Public Health Consequences and Cost of Climate Change Impacts on Indoor Environments

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Foreword

This paper accepts the conclusions of the world scientific community that the warming of the Earth over the past several decades has been caused largely by anthropogenic greenhouse gas emissions and that such emissions, if continued, will likely lead to a variety of climatic changes throughout the world. This is the general conclusion of the Intergovernmental Panel on Climate Change (IPCC) and the U.S. Climate Change Science Program (CCSP). The IPCC was established by the United Nations Environment Programme (UNEP) and the World Meteorological Organization (WMO) to present a clear scientific view on the current state of climate change and its potential consequences, while the CCSP is an organization of 13 federal agencies working to improve our understanding of the science of climate change and its potential impacts. These organizations provide up-to-date scientific information and reports on various aspects of climate change, along with major references to the general literature.[1] The literature on the impact of climate change has focused almost exclusively on the outdoor environment. Girman et al. (2008), however, rightly point out that the impact of climate change on the indoor environment could also be substantial, and they identify several areas of concern such as greater use of air conditioning, increased risk of mold from flooding, increased exposure to ozone indoors, increased pressures to reduce ventilation rates, increased risk from vector-borne diseases and increased risk of pesticide exposure. They also suggest that government agencies and non-profit organizations provide information and programs necessary to design, construct, maintain and operate indoor environments that are capable of protecting occupants from climate change impacts. This document expands and elaborates on the issues raised in that paper.

Note: This report presents the findings, recommendations and views of its author and not necessarily those of the U.S. Environmental Protection Agency.

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[1] Reports from the IPCC are available at www.ipcc.ch/. The CCSP provides a series of synthesis and assessment reports available at www.climatescience.gov/Library/sap/sap-summary.php. (websites available as of 1/11/2010.)

Executive Summary

Introduction

Buildings protect people from the elements and otherwise support human activity. Unless managed well, however, environmental conditions inside buildings have the potential to make people sick, cause them discomfort, or otherwise inhibit their ability to perform.

Degradation in indoor environments resulting from climate change involves impacts to the public health not heretofore considered in the climate change literature. A closer look at the impacts of climate change on indoor environments strongly suggests the need to plan for indoor environmental protections to mitigate potentially large increases in public health risks.

This report presents a preliminary analysis of the changes in indoor environmental quality likely to result from changes in climate and assesses the potential public health consequences of those changes. This report also provides a preliminary analysis of the economic cost of these public health consequences. This preliminary economic analysis is intended only to help policy makers decide how important indoor environmental concerns might be when setting priorities for further research or further policy exploration.

Chapter Summaries

Chapter 1: Indoor Environmental Quality and Its Role in Protecting Public Health

Chapter 1 provides a rudimentary framework for understanding the critical factors that determine the indoor environmental quality of buildings in order to better understand how climate change will affect indoor environments and what the associated public health consequences will likely be.

Key Points from Chapter 1

- Indoor temperature and humidity are important to public health. Moderately high temperatures and humidity in buildings (e.g., the high end of the thermal comfort zone) have been associated with increased occupant discomfort, perceptions of poor indoor air quality (Bergland and Cain, 1989; Fang et alet al., 1998), unsolicited occupant complaints (Federspiel, 1998),; reduced productivity(SeppanenSeppänen and Fisk, 2005),; and adverse respiratory health symptoms(Mendell et alet al., 2002)..The ability of buildings to mitigate the heat and moisture impacts of climate change indoorss, particularly for susceptible populations, is therefore a concern.

- Much of a building's structure, its furnishings and equipment, and its occupants and their activities produce pollution. In a well-functioning building, some of these pollutants will be directly exhausted to the outdoors through exhaust ventilation, and some will be removed as outdoor air is brought into the building and displaces the air inside. However, the air outside may also contain pollutants, which will be brought inside in this process.

- Reducing emissions from indoor sources (source control) and providing adequate outdoor air ventilation play complementary roles in protecting public health by controlling indoor environmental exposures to indoor pollutants. The use of air-cleaning devices can augment source control and ventilation strategies.

- As outdoor ozone enters indoors, it reacts with compounds found on the surfaces of commonly used building materials, furnishings, cleaning products and other surface treatments, air fresheners, and other products. The result is the production of carcinogens and irritants such as formaldehyde, acrolein, other aldehydes, acids, and ultrafine particles that are often more toxic than the original constituent compounds (Weschler, 2000; Nazaroff and Weschler, 2004). The impact of these byproducts on public health can potentially quite significant.

