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Editorial

Climate change, indoor environments, and health

For many of us working in the indoor air sciences, it is clear that climate change has implications to buildings beyond modifying cooling and heating demands. Thus, it is surprising that in the world of climate science and policy, so little is said about how extreme weather events and long-term climate conditions might affect health through modification of indoor environments. Even in the most recent *Intergovernmental Panel on Climate Change* report (IPCC, 2007a), there is only brief reference to indoor health risk in terms of occupational heat stress and possible co-benefits of reducing biomass fuel use. The health concerns that climate scientists have focused on include ecosystem disruption and zoopathogens, toxic algal blooms, vector-borne diseases, heat stress, crop losses, and diminished nutritional value of food. Meanwhile, the indoor environment, until recently, has not been considered.

The US Environmental Protection Agency (EPA) asked the Institute of Medicine (IOM) of the National Academy of Sciences to convene an expert committee to summarize the current state of scientific understanding of the effects of climate change on indoor air and public health and to identify priorities for action. The committee, which I chaired, included members with expertise in climate science, aerosol physics, architecture, mycology, medicine, infectious diseases, exposure assessment, and epidemiology. Table 1 lists the committee members. The committee was greatly aided by EPA-commissioned white papers (http://www.epa.gov/iaq/pubs/index.html) and by workshops held in Washington, DC, and Berkeley, CA, where we heard from indoor air and building scientists, physiologists, and insurance risk assessors.

The specific topic of climate change and indoor environments is so new that our insights have to be gleaned from what is already known about building conditions and occupant behaviors and from inferred responses to environmental conditions that might result from the perturbed climate that nature has in store for us. However, this limitation does not mean that little can be said about the implications of climate stresses on infrastructure. Relying substantially on synthesis from a large body of information on building conditions that lead to discomfort, degraded health, and lost productivity, the committee recognized that indoor environmental conditions already pose considerable health risk and that a warmer atmosphere with increased outdoor air pollution, forest fires, pollen and dust, heat waves, excessive rainfall, droughts, and the longer-term aberrations of regional climates would impact building performance and occupant health.

Several scenarios can be envisioned in which climate change and weather extremes might impact buildings. Pollution and pollen, which are expected to increase, can penetrate indoors. Once indoors, reactive air pollutants like ozone can undergo further reactions. Building elements and furnishings can become wet and lead to mold growth or infestations. Building envelopes can become hotter during heat waves, adding to thermal stress. Changes in the atmospheric conditions over time will challenge building HVAC systems currently designed to manage contaminants and meet thermal comfort expectations that are based on the past 30 years of weather records. Figure 1 displays some of the possible pathways by which weather changes could influence the health of building occupants.

We cannot blame all potentially adverse outcomes on weather alone. Actions are being taken to reduce greenhouse gas emissions through energy reduction by promoting high-efficiency building designs, renovations, and operation. Buildings are being audited (via

Table 1 IOM Committee on climate change, indoor environments, and health

John D Spengler	Harvard University (chair)	Exposure assessment, IAQ
John L Adgate	University of Colorado	Exposure assessment, IAQ, risk assessment
Antonio J Busalacchi	University of Maryland	Climate science, oceanography, climate change, and national security
Ginger L Chew	Centers for Disease Control and Prevention	Aeroallergens, fungi, childhood asthma
Andrew Haines	London School of Hygiene and Tropical Medicine	Environmental medicine, climate change, and public health
Steven M Holland	National Institutes of Health	Immunopathogenesis, mycobacterial infection, internal medicine, and infectious diseases
Vivian E Loftness	Carnegie Mellon University	Architecture, building performance, energy
Linda A. McCauley	Emory University	Occupational and environmental health, risk to vulnerable populations
William W Nazaroff	University of California, Berkeley	Environmental engineering, aerosol physics, IAQ
Eileen Storey	NIOSH/CDC	Indoor occupational and environmental health, internal medicine

