Environment, Global Climate Change, and Cardiopulmonary Health

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Global mean temperatures have risen markedly in the last century, in large measure as a result of human activities that emit greenhouse gases (GHGs) (1) (Figure 1). This perturbation in the global climate contributes negatively to both ecosystem and human health, particularly for the most vulnerable populations. Consequently, there is increasing interest in the health impacts of global climate change in the general public, and a growing concern among health professionals. The Lancet Commission in 2009 called climate change the biggest public health threat of the century (2), but also more recently, the greatest public health opportunity of our time, if climate mitigation policies are chosen so as to maximize their human health benefits (3).

Health impacts from climate change are already being observed (Table 1), and are expected to increase in the coming decades. A 2015 survey by the American Thoracic Society documented that a strong majority of its pulmonary health practitioner members have concluded that climate change is occurring, and is having an effect on patient care, particularly due to heat-related impacts at present (48%), or within the next 10–20 years (67%) (4). In addition, 77% of respondents noted increases in the

severity of chronic illness resulting from air pollution as a consequence of climate change, and several observed increased regional wildfire activity and urban high-ozone (O₃) events affecting their patients with asthma or chronic obstructive pulmonary disease.

The present Perspective is a synthesis of the symposium, “Environment, global climate change, and cardiopulmonary health,” at the 2015 American Thoracic Society Annual Meeting, highlighting the pulmonary and cardiovascular impacts of climate change and the potential human health co-benefits from climate change mitigation and adaptation. The symposium opened with a powerful *patient perspective*. An example of climate change impacts on pulmonary health was described by a mother (C.M.) from Reno, Nevada, whose children suffer from severe asthma. She described how her family could limit asthma triggers, but could not control the quality of the air they breathe. Several environmental factors influenced her children’s asthma severity, including rising temperatures followed by prolonged allergy seasons, drought, and increased risk of wildfire pollution. She constantly worried about the global climate change effects on her own children’s health and her community, and

asked that research continue to be done to better understand the risks of climate change to human health.

It is expected that reductions in both carbon emissions and other associated air pollutants, such as O₃ and fine particulate matter less than 2.5 µm (PM_{2.5}), will result from climate change mitigation efforts (5). It is estimated that climate mitigation measures will result in the greatest reductions in PM mortality in those places that implement the most CO₂ reductions, and the financial valuation of the mortality benefits will outweigh the costs of the climate mitigation measures (6). A recent successful example discussed here is California, where the state has adopted a multipronged policy approach to climate change mitigation, and is reported to have had a positive impact on reductions of GHG emissions, along with other public health parameters (7). We also provide suggestions to initiate improved education for pulmonary physicians, clinician scientists, and public health officials to enable them with appropriate resources to develop an understanding of climate change impacts on human health to increase future advocacy (Table 2).

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Figure 1. Observed global mean combined land and ocean surface temperature anomalies, from 1850 to 2012 from three data sets. *Top panel:* annual mean values. *Bottom panel:* decadal mean values including the estimate of uncertainty for one dataset. Anomalies are relative to the mean of 1961–1990 (reprinted from Reference 1, their Figure SPM.1).

Health Implications of Physical Changes in Earth Climate Systems

Over the last 150 years, global mean temperatures have risen by nearly 1°C (1), resulting in some very visible impacts on the Earth's systems, including increases in sea level, a dramatic shrinking of Arctic sea ice, and changes in ecosystems around the globe. It is widely recognized in the scientific community that human activities and the associated emissions of GHGs are the primary cause (8). Greenhouse warming has documented physical and chemical properties resulting in heat being trapped in the atmosphere (9).

From disruption of our habitat, to impacts on human health worldwide, the future effects of climate change on our daily lives are likely to be far reaching and profound, and they are closely tied to the

choices we as a society make today. The Intergovernmental Panel on Climate Change (1) reports that an aggressive approach to reducing CO₂ emissions through alternative energy sources could stabilize temperatures below a 2°C increase above preindustrial averages—generally assumed to be the level below which the worst effects of climate change may be avoided—whereas a business-as-usual approach, that does not involve substantial reductions in our projected GHG emissions in the coming decades, will likely lead to temperature increases on the order of 4°C (1).