- Biocontaminants found indoors include mold, dust mites, and allergens from cockroaches, rodents, and other pests. Biocontaminants can trigger allergies, asthma attacks, and other respiratory conditions. There are many sources of excess moisture that can lead to biocontamination. They include high humidity and condensation; wet conditions from spills, flooding, or poor drainage of rainwater; leaks in the building envelope or from water pipes; and poor HVAC maintenance.

- A rigorous and adequately funded building maintenance program is fundamental to sustaining good indoor environmental quality and energy efficiency in buildings. Inadequate attention to and funding of maintenance budgets, or poorly trained personnel, often lead to malfunctioning equipment or lack of moisture control leading to inadequate ventilation, biocontamination, or the unintentional introduction of pollutant sources. There is ample evidence of the association between common maintenance shortfalls and reduced health and productivity in buildings (Mendell, 2003; Wargocki et al., 2002b; Cole et al., 1994; Raw et al., 1993).

Chapter 2: Climate Change Impacts on the Outdoor Environment

Chapter 2 discusses the impact that climate change is expected to have on the outdoor environment, focusing on those aspects most likely to have significant impact indoors. The chapter covers gradual and episodic impacts. For example, a gradual rise in mean temperature or precipitation will be accompanied by episodic extreme weather events such as heat waves, storms, and heavy precipitation, which are expected to be more intense and occur more frequently.

Key Points from Chapter 2

A recent U.S. Government report (USGCRP, 2009) provides a useful summary of anticipated impacts of climate change.The main findings of this report are summarized below.

- Warming over this century is projected to be considerably greater than over the last century. The average temperature of the Earth has risen about 1.5 ºF since 1900. By 2100, it is projected to rise another 2 to 11.5 ºF. By the end of this century, the average temperature in the United States is projected to increase about 7 to 11 °F under high emissions scenarios and about 4 to 6.5 °F under low-emissions scenarios.

- Atmospheric conditions in northern regions will change from very cold and dry to warmer and more humid. Droughts are likely to become more frequent and severe, particularly in the Southwest.

- Excess heat events that now occur once every 20 years are projected to occur about every other year in much of the country by the end of this century, and these very hot days are projected to be about 10 °F hotter than they are today. The number of heat wave days in Los Angeles is projected to double, and the number in Chicago is projected to quadruple if greenhouse gas emissions are not reduced.

- Heavy downpours that are now 1-in-20-year occurrences are projected to occur about every 4 – 15 years by the end of this century, depending on location. The intensity of heavy downpours is expected to increase. The 1-in-20-year heavy downpour is expected to be between 10 percent and 25 percent heavier by the end of the century than it is now.

- The destructive energy of Atlantic hurricanes has increased in recent decades. The intensity of these storms is likely to increase in this century.

- Cold-season storm tracks will continue to shift northward, and the strongest storms are likely to become stronger and more frequent, with greater wind speeds and more extreme wave heights in northern areas (e.g., Northeast and upper Midwest). Lake-effect snowstorms in the Great Lakes region are likely to increase, causing potentially heavy snow storms such as the February 2007 storm in western New York.2

- Assuming historical geological forces continue, a 2-foot rise in global sea level (within the range of recent estimates) by the end of this century would result in a relative sea-level rise of 2.3 feet at New York City, 2.9 feet at Hampton Roads, Va., 3.5 feet at Galveston, Texas, and 1 foot at Neah Bay in Washington State. Sea-level rise will increase risks of erosion, storm surge damage, and flooding for coastal communities, especially in the Southeast and parts of Alaska.

- The western United States and Alaska will experience increased frequency of large fires and an extended fire season. Deserts and dry lands in the arid Southwest and elsewhere will become hotter and drier, and they will expand to the north and east and move into higher elevations.

- Increased drought conditions will continue to encourage non-native grasses to invade the Southwest, where they will provide fuel for fires, which are expected to increase in frequency and intensity.

- Unforeseen ecological changes could result in massive dislocations of species or in pest outbreaks. With global trade and travel, disease flare-ups brought about by climate change in any part of the world, particularly in poorer nations, have the potential to reach the United States, where extreme weather events could undermine the public health infrastructure and make people more vulnerable as disease transmission from food, water, and insects is likely to increase. Rising temperatures and carbon dioxide concentrations increase pollen production and prolong the pollen season in a number of plants that have highly allergenic pollen, presenting a health risk.