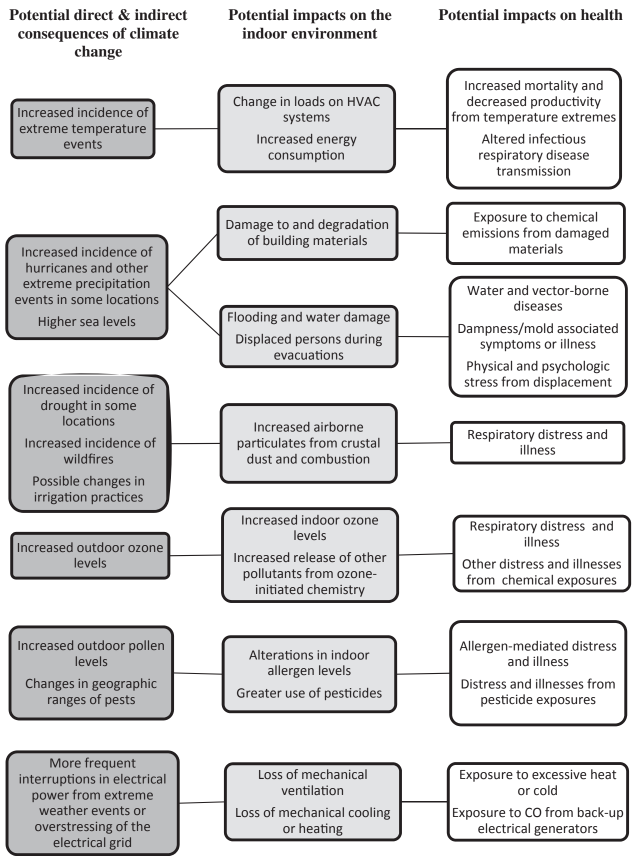

Fig. 1 Scenarios where climate changes impact buildings and could possibly affect occupant health, comfort, and productivity (Reproduced with permission from *Climate Change, the Indoor Environmental and Health*, IOM, 2011 by the National Academy of Sciences, Courtesy of the National Academies Press, Washington, D.C. Original figure adapted from Su, undated.)

commissioning), and existing homes are undergoing weatherization to save energy and reduce carbon emissions. Besides mitigation efforts, more individuals, businesses, and government entities, anticipating greater variability and more frequent extreme weather events, are in the early stages of adaptation. It is likely that some of these actions will have unintended negative consequences on building performance and indoor air quality. On the positive side, efforts funded through clean development mechanisms to reduce carbon emissions will offer more efficient cook stoves, improving indoor air quality. Biomass fuels in households are estimated to be responsible annually for approximately 0.7 to 2.1 million premature deaths in low-income countries, from a combination of lower-respiratory infections, chronic obstructive pulmonary disease, and lung cancer (Smith et al., 2004). Energy and carbon mitigation in this context can have substantial health co-benefits, particularly for young children and women (Smith et al., 2000, 2005).

Energy conservation activities that reduce ventilation rates in homes and other buildings have the potential to increase exposures to indoor pollutants and to increase the rates of infectious disease transmission. Recently, an expert panel convened by ASHRAE critically reviewed the literature on ventilation and indoor health effects and concluded that there is an association between low ventilation rates and an increased risk of allergies, SBS symptoms, and respiratory infections (Sundell et al., 2011). In a large Swedish epidemiologic study, Bornehag et al. (2005) reported that low ventilation rates in dwellings increased the risk of allergic symptoms among children. At many Chinese universities, students share a standard-size, 20 square meters, dormitory room. Occupancy rates depend on degree status: six to eight per room for undergraduate students, four per room for master students, and three per room for doctoral students. Sun et al. (2011) reported that more crowded dorm rooms had lower outdoor airflow rates and more respiratory infections. In some respects, it seems that twenty-first-century research is simply confirming what Florence Nightingale and Max von Pettenkofer taught us 150 years ago.

Weather fluctuations and climate variability may influence the incidence of many diseases in other ways as well. The geographic ranges of vector-borne diseases are being altered, and some may include indoor exposure pathways. Following flooding or excessive rainfall, rodents might migrate indoors, increasing the risk of hantavirus pulmonary syndrome (Bayard et al., 2000).

Past research on the influenza virus has focused on airborne viruses and generally suggests that survival and/or transmission is facilitated by low relative humidity (Weber and Stilianakis, 2008). The influenza virus has been found to persist in the environment for hours to days, allowing for secondary transmission of influenza via inanimate objects known as fomites. How long viruses survive on fomites is important to transmission potential when an uninfected person contacts that surface. The survival of viruses on surfaces is influenced by temperature and humidity. In a recent publication, Shaman and Kohn (2009) concluded that absolute humidity is the controlling factor in both the inactivation of influenza virus and the transmission of influenza. While some regions will get warmer and more humid, thus reducing the chance of some viruses surviving on surfaces, other regions will become drier. Hotter and drier climates imply that some viruses on surfaces in air-conditioned buildings, with lowered absolute humidity, might survive longer on fomites.