In addition to the rising seas and shrinking ice cover, the physical changes due to increased temperatures are expected to include changes in atmospheric and ocean circulation patterns that drive regional climate, increased likelihood of drought in some areas and flooding in

others, increased ecosystem stress and disturbance (e.g., wildfires), and increasing ocean acidification (1). Through these physical effects, climate change significantly impacts human health (Table 1).

The climate impacts we face are unprecedented in modern history. Our success in meeting those challenges will depend on the magnitude and rates of changes, and on the choices we make. Those choices will directly influence the health challenges our children and grandchildren will face.

Heat Stress, Extreme Weather Conditions, and Sand Dust Storms

Heat stress induces the mortality and morbidity of cardiopulmonary diseases (1, 10). It was recently reported that heat waves significantly increased the daily mortality in European cities. The highest effect was observed for pulmonary diseases in elderly women, suggesting that females and the elderly are more susceptible subpopulations (11). More recent studies have associated rising temperatures with increased emergency department visits due to pulmonary diseases (12). An association has also been found between increased temperatures and emergency room visits as well as hospitalization due to cardiopulmonary diseases (12–14), including pneumonia, asthma, chronic obstructive pulmonary disease, and cardiovascular diseases (14). Although the mechanisms underlying excessive temperature-induced cardiopulmonary pathologies are not clear, a recent study reported that O₃ may impair fibrinolytic activity under higher temperatures (15), thus providing one mechanism by which temperature influences response severity.

Extreme weather conditions can also create pulmonary hazards from a variety of cofactors. An increased number of wildfires from drought and excessive temperatures can have devastating effects on the environment, and human health and welfare. Rising temperatures lead to increased formation of secondary PM_{2.5} pollution, adversely affecting the cardiopulmonary system, and are associated with increased wheezing in both children with and those without asthma (16). The effects of hurricanes, tornados,

Table 1. Summary of Potential Cardiopulmonary Health Effects Associated with Climate Change Parameters

Climate Change–related Parameters	Adverse Health Effects	References
Heat stress	Increased mortality, emergency room visits, and hospitalization due to cardiopulmonary diseases, including asthma.	1, 10–14
Extreme weather conditions (i.e., creating hazards, including wildfires, hurricanes, and floods)	Asthma exacerbation, increased risk for respiratory infections, gastrointestinal illness, food insecurity, and mold exposures.	1, 16, 17
Sand dust storms	Increased cardiopulmonary mortality and emergency room visits, hospitalization due to asthma and COPD; increased risk for respiratory infections and myocardial infarction.	20–24
Air pollution	Increased cardiopulmonary mortality, increased emergency room visits, hospitalization due to asthma, COPD, cardiac diseases; increased risk for respiratory diseases.	25, 31, 32, 34, 39
Aeroallergen production	Increased prevalence and exacerbation of allergic airway diseases, such as asthma, rhinitis; increased cardiopulmonary mortality.	33–35

Definition of abbreviation: COPD = chronic obstructive pulmonary disease.

cyclones, and floods can also be exacerbated, as extreme weather events increase and sea levels rise, and may cause degraded and damp housing, with increased levels of microbial and fungal growth, in addition to their immediate health effects (17).