- Emissions of volatile organic compounds (VOCs) and the formation of ozone outdoors are expected to increase, as is the frequency and duration of stagnant air masses. Under constant pollutant emissions, by the middle of this century, Red Ozone Alert Days in the 50 largest cities in the eastern United States are projected to increase by 68 percent due to warming alone.

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[2] However, the heavy precipitation is projected to eventually fall as rain rather than snow with increased warming in the long term.

- The projected rapid rate and large degree of climate change over this century will challenge the ability of society and natural systems to adapt. Adaptation will be particularly challenging because society will not be responding to a new steady state, but rather to a rapidly moving target. Climate will be changing continually and rapidly at a rate outside the range to which society has adapted in the past.

Chapter 3: Impacts Of Climate Change On Indoor Environmental Quality And Implications For The Public Health

Chapter 3 discusses how changes in the outdoor environment brought about by climate change will affect the indoor environment and lead to changes in the health, comfort, and productivity of people as they occupy their residences, schools, commercial and institutional buildings.

Key Points from Chapter 3

Temperature

- Higher temperatures from climate change will increase the use of air conditioning, leading to substantial increases in demand for electricity and the need for increased electricity generation. However, areas that have little current air-conditioning capacity—along with substantial disruptions in power generation and distribution created by other climate change impacts—will create unmet needs for cooling, resulting in increased indoor air temperatures.

- Moderately high temperatures will likely result in perceptions of indoor air quality as being poorer, with higher rates of unsolicited occupant complaints, sick building syndrome and lost productivity, and potentially increased respiratory symptoms.

- The increased frequency and intensity of extreme heat events will create stresses on indoor environments that will not be fully met, causing increased morbidity and mortality from extreme heat indoors.

Ventilation

- Increased electricity demand and interruptions in supply are expected to raise energy prices, which, combined with the desire to reduce greenhouse gas emissions, will likely encourage individuals and public policy toward greater energy conservation through reduced outdoor air ventilation in buildings.

- Reduced outdoor air ventilation raises indoor concentrations of indoor-generated pollutants and increases the adverse health, comfort, and productivity impacts of these contaminants.

- Strategies are needed to protect indoor environments while reducing energy use. Such strategies could include increasing the energy efficiency of equipment, employing ventilation strategies that use less energy (e.g., separating outdoor air delivery from the heating and cooling airflow requirements, or employing more natural ventilation), adopting ventilation strategies that are more efficient in removing contaminants (e.g. displacement ventilation, increased exhaust ventilation), and strategically integrating more air cleaning into the ventilation system. In addition, a major effort to reduce pollutant emissions from products and materials used in buildings would help reduce the need for ventilation to maintain adequate indoor air quality and protect the public health.

Indoor Chemistry

- Climate change has the potential to produce significant increases in near-surface ozone concentrations throughout the United States (EPA, 2009). Ozone is known to react with many VOCs found indoors to create a variety of chemical byproducts with potentially troubling adverse health consequences that could present a significant unanticipated public health issue. Recent studies indicate that ozone reacts with the constituents of carpets, cleaning products and air fresheners, paints (particularly low-VOC paints which use linseed oil), building materials, and a variety of surfaces to produce some irritating and toxic compounds such as formaldehyde and other aldehydes, acid aerosols, and fine and ultrafine particles (Weschler (1992, 2000, 2004, 2006, 2007); Weschler and Shields (1997, 2004); Nazaroff and Weschler (2004); Morrison (2008,); Levin (2008)).

- Of particular concern for ozone reactions is the prolific use of cleaning products and air fresheners, which contain selected terpenes (e.g., a-pinene, limonene, and isopropene) that readily react with ozone. Studies suggest that such reactions produce substantial quantities of toxic secondary byproducts. In addition, unstable byproducts such as the OH radical can set off a cascade of chemical reactions that, depending on the indoor and outdoor air constituents, can produce further stable and unstable byproducts. The potential impact of these reactions on the public health is just beginning to be appreciated.

- Improved testing to reduce pollutant emissions from products and materials and to reduce the use of chemical compounds in products that readily react with ozone would be important public health strategies to consider.

Moisture

- Increased relative humidity from climate change will increase the moisture content of materials indoors and thus increase the risk for mold growth. These conditions will be exacerbated by heavy periodic rainfalls that will likely stress the ability of buildings of all types to adequately manage excess water flow.

- The current prevalence of dampness and mold conditions in U.S. buildings already suggests a lack of proper building defenses against excess moisture flows. In the absence of increased maintenance and retrofit activity in the U.S to control moisture, these problems could easily grow exponentially in the face of increased humidity, heavy rainfall, storms, and flooding. The rampant mold problems caused by flooding during Hurricane Katrina (Hamilton, 2005) provide ample evidence that mold issues could be a significant problem related to climate change.