Extreme heat and cold have well-documented adverse health effects. High humidity exacerbates the effect of heat. Populations with poor housing in high-density urban areas will be at increased risk owing to urban heat island effects, which increase the intensity of heat waves (Wilby, 2003).

Rural populations and people in smaller cities are also at risk. Lincoln et al. (2011a) computed the incident risk ratio (IRR) for hospital admissions for all causes and for nine specific health outcomes across Maine for hot days (defined to be the 5% of days that deviated most from the 30-year climate normal for that day for May–September in years 2000 through 2008). The IRR was significant at 11 for heat-related illness hospitalizations, and it was significant for several other morbidities including cardiovascular disease, myocardial infarction, diabetes, nephritis, and electrolyte imbalance (Lincoln et al., 2011b). For a 'cool' state such as Maine, with limited use of residential air conditioning and relatively mild summers, unusually hot days were still associated with elevated morbidity. And if heat wave mortality and morbidity were not bad enough, Filleul et al. (2006), analyzing the 2003 western European heat wave, showed that adding the effect of ozone exposure during the prolonged heat wave elevated the mortality risk by 175%.

Heat waves strain the electrical grid. In the United States, an aging electrical infrastructure, as reported by Patterson (2010), has experienced a 124% increase in non-disaster US power outage rates since early 1990s. US electricity reliability is low compared to some nations, leaving at least 500,000 without power on a daily basis. Loss of power during heat waves or other weather disasters leaves people without air conditioning and without refrigeration. The elderly and infirm are less capable of coping during these situations, particularly those depending on refrigerated medicines. Flood waters were directly responsible for two-thirds of the 771 Katrina-related deaths. But one-third of the fatalities were associated with other flood-related circumstances, including lack of access to potable water or medical services and exposure to extreme heat as a result of power outages (Jonkman et al., 2009).

It is not surprising that more people are turning to electrical generators powered by gasoline. These engines typically have no exhaust controls and can produce high carbon monoxide emissions. The US Centers for Disease Control and Prevention (CDC) has observed an increase in carbon monoxide poisonings coincident with recent hurricanes that led to increased use of these polluting generators (CDC, 2006). CDC commissioned the US National Institute of Standards and Technology (NIST) to evaluate the impact of portable electrical generators when operated close to homes. Clearly, generator use indoors is not advised, although it is still done. Blair and his team of NIST investigators evaluated the impact inside homes when generators are operated outdoors but too close to structures so that exhaust is entrained indoors (NIST, 2008).

A large fraction of the world's population resides within cities along the coastline or on major rivers. Increased urbanization and demographic growth over the coming decades will increase this population. Climate change could affect coastal areas through rising sea level, rising sea-surface temperatures, an intensification of tropical cyclones, and changes in wave and storm surge characteristics. The *IPCC Fourth Assessment Report: Climate Change 2007* (IPCC, 2007b) states that these changes could affect human health through coastal flooding and damaged coastal infrastructure. The IPCC report from Working Group 1 contributors (IPCC, 2007c) concludes, '... with high confidence, that heatwaves will increase, cold days will decrease over mid- to low-latitudes, and the proportion of heavy precipitation events will increase, with differences in the spatial distribution of the changes (although there will be a few areas with projected decreases in absolute numbers of heavy precipitation events) (Meehl et al., 2007)' (IPCC, 2007b).

Even in areas away from coastlines and major rivers, flooding and intense downpours can damage building materials and furnishings, creating conditions that promote growth of fungi and bacteria. The literature associating morbidity with indoor conditions of dampness and mold has been critically evaluated by multidisciplinary expert committees in the United States and Europe (Bornehag et al., 2001, 2004; IOM, 2004; WHO, 2009; Fisk et al., 2007). In the Fisk et al.'s (2007) analysis, building dampness and mold were determined to be associated with 30% to 50% increases in the risks to occupants of a variety of respiratory and asthma-related health outcomes. Mudarri and Fisk (2007) attributed 21% (with uncertainty bounds of 12–29%) of current US asthma cases to dampness and mold exposure. The associated annual costs of these approximately 4.6 million dampness-related cases of current asthma were estimated to be \$3.5 billion (range: \$2.1–\$4.8 billion) (Mudarri and Fisk, 2007).