Land degradation is another serious consequence of global climate change; in the last 4 decades, an estimated 15–63% of all

the global land has been degraded, including increased desertification (18). Data suggest that there is a rising rate of sand dust storms from deserts worldwide (19). In addition, land degradation contributes a significant amount of stress on food production that could potentially lead to future famine in affected countries. Sand dust storms have been associated with increased risk of cardiopulmonary

Table 2. Opportunities to Improve Education and Advocacy for Climate Change Impacts on Cardiopulmonary Health

- Get involved in groups like Physicians for Social Responsibility (and related groups, some of which are more climate change focused; i.e., the American Lung Association or the Union of Concerned Scientists).
- Press medical and K–12 schools for more curriculum on climate change.
- Volunteer to give seminars about climate change, and infuse other seminars with some climate change–related information when appropriate.
- Take time to speak with relevant government officials at both the state and federal levels (i.e., contact your congressmen).
- Improve current clinical intake forms to track climate-related health outcomes. The CDC Environmental Public Health Tracking Network is already working on this sort of system.
- Become more informed on climate change at <http://usclimateandhealthalliance.org/> and by reading reports such as “An Official American Thoracic Society Workshop report: climate change and human health” (10).

Definition of abbreviation: CDC = Centers for Disease Control and Prevention.

morbidity (20–23), as well as mortality (24), although the evidence is somewhat inconsistent for mortality due to ischemic heart disease (25). Laboratory models point to an inflammatory mechanism with desert dust particles increasing cellular permeability, inflammatory markers, and cellular toxicity in both *in vivo* (26) and *in vitro* models (27).

Climate Change, Air Pollution, Aeroallergens, and Pulmonary Health

As described in the previous sections, predictions indicate that climate change will worsen O₃ and PM_{2.5} pollution across the United States and increase associated health effects (28). Increased temperatures lead to drier conditions, more dust generation, higher risk for wildfires, and increased demand for air conditioning that is largely powered by fossil fuel combustion, all of which contribute to higher PM concentrations (29). An increase of up to 2 µg/m³ in average daily maximum PM_{2.5} due to climate alone has been predicted by 2040, relative to 2006, for large areas of North America (30).

O₃ production in the atmosphere increases at higher temperatures. A dramatic example of this connection between ambient heat and surface O₃ occurred during the 2003 heatwave in Europe (31). An increase of up to 7 ppb in average daily maximum O₃, due to climate change alone, has been predicted in the United States and Canada by 2040, relative to 2006 (30). It is estimated that climate change was responsible for a 4% increase in O₃–related deaths from 1960 to 2009 (32).

Increased temperatures have also been associated with a longer growing season, faster plant growth during the growing season, and more pollen per plant, all of which is anticipated to increase allergic disease, including asthma (33). Increased ambient allergens were reported to increase cardiopulmonary mortality up to 10% (34). Fungal and other biological growth is also impacted by climate change.

Combinations of air pollutants, aeroallergens, and increased temperatures appear to have additive, or greater, effects. For example, coexposure to a range of common aeroallergens significantly increased asthma hospitalization due to air pollution (35). Furthermore, O₃ has been

shown to augment airway responsiveness to allergen (36). PM plus allergen has also been linked to increased innate and adaptive immune responses implicated in the pathophysiology of airway disease (37, 38). Lastly, effects of these combined exposures need to be considered based on evidence (39) that chronic O₃ exposure at lower levels is associated with cardiopulmonary mortality; combined with increasing levels of additional pollutants (e.g., PM_{2.5}) and allergens, these chronic effects could be further exacerbated.

Interactions between Chemical and Climate Stressors

Environmental factors, such as temperature, precipitation, salinity, and pH, are all influenced by climate change, and can significantly alter the kinetics of absorption, distribution, metabolism, and excretion of chemicals in environmental and biological systems. Hooper and colleagues (40) have shown interactions between climate change, chemicals, and some of the biological molecules critical for homeostasis in thermoregulation, nutrition, and the function of the immune, endocrine, and neurological systems.

Adverse outcome pathways incorporate mechanisms and action/toxicity pathways to predict outcomes and effects in highly dimensional systems, such as climate and human health. Ankley and colleagues (41) described a conceptual framework based on these paradigms, which depict linkages between molecular initiating events and the subsequent cascade of responses that occur across biological levels of organization and impact individuals, and can thus be used for assessing risk. In 2007, the National Research Council proposed toxicity testing regimes that use computational biology and *in vitro* tests based on human biology (42). However, mechanistic data in risk assessment continues to be criticized for the multiple layers of uncertainty. Applied to global climate change and the chemical interaction scenarios with humans, adverse outcome pathway methods could reduce these uncertainties. Future research is needed into temperature and precipitation effects on cardiopulmonary health outcomes that would examine mechanisms and physiological processes, including potential interactions with exposures to toxic chemicals.