- Damage caused by flooding plus the abundance of water available to pests will likely increase pest-harborage opportunities and increase the capacity of buildings to support pests infestation. (Cockroaches, for example, are primarily attracted to water sources and food debris.) An increase in pests could increase exposure to pest allergens, infectious agents, and to pesticides.

- A careful analysis of regional vulnerabilities to moisture intrusion into existing buildings, and to building practices to prevent such intrusions in new building construction, would be worthwhile. In addition, widespread dissemination of guidelines for remediating dampness and mold in buildings, integrated pest management techniques, and revised specifications for temporary housing could help mitigate moisture-related public health consequences of climate change in buildings.

Vulnerability to Diseases, Pests and Pesticides

- Changes in the ecological balance brought about by climate change can alter the geographical distribution and biological cycle of many disease vectors, allowing the establishment of new breeding sites and bursts of disease carriers, thus posing significant disease risks to humans. In addition, climate change is expected to deplete the upper stratospheric ozone layer and thereby increase population exposure to ultraviolet (UV) radiation, which could suppress immune responses to various diseases and to vaccinations (de Gruijl et al., 2003) and could leave the general population more vulnerable to disease outbreaks.

- Increases in populations of structural pests, crop pests, and forest pests are also likely to increase the use of pesticides and pesticide exposure both indoors and outdoors. Policies to encourage the use of Integrated Pest Management (IPM) to minimize the use of pesticides would be wise.

Implications

- In general, buildings will be used as shelters to avoid exposure to disease vectors outdoors, to avoid excessive exposure to UV radiation, and to avoid extreme environmental events such as heat waves. If indoor environments are to be relied upon to protect the public, a paramount concern is whether the indoor environment itself will be sufficiently capable of providing environmental conditions conducive to supporting the health and well-being of populations. Attention to healthy conditions indoors becomes more important as populations become more vulnerable by disease, UV radiation, and other environmental stressors. A hard look at building design and maintenance practices in light of this vulnerability would be worthwhile.

Chapter 4: Public Health Cost of Climate Change Resulting from Changes in Indoor Environments

Chapter 4 provides a very rough estimate of the economic value of the public health impacts of climate change on indoor environments described in Chapter 3. The estimates are limited to the economic value of the impacts on public health and do not account for expenditures or for other adaptations that may occur as society attempts to adjust to such impacts.

Key Points from Chapter 4

Methodology

- The economic value of changes in public health, comfort and productivity are estimated in terms of percentage increments to baseline public health costs associated with current inadequacies of indoor environmental quality. The assessments are made first by establishing baseline public health costs and then by estimating a likely percentage change from that baseline due to specific climate change effects on the indoor environment. The total public health cost estimate is derived by summing the public health cost of specific climate change effects.

- The 75-year time frame adopted for this assessment is generally consistent with the time frames used in most government publications concerning climate change. Since public health costs are evaluated over time, discounting the value of future costs is appropriate.

- There are three time frame issues incorporated into the discounting procedure. The first relates to situations in which a given health impact from exposure is delayed after an initial climate change effect occurs. This is applied to premature deaths caused by long-term exposure to environmental tobacco smoke (ETS). It is assumed that the full impact on premature death would gradually evolve in equal increments over 70 years. The second relates to situations where exposure in the absence of climate change is expected to change over time. Since the prevalence of smoking is declining, it is assumed that exposure to environmental tobacco smoke in the absence of climate change would gradually decline to 40 percent of its current level over a 25-year period. The third relates to the fact that climate change itself does not happen all at once, but is expected to evolve. It is assumed that predicted changes would occur in equal increments over 75 years.

- With the exception of the effect of heat waves, where the literature provides a basis for an impact estimate, one of three levels of impact are chosen through reasoned judgment for each effect: low impact (1 percent – 20 percent), medium impact (21 percent – 35 percent), and high impact (36 percent – 50 percent).

Pubic Health Cost Estimates

- Tables ES-1 summarizes estimates of baseline public health costs from current indoor environmental conditions. Table ES-2 provides consolidated impact categories used to estimate public health costs from climate change impacts on indoor environments. Table ES-3 maps the effect of outdoor climate change on indoor environments and identifies the impact categories affected.