These findings are consistent with the earlier European reviews (NORDAMP and EUROEXPO) reported by Bornehag et al. (2001, 2004). In fact, the IOM (2004) and WHO (2009) reports confirm that dampness and moisture-related health effects are widely reported across many countries representing diverse housing stock and climates.

For buildings that rely on mechanical cooling, higher ambient humidity and warmer temperatures will increase the performance requirements to cope with future climate conditions. Cool indoor surfaces when humidity levels are too high lead to undesirable condensation. Shedding sensible heat loads in buildings with oversized HVAC equipment leads to frequent cycling in which cooling coils do not dry out during off periods, leading to higher indoor humidity and promoting fouling of cooling coils. Thermal bridges or thermal discontinuities in the building envelope, especially those with vapor barriers, can cause not just moldy conditions but also could lead to material degradation, releasing chemical contaminants.

It is not clear whether climate change will alter the prevalence of mite and cockroach allergy. Warmer and moister winters will favor mite survival, but more reliance on air conditioning will lower indoor humidity and hence mite populations. Cockroaches, being ubiquitous, are likely to simply adapt to climate change and will be with us for some time to come. Shifts in the geographic location of prevalent pests might be accompanied by more widespread use of pesticides with concomitant increases in human exposures and associated health risks.

Beyond how changing weather patterns might impact buildings, programs and actions to save energy (reduce greenhouse gas emissions) may be modifying indoor environments on a large scale. It has long been recognized that buildings and homes leak energy and hence are prime targets for conservation efforts. About a third of energy used for residential heating and cooling is lost to unintentional air leakage. Air sealing, increased insulation, higher-efficiency combustion and air-handling equipment, and improved operations for buildings have demonstrated impressive returns for energy savings (Mills, 2009). Since 1994, in Germany, the innovative 'Fifty/Fifty' energy education program has been motivating students, teachers, and janitors to reduce school energy consumption with great success. The program is now being promoted throughout Europe offering the incentive of returning 50% of the reduced energy cost to the participating school (http://www.euronet50-50.eu/). There are many examples of national and utility energy conservation programs throughout Europe and Asia with similar goals of reducing energy consumption in buildings and promoting energy-efficient appliances and equipment.

For more than three decades, the US Department of Energy (DOE) has sponsored a residential assistance program for weatherizing the households of low-income families. Several million homes have received energy weatherization services. In the last few years, the US Recovery Act invested $5 billion in the program to help lower the energy bills of nearly 600,000 low-income families across the country. The program is weatherizing 25,000 homes a month. Weatherization programs have been expanded by state and utility residential audit and upgrade programs, and these have achieved impressive outcomes, ranging from 10% to more than 40% reduction in energy losses. The program translates into real savings, reducing the financial burden of costly utility bills for low-income households.

In 1996, EPA partnered with DOE extending the program for Energy Star labeling (formerly applied only to appliances and equipment) to new homes. About a million homes have earned an Energy Star rating, and this designation is now being earned by about 20% of all new homes in the United States. In 1999, the US Department of Housing and Urban Development (HUD) joined the effort, starting the Home Performance with Energy Star improvements program for existing homes.

The resurgence of energy-saving programs for homes and other buildings raises real indoor air-quality concerns. Responses to the energy crisis of the early 1970s led to serious indoor air problems with moisture, formaldehyde, unvented combustion, and inadequate ventilation. We now are beginning to understand the consequences of lowered ventilation rates on symptoms and performance in homes, schools, and offices (IOM, 2011). With a large and relatively uninformed workforce engaged in residential energy conservation efforts, there is a challenge to avoid repeating old mistakes. Fortunately, DOE and EPA have recognized the need to educate this workforce, now estimated at 200,000, and to establish clear criteria about when not to undertake certain weatherization activities because of potential indoor air problems (DOE, 2010; EPA, 2011). However, only a few states have training programs, and the impact of weatherization programs in terms of altered levels of radon, indoor moisture, and actual air exchange rates, among other potential factors that define indoor environmental quality, remains inadequately understood. In addition, low-income communities, where indoor pollutant levels are elevated (Adamkiewicz et al., 2011), may have higher potential for unintended consequences from weatherization.

It is now appreciated that climate change will impact ambient air pollution through increased emission rates and faster chemical reaction rates associated with higher temperatures. In the absence of more effective emission controls, particulate matter and ozone levels are projected to increase. Regional droughts and early spring melt of mountain snow render large areas of forest and grasslands prone to fire. It has long been documented that particles and gases of outdoor origin penetrate into homes and buildings. Buildings without air-conditioning equipment and without effective filters will experience outdoor air pollution indoors to a greater degree.