Clean Air Health Co-benefits of Climate Mitigation Action

There is a shift in the conversation in public health about climate change, from fossil energy and our dependence upon oil and gas, to our health and the human health co-benefits of GHG emission reductions. The shift is in part due to the politically charged nature of the “dirty energy” discussion, along with more universal concerns about health (43). Although most analyses of climate change effects consider the environmental and human health consequences of the business-as-usual scenario, the human health co-benefits approach also considers the additional health benefits on top of the direct weather-related benefits, if we adopt health-promoting climate change mitigation measures. For example, reducing carbon pollution emissions will usually also reduce other health-related air pollutants, such as PM_{2.5} and O₃, that are generated as a consequence of fossil fuel combustion (5), providing clean air health benefits as well.

O₃, PM, and other air pollutants associated with oil-, coal-, and natural gas-fired power plants have well documented adverse cardiopulmonary health effects. The health impact is particularly high for PM_{2.5} from coal-burning facilities, which has been associated with an ischemic heart disease mortality risk that is roughly five times that of the average for PM_{2.5} particles from other sources (25). GHG mitigation measures can therefore also provide both local and immediate clean air public health benefits to nations, states, and localities that enact fossil fuel emission reduction measures.

Recent peer-reviewed analyses show the potential health co-benefits of the implementation of climate mitigation policies in the United States (44), including estimates of over 3,000 deaths, more than 850 hospital admissions, and some 200 heart attacks that could be avoided each year in the United States. Indeed, it has been estimated that clean energy policies in the United States could prevent 175,000 premature deaths by 2030, and 22,000 fewer annually thereafter, and clean transportation could prevent 120,000 U.S. premature deaths by 2030, followed by about 14,000 annually thereafter (45). Implementation of the U.S. Environmental Protection Agency’s Clean Power Plan has

been estimated to provide every American family with up to \$7 in health benefits for every \$1 dollar invested in reducing GHGs (46). Implementation of this effort by the U.S. government, which is the nation’s principal commitment to the 2015 climate change accords in Paris, will therefore also provide significant clean air health benefits to those localities and states participating in the Clean Power Plan. These potential impacts could be seen as futuristic in nature if it were not for the recent efforts of the State of California, to be discussed next.

Action on Climate Change Mitigation: The California Experience

Considering the significant impacts of climate change, the California state legislature passed a landmark bill in 2006 (AB32), the “Global Warming Solutions Act” (47). This bill mandated a reduction of GHG emissions down to 1990 levels by 2020 (a 30% reduction), and a further 80% reduction below 1990 levels by 2050. The California Air Resources Board (CARB) was given the responsibility of overseeing the implementation of policies designed to meet these ambitious goals. One of the first actions taken by CARB was to require an inventory of GHG emissions across all sectors of the California economy. This inventory showed that transportation accounted for 37%, electric power generation 34%, and industry 20% of GHG emissions in 2008. Climate change mitigation policies adopted by California include the Zero Emission Vehicle program, initially designed to reduce emissions of air pollutants, but now with the additional goal of reducing GHG tailpipe emissions (48). A total of 11 other U.S. states have adopted the California Zero Emission Vehicle mandate. CARB also promulgated a legislatively mandated standard to reduce GHG tailpipe emissions from gasoline cars that eventually became the basis of the current U.S. fuel efficiency standard.

California Senate Bill 375 mandates that “Sustainable Communities Strategies” be developed by metropolitan planning organizations to achieve target reductions in GHG emissions set by CARB (49). The primary approach of the metropolitan planning organizations has been to reduce vehicle miles traveled by encouraging smart growth through urban infill, high-density

housing along transportation corridors, investment in public transportation, and efforts to promote active commuting and walkability of neighborhoods.