- Table ES-4 provides the undiscounted estimates of the public health cost from the climate change impact on indoor environments. The approximate range of total costs is $75 billion – $175 billion per year. This represents in current dollars the annual cost burden that would occur after 75 years.

- Table ES-5 presents the discounting factors used to account for discounting and adjustments described above using social discount rates of 3 percent and 7percent. Table ES-6 presents the discounted and adjusted annual costs. The approximate range of total costs is $10 billion – $60 billion per year. This represents the present value of the future varying annual cost stream converted to a constant annual equivalent.

- Given the uncertainties and the unrefined nature of these estimates, it is perhaps more appropriate to conclude that the discounted and adjusted public health costs are in the low-to-mid tens of billions of dollars per year, but could be in the high tens of billion of dollars per year if all health impacts were included.

Table ES-1: Baseline Economic Cost of Health, Comfort, and Productivity Impacts

Health or Exposure Category	Approximate Annual Cost (Billions)	Comment
ETS exposure mortality	$369 (current) $148* (future)	49,830 premature deaths from cancer, heart disease, and SIDS (from CARB, 2005)
ETS exposure morbidity	$4 (current) $2* (future)	Includes 24,500 cases of low birth weight and 17,000 new cases of asthma only (CARB, 2005)
Heat waves	$5	688 premature heat-related deaths including hypothermia as a contributing factor (CDC, 2006)
SBS	$93	Midpoint of productivity loss of $73 billion from SBS (Fisk, 2000) and $87 billion (EPA, 1989), adjusted for inflation to 2008 dollars
Allergies and asthma	$6	Midpoint of $2 billion – $8 billion (Fisk, 2000), adjusted for inflation to 2008 dollars
Communicable respiratory illnesses	$13	Midpoint of $6 billion – $14 billion (Fisk, 2000), adjusted for inflation to 2008 dollars
Total Baseline Annual Cost	**$490 billion (current)** **$267 billion (future)**	

***** Adjusted to 40% of the dollar value for declining smoking prevalence.

Table ES-2: Consolidated Cost Impact Categories

Category	Source
(1) Sick building syndrome (SBS)	Increased indoor temperatures and pollution from VOCs, pesticides, and formaldehyde
(2) Heat waves	Extreme heat events
(3) Allergies, asthma, and respiratory symptoms	Moisture-related contaminants such as mold, dust mites, cockroaches, and rodents, plus symptoms from fine particles resulting from indoor air chemistry involving ozone
(4) Communicable diseases	Ecological shifts that increase disease vectors and from reduced immunity due to ultraviolet radiation
(5) All health effects except heat waves	Reduced ventilation, which increases all indoor air contaminants. Includes all the effects in Table 4-2 except heat waves

Table ES-3: Effects of Climate Change (Global Warming) on Indoor Air Quality

Climatological Effect and Adaptations	**Indoor Environmental Effect**		
	Effect on indoor climate and indoor pollution	**Effect on health, comfort & productivity**	**Value (cost) of health, comfort, & productivity change***
Outdoor Temperature Mean rise in outdoor temperature rise	Indoor temperature rises.	Sick Building Syndrome (SBS) increases from temperature rise.	Percentage increase in SBS (1)
	Increased use of air conditioning Potential for increased off-gassing of VOCs.	Potential increase in respiratory symptoms	Percentage increase in SBS (1)
Increased frequency and intensity of heat waves	Inability of air conditioning to condition indoor air		
	Extreme heat stress	Multiple effects	Percentage increase in respiratory symptoms (2) Percentage increase in premature death (2)
Outdoor Pollution Increased outdoor pollution (especially particulates and ozone)	Increased particulates and ozone come indoors	Increased respiratory ailments	Percentage increase in respiratory symptoms (3).
	Increased ozone reaction byproducts (indoor chemistry)	Increased SBS and respiratory symptoms	Percentage increase in SBS (1)

Climatological Effect and Adaptations	**Indoor Environmental Effect**		
	Effect on indoor climate and indoor pollution	**Effect on health, comfort & productivity**	**Value (cost) of health, comfort, & productivity change***
Moisture and Water Events Increased mean outdoor humidity	Increased indoor relative humidity, condensation, and mold growth	Asthma, allergies, and respiratory symptoms	Percentage increase in allergies, asthma, and respiratory symptoms (3)
Increased frequency and intensity of extreme precipitation episodes, with flooding in inland areas Higher intensity of storm surges and sea level rise in coastal areas, with increased flooding in East and Gulf Coast Regions	Increased wet, damp conditions, building damage, and mold	Asthma, allergies, and respiratory symptoms.	Percentage increase in allergies, asthma, and respiratory symptoms (3)
Increased harborage of rodents	Increased rodent infestation indoors due to rodent migration from outdoors to indoors and possible cockroach infestation due to dampness	Allergies, asthma, and respiratory symptoms.	Percentage increase in allergies, asthma, and respiratory symptoms (3)
	Increased use and exposure to pesticides		Percentage increase in SBS (1)
Temporary housing provided in flooded areas	Increased formaldehyde and VOC exposures	SBS from pesticides, formaldehyde, and VOC	

