource areas to maintain adequate food production. The WHO ranked malnutrition as the largest global health problem associated with climate change (86). The risk of drought-related health effects depends on the severity of the drought and resources to mitigate impacts of the drought (87). Sub-Saharan Africa and South Asia, whose food supplies are already limited, are anticipated to have the largest reductions in food supply as a result of climate change (88). A large proportion of global deaths from pneumonia in children under the age of 5 years are attributed to malnutrition (89), and pediatric pneumonia deaths in low resource arid climates may rise as a result of an increasing frequency of droughts.

Climate Change Solutions

The intent of this review is to describe how climate change is anticipated to affect global cardiopulmonary health and not to provide a comprehensive discussion of mitigation solutions. However, it is important to note that there is hope. The worst climate change scenarios may be avoidable with aggressive policy measures. The international community has agreed to a goal of limiting global warming to 2°C above preindustrial levels, based on evidence that further warming would be extremely difficult for contemporary societies to tolerate and concern that a "tipping point" could be reached after which there could be abrupt or even irreversible climate shifts (90, 91). Reaching this target will require dramatic (70%) reductions in cumulative greenhouse gas emissions between 2010 and 2100 compared with a baseline scenario, according to the climate model scenario selected by the IPCC that evaluated this target (2, 92). Is this achievable? A motivational success story is the Clean Air Act of 1970. The United States reduced most primary pollutants by more than two-thirds despite a growing population and economy. The public health benefits of the Clean Air Act have been substantial. A recent study attributed 15% of the increase in U.S. life expectancy in the 1980s and 1990s to improvements in particulate air pollution (93). The EPA estimates a return of $30 for every dollar spent on reducing air pollution through the Clean Air Act (94). Climate change policy can be such a success story, too.

Perhaps the largest problem with climate as a policy issue compared with air pollution is that many of the most devastating consequences of climate change, such as rising sea levels and desertification, occur incrementally over the course of decades, and policymakers tend to discount events that occur further into the future, preferring to react to what affects people "here and now" (95). Though the consequences of CO_2 emissions are not always immediate, the air pollutants including particulate matter and black carbon that are emitted along with CO_2 when fossil fuels and biomass are burned have immediate adverse cardiopulmonary health effects. A recent analysis compared the costs of reducing global greenhouse gas emissions according to one of the intermediate-level mitigation scenarios selected by the IPCC to the cardiopulmonary mortality benefits of reduced air pollution emissions that will accompany the reduction in CO_2 emissions

(96). The study found that the health benefits of cleaner air will exceed the cost of the proposed mitigation measures. These health benefits were projected to be gained immediately and locally by the regions that reduce their CO_2 emissions, unlike the health benefits of the reduced CO_2 itself, which are more delayed and global. Other cost–benefit analyses assessing the outdoor air pollution cobenefits of greenhouse gas emissions reductions have found similar results (97). There are also substantial and immediate cardiopulmonary health benefits of reducing indoor black carbon emissions through the introduction of cook stoves in the developing world (98). These cost–benefit analyses do not even consider the many other long-term global health benefits of mitigating climate change itself, including benefits of avoiding high temperatures, storms, floods, and droughts as discussed above. Given the enormous and immediate health benefits of the cleaner air that results from reduced fossil fuel and biomass combustion, a case can be made for *harmonizing* clean air and climate change policy, so that they each consider the other when one is being set (95). Public health benefits will be maximized by selecting climate mitigation measures that also minimize toxic air pollution emissions (e.g., focusing on coal and diesel emissions) and selecting air pollution measures that minimize CO_2 emissions (e.g., reducing or eliminating coal emissions rather than applying scrubbers to remove particulate matter) (95).

In 2010, parties to the United Nations Framework Convention on Climate Change, which included the Obama Administration, agreed to a goal of limiting growth in CO_2 emissions to a corresponding temperature increase limit of 2°C above preindustrial levels. It was suggested at the World Economic Forum that achieving this goal would require a global investment in clean energy of about $500 billion per year by 2020. In 2009, only $145 billion in public and private investment was spent on clean energy, a far cry from what is needed. The 2013 United Nations report on the 2°C target concluded that achieving the emissions goal is still possible with existing policy options—the major barrier is insufficient political will (99). Reducing CO_2 emissions will require investment in multiple strategies, including the use of alternative energy sources, improved power plant efficiency, a reduction in coal-based power production in favor of natural gas and other alternatives, transportation strategies to reduce single-occupancy vehicle driving, advanced clean vehicles with improved fuel efficiency (such as plug-in–hybrid, battery electric, and fuel cell vehicles), modified construction to reduce the energy use of buildings, development of carbon sinks (such as forests and carbon capture and storage technology), and foreign aid to help lower-income countries achieve these goals. Efforts to reduce emissions of short-lived climate-forcing agents such as methane and black carbon will be particularly important toward reducing the rapid trajectory of global warming in the near term (7). The technology for most of these climate mitigation solutions already exists on an industrial scale (100). The global policy solution should also give low-resource countries a voice in initiatives to reduce greenhouse gas emissions, as they are disproportionately affected by the health consequences of climate change yet contribute relatively little to CO_2 emissions.

Conclusions

Climate change is a growing public health problem of enormous proportions. The American Thoracic Society has identified climate change as an urgent issue facing our clinical profession, our research community, and our patients around the world, because people with cardiopulmonary disease are among the most susceptible to death and disease as a result of climate change. We need a paradigm shift to foster the magnitude of political will and investment required to solve this problem. Yet this is a problem that can be mitigated with existing tools. The value of the immediate cardiopulmonary health benefits of reducing emissions of CO_2 and its associated air pollutants will outweigh the costs of mitigation. The long-term health benefits of avoiding mortality and morbidity due to temperature extremes, air pollution, pollen, floods, droughts, storms, desertification, and malnutrition justify climate change mitigation not only from an economic standpoint but also from a moral one. ■

Author disclosures are available with the text of this article at www.atsjournals.org.

Acknowledgment: The authors thank Gary Ewart of the American Thoracic Society and members of the Environmental Health Policy Committee and International Health Committee for their contributions to this manuscript.

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