The Sustainable Freight Transport Initiative seeks to achieve both GHG and health benefits through electrification of freight handling vehicles (e.g., cranes and forklifts), and by reductions in diesel emissions through state subsidies for new, cleaner diesel trucks and locomotives (50).

A key component of California's AB32 implementation policy is the Renewables Portfolio Standard that requires that 33% of the state's power be renewable energy by 2020 (51). Because the state is well on its way to achieving this goal, a new bill was passed increasing the goal to 50% by 2030.

The most controversial of California's climate change mitigation policies is the Cap-and-Trade Program, which is expected to provide only about 16% of the state's GHG emission reductions in 2020 (52). The Cap-and-Trade Program is a market-based mechanism that allows capped facilities to trade state-issued GHG emissions allowances, providing flexibility and reducing costs of compliance with mandated emission reductions. The "cap" limits total GHG emissions from all regulated sources, and declines over time to progressively reduce emissions. Critics of Cap-and-Trade say that it encourages heavily polluting facilities to buy allowances from clean facilities, rather than invest in emission reduction technologies, thereby continuing to impact the health of low-socioeconomic communities, where such dirty facilities are often located. For this reason, environmental justice advocates tend to support a carbon tax mechanism to put a price on carbon. Unlike a cap-and-trade program that places a cap on carbon emissions and lets the market determine

price, a carbon tax leads to variable reductions in carbon emissions, because it fixes the price of carbon (53). To address any unintended negative environmental justice consequences of the program, legislation requires that 25% of Cap-and-Trade revenue be spent on projects that benefit disadvantaged communities, at least 10% of which must be spent in these communities (54). An innovative mapping tool, *Cal Enviroscreen*, was developed to identify disadvantaged communities (55).

Conclusions

In this article, we describe some of the major cardiopulmonary impacts of climate change, and suggest some opportunities for, and benefits of, intervention to mitigate these impacts. The changes in the Earth's systems are complex, both in mechanisms and impacts. Warmer temperatures, altered precipitation patterns, increases in PM_{2.5}, O₃, and aeroallergens, and changes in multiple ecosystems that impact humans are expected. Climate change hazards, such as heat stress, extreme weather conditions, wildfires, sand dust storms, and damp buildings from excessive precipitation, can contribute to adverse cardiopulmonary health effects. In combination, the effects may be synergistic and severe, especially within vulnerable populations (e.g., children, older adults, those with pre-existing disease, and those populations more genetically susceptible). The impacts described here are significant, but likely represent only a small part of the global impact of climate change. Climate-driven food and water scarcity in a time of increasing global insecurity are likely to also have significant impacts on public health, social unrest, and economic instability in the future (56, 57). Given the complexity

and potential for severe effects, more research in science and policy, knowledge translation, and tested implementation strategies are needed.

The public does not readily "connect the dots" on the relationships between climate change and health, and most physicians do not recognize these health impacts in the scope of their practice. To make the connections will require more education for healthcare providers, including local narratives that speak to current conditions in the community, such as the forest fire and asthma example noted earlier (Table 2). It is imperative that health professionals seize the public health opportunities offered in dealing with this crisis. There are multiple potential human health co-benefits to mitigation actions. European countries have made significant progress in developing both mitigation and adaptation policies to address climate change. California's multipronged policy approach to climate change mitigation sets a North American standard. An important element is to integrate public health considerations, such as clean air health benefits, with GHG emissions reductions. These jurisdictions show what can be achieved in a complex political environment to seize the public health opportunity of climate change. Surveys have shown that patients are already experiencing the impacts of climate change today, and we can expect these to only increase with time. We must bring more of our science and political will to bear, and without delay, to avert as many of the potential negative climate change impacts as possible, and to maximize the potential public health benefits of our climate change mitigation actions. ■

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

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