Climatological Effect and Adaptations	**Indoor Environmental Effect**		
	Effect on indoor climate and indoor pollution	**Effect on health, comfort & productivity**	**Value (cost) of health, comfort, & productivity change***
Outdoor Air Ventilation Pressure to reduce energy use to lower GHG; because of the cost of increased air conditioning results in reduced outdoor air ventilation	All existing indoor pollutants rise in inverse proportion to reduced ventilation	Increases in all existing indoor air health, comfort, and productivity effects	Percentage increases in all categories except heat waves (5)
Ecological Shifts and UV Radiation Changes in population and geographical distribution of disease pathogens, vectors, and hosts	Increases in disease outbreaks	Disease transmission in indoor environments	Percentage increase in communicable diseases (4)

*The numbers in parentheses correspond to the corresponding cost impact category in Table ES-2
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Table ES-4: Undiscounted Public Health Cost Estimates

Category	**Annual Public Health Cost (billion$)**	
	Low	**High**
Sick Building Syndrome	1	19
Heat Wave Mortality	3	4
Allergy, Asthma, and Respiratory	1	2
Communicable Disease	3	5
Ventilation ETS (mortality)	40	80
Ventilation (morbidity**)**	1	1
Ventilation (other)	30	60
Total	**79**	**171**
Approximate Range	**75 – 175**	

Table ES-5: Discount Factors for Annual Equivalent Impact Estimates

	3%	7%
	Annual Equivalent	Annual Equivalent
Delayed premature death (70 yrs)	0.425	0.216
Incremental climate change (75 yrs)	0.405	0.202
Smoking prevalence reduction from 25 percent to 10 percent in 25 yrs	0.568	0.701
All effects combined	0.115	0.038

Table ES-6: Discounted and Adjusted Annual Equivalent Public Health Cost of Climate Change on Indoor Environmental Quality ($billion)

	3%		7%	
	Low	High	Low	High
Sick Building Syndrome	0	8	0	4
Heat Wave mortality	1	2	1	1
Allergies, asthma, respiratory disease	1	1	0	0
Communicable respiratory disease	1	2	1	1
Ventilation ETS mortality	11	23	4	8
Ventilation ETS morbidity	0	0	0	0
Ventilation other*	12	24	6	12
Total	**27**	**60**	**12**	**26**
Approximate Range	**10 – 60**			

*Excludes heat waves

Chapter 5: Summary and Conclusions

Chapter 5 summarizes the impacts and discusses the implications for public and private actions to protect the public health through improved indoor environmental planning and control. All of Chapter 5 is presented below.

Warmer Temperatures

- Warmer outdoor temperatures caused by climate change are expected to increase indoor temperatures.

- While partly mitigated by increased use of air conditioning, overall, the rise in indoor temperatures can be expected to have some health impact, including perceptions of poorer indoor air quality, increased SBS symptoms, and some increase in respiratory symptoms. Greater use of air conditioning will likely increase carbon emissions, which in turn will accelerate the warming effect.

- Temperature extremes are expected to experience proportionally higher increases than mean temperatures, and extreme temperature events will occur more often. This will greatly increase peak electricity demand, perhaps beyond the capacity to meet the increased demand for air conditioning, and this will exacerbate the health effects from indoor exposure.

- Heat waves will result in a host of health effects, including increased deaths of vulnerable populations from indoor heat exposures.

Implications

- Significant unmet needs for cooling through air conditioning will require greater attention to alternative cooling strategies in building design (e.g., building orientation, roofing and window systems) and operational practices (e.g., night cooling). This is consistent with the “green building” movement, which may be further encouraged in response to climate change.

- The generally agreed upon recommended public health response to heat waves is a notification and response program. This approach does not address the likelihood that many buildings, including many that are relied upon in these programs to be available to cool sensitive populations, may not be capable of doing so due to disruptions in energy supplies and building damages from other climate change events. Further consideration of this issue is needed.