Earlier onset of spring in northern temperate climates and the spread of invasive species, such as ragweed, are introducing new aeroallergens and increasing sensitization (Asero, 2002; Voltolini et al., 2000). Increased carbon dioxide (CO_2) in the atmosphere has already led to more vegetative growth. Based on laboratory and field experiments, it is reasonable to expect that pollen levels in outdoor air will rise as a consequence of higher CO_2 levels, warmer temperatures, and concomitant longer growing seasons associated with anthropogenic climate change (Rogers et al., 2006; Singer et al., 2005; Wan et al., 2002; Wayne et al., 2002; Ziska et al., 2005, 2009). These changes could have adverse consequences for health outcomes like allergic rhinitis, asthma, and atopic dermatitis (Reid and Gamble, 2009).

A rise in ambient CO_2 and lower ventilation have other implications of indoor environments. CO_2 levels in excess of 1000 ppm, once thought benign, have recently been investigated by Usha Satish from the Department of Psychiatry, SUNY Upstate Medical University, Syracuse, NY, and a team from Lawrence Berkeley National Laboratory, Berkeley, CA, led by William Fisk. Fisk presented the results of their research, 'Impact of CO_2 on Human Decision Making and Productivity', at the Indoor Air 2011 conference (Satish et al., 2011). Twenty-two subjects were exposed in a double-blind chamber study to three different levels of CO_2: 600, 1000, and 2500 ppm. After acclimating, the subjects' executive decision-making performance was evaluated with a *Strategic Management Simulation* (SMS) methodology. This computer simulation has various possible scenarios with tasks that are potentially complex and volatile, have ambiguity, and have delayed feedback. SMS has been used widely in professional settings, including health care, as it provides results on parameters for 'decision making' (e.g. responsiveness, initiative, emergency responses, planning, strategy, etc.). This study is the first to examine the effects of moderate levels of CO_2 on executive decision making as measured by SMS. The findings, if substantiated, have particular relevance to buildings and schools where CO_2 levels are typically between 1000 and 1500 ppm (or higher) for extended periods. Satish et al. (2011) found statistically significant decrements in decision-making performance at 1000 ppm CO_2, which may be important at the societal level. Larger decrements in decision-making performance were observed at 2500 ppm CO_2. These provocative results will need to be confirmed, but the implications for 'knowledge-based economies' could be profound. If global CO_2 levels continue to increase at 3 ppm per year and fossil fuel combustion in urban areas adds to the global background, ambient urban CO_2 levels might be 500 to 700 ppm by 2050, requiring substantially higher ventilation rates to maintain CO_2 levels indoors below absolute targets, e.g. 1000 ppm.

Table 2 Ways for ISIAQ to promote a more comprehensive understanding of the impact of climate change on the indoor environment

Promote research and integrated assessments of the role of ventilation for enhancing health and productivity.
Promote the harmonized emission testing of consumer products and building materials.
Provide evidence-based research on the benefits and consequences of energy mitigation programs for residences, schools, and buildings.
Further the utility of financial tools, such as lifecycle costing by monetizing the IAQ-related costs and benefits of health, comfort, productivity, and material durability.
Advance the understanding of IAQ implications for climate mitigation and adaptation through:
Developing and disseminating educational material for use in public and professional education;
Contributing to weatherization and building energy conservation training information; and
Organizing symposia, workshops, technical sessions, and design competitions for Healthy Buildings 2012, IA 2014, and for joint conferences with other societies.

The IOM Committee made several recommendations to EPA and other US federal entities. Changes in weather around the world will eventually impact all of us, if they have not already done so. ISIAQ is unique among all professional scientific societies in that it explicitly and singularly is focused on indoor environments. Therefore, our society has an important role to articulate—through our journals, meetings and position statements—about the impacts of climate change on indoor environments and the health, comfort, and productivity of people. Toward that aim, Table 2 suggests some activities by which ISIAQ can carry forward the policies and practices emanating from our collective scientific endeavors.

The Institute of Medicine's full report on *Climate Change, the Indoor Environment and Health* and a brief summary are available as free downloads at the National Academies Press Web site, http://www.nap.edu/catalog.php?record_id=13115.

John D. Spengler

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