Reduced Outdoor Air Ventilation

- Non-industrial buildings account for almost 40 percent of the energy consumed in the United States. The rise in energy demand for air conditioning combined with the need to reduce carbon emissions is expected to result in reduced outdoor air ventilation of buildings. Since ventilation is a primary means of controlling concentrations of pollution generated indoors, this is expected to have a profound affect on all categories of health impacts associated with exposure to indoor pollution.

- Outdoor air ventilation was significantly reduced during the energy crisis of the 1970’s. Complaints of building sickness brought about the recognition that indoor air pollution can be a major public health threat and that adequate ventilation is important for acceptable indoor air quality.

Implications

- A major effort to install more energy-efficient ventilation equipment and more effective and efficient ventilation strategies may be needed. These changes would reduce the energy used for ventilation and mitigate the need to save energy by reducing ventilation rates. Such strategies could include more reliance on natural ventilation or greater ventilation efficiency (e.g., displacement ventilation).

- Efforts to increase control of indoor pollution sources and promote the use of advanced filtration and air-cleaning technologies could allow ventilation rates to be modestly reduced without affecting indoor air quality.

Elevated Ozone

- Elevated levels of outdoor ozone due to climate change are expected to increase ozone levels indoors where people spend most of their time, and where the public is traditionally advised to go when outdoor ozone levels are high.

- Ozone indoors is known to react with a host of commonly used chemicals and produce toxic byproducts to which people indoors are exposed. The byproducts include fine and ultrafine particles, formaldehyde and other aldehydes, acrolein, and other chemicals. Other byproducts are unstable compounds that stimulate additional chemical reactions.

- While elevated ozone is rapidly emerging as an important indoor air concern, the specific health impacts from the reactive byproduccts generated by ozone are not well understood. Nevertheless, it is thought that the often-cited health impacts from ozone and particulate pollution outdoors may in fact reflect exposures to toxic compounds indoors from ozone reaction byproducts.

- With ozone levels expected to increase, this issue may be one of the most important indoor environmental impacts on public health due to climate change. Important chemicals of concern indoors because they react readily with ozone include terpenes, which are natural oils increasingly used in fragranced products and cleansers (including many “green” cleaning products). The rapid growth of fragranced products and air fresheners may be of particular concern in view of climate change. This issue is worth further study.

Implications

- Fortunately, it may be possible to mitigate the potentially significant public health impacts from direct exposure to ozone and from exposure to byproducts of chemical reactions with ozone indoors.

- Strategies to reduce direct exposure to ozone indoors could include the use of air cleaning systems to remove ozone from outdoor ventilation air and from indoor air. Charcoal and other chemical sorbents are used to remove ozone within filtration systems and are suggested for use in high ozone areas. That these systems require careful monitoring and diligent maintenance emphasizes the need for improvements in building maintenance. Further research into improved gas phase air-cleaning systems may prove to be highly beneficial.

- The most direct strategy to reduce exposure to ozone-reaction byproducts is to have manufacturers change their product formulations to reduce the use of those VOCs that readily react with ozone. Filters typically found in HVAC systems may also be a cause of concern when ozone levels are elevated. Filters continually collect dust particles that contain VOCs that may react with ozone and create undesirable byproducts such as formaldehyde that is then delivered into occupied spaces. In fact, formaldehyde has been shown to be a common product of reactive chemistry on filters (Hyttinen et al., 2006). The synthetic media of the filters themselves also appear to be a problem (Buchanan et al., 2008). This suggests the possibility that proper filter medium selection or treatments could reduce adverse health symptoms from chemical reactions with ozone.

Extreme Water Events

- Extreme water events from heavy rainfall, flooding of interior rivers and streams, and flooding in coastal areas caused by sea level rise are expected to put great strains on the building stock, increasing infestations of molds, rodent, cockroach and dust mites.

- Allergy, asthma, and respiratory effects from these problems are expected to increase substantially. Problems are likely to be made worse by power outages and infrastructure damage caused by extreme weather.

- Providing temporary housing for displaced populations is expected to increase in areas susceptible to flooding. Exposure to formaldehyde in temporary housing has been a problem and will likely become a far greater problem unless provisions are made for removing formaldehyde-laden materials from these units. Problems caused by inadequate ventilation and poor drainage have also been experienced in some of these structures.

Implications

- Delays in the ability to pump out water and dry buildings will likely extend exposures well beyond the events themselves, and these exposures may become endemic if the time needed for recovery extends beyond the time between extreme water events.

- Areas where buildings are perpetually wet or very damp from extreme water events may become uninhabitable and abandoned, leaving large swaths of economically depressed areas and causing significant population relocation.

- Research to identify vulnerable areas could provide advanced warning and time for the development of mitigation strategies. Codes, standards, and the widespread dissemination of guidelines to protect buildings from damage where possible, and to mitigate dampness and mold problems, may be useful.

Ecological Shifts

- Ecological shifts are expected to alter the breeding cycles and geographic distribution of many disease vectors, and this trend raises the potential for major disease outbreaks in the United States. The globalization of commerce and increased international travel adds to this threat. The increase in UV radiation from climate change also has the potential to compromise a person’s immune system, making the population more vulnerable to disease.

Implications

- Reduced ventilation in buildings could expand the potential for disease transmission.

- Building O&M practices could be critical elements of control, particularly in hospitals, medical centers, schools, and other high-occupant-density buildings.

- Cultural attitudes in the building community that consider maintenance to be an expense to be minimized rather than an investment to be made in building environmental quality may need to be addressed through educational and training programs. A change in attitude and a move toward more scientifically based maintenance and cleaning practices would be needed.

- Building policies and guidelines specifically addressing disease transmission may need to be developed, widely disseminated, and promoted.

- The improved design and construction of temporary housing would help protect the health of displaced occupants housed in these facilities.

Economic Costs

- The undiscounted public health costs of climate change impacts on indoor environments appear to between the high tens of billions and two hundred billion dollars per year. These are annual costs that would occur toward the end of this century valued in current dollars. Using social discount rates of 3 percent and 7 percent, the discounted public health costs appear to be in the low-to-mid tens of billions of dollars per year, and would likely be in the high tens of billions of dollars per year if the full range of health effects were included in the estimate. These ranges represent the current value of discounted annual costs that are expected to occur indefinitely into the future.

Implications

- From a public policy standpoint, the impact of climate change on indoor environments and public health appear to be at levels that would warrant more attention. Focused study is needed to determine how best to ensure that policies, building practices, and technologies are implemented to prevent the degradation of indoor environments and ensure that buildings can fulfill their primary role of providing indoor spaces that are supportive of occupant health, comfort, and productivity in the face of climate change.

Introduction

Implicit in many of the recommended societal responses to climate change is the assumption that buildings will shelter the population from climate change impacts. But what kind of environments will buildings offer under climate change conditions? Buildings exist to protect people from the elements and to otherwise support human activity. However, unless buildings are managed well, indoor environmental conditions have the potential to make people sick, cause them discomfort, or otherwise inhibit their ability to perform.

Degradations in indoor environments resulting from climate change involve impacts to public health not heretofore considered in the climate change literature. A closer look at the impacts of climate change on indoor environments strongly suggests the need to plan for indoor environmental protections to mitigate potentially large increases in public health risks.

In the United States, people spend the majority of their time indoors at home, work, school, or other venues. Contaminants and climatic stressors found indoors are largely determined by how well buildings shelter occupants from adverse outdoor conditions, what indoor conditions are created by the building and its environmental control systems, and occupant activities. The public health risks from current indoor environmental conditions are already quite large.[3]

Preliminary analysis suggests that climate change can seriously affect indoor environmental quality through several mechanisms that have impacts on public health. Some examples discussed in this paper are higher indoor temperatures including extreme heat events; higher ozone levels and increased chemical byproducts caused by chemical reactions with ozone indoors; increased outdoor pollution that raises pollution levels indoors; reduced ventilation that saves energy but also increases indoor pollution concentrations; increased moisture and humidity leading to indoor mold and other bio-contamination; and ecological shifts leading to the increased spread of infectious diseases indoors.

Purpose

This report presents a preliminary analysis of the changes in indoor environmental quality likely to result from changes in climate and assesses the potential public health consequences of those changes. To determine how significant such changes might be from a public policy standpoint, the economic cost of the public health consequences are also assessed. Although quantitative, the economic analysis is very rough. It is intended only to help policy makers decide how important indoor environmental concerns might be when setting priorities for further research or further policy exploration.

Organization of this Report

The report is organized as follows:

- The **Executive Summary** briefly recaps the key points covered in each chapter and provides a useful overview of the document.

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[3] For example, EPA estimates that radon and environmental tobacco smoke are responsible for 24,000 premature deaths (21,000 and 3,000 respectively) from lung cancer annually (EPA, 2003 and EPA, 1992). Indoor moisture and mold are estimated to account for 21 percent (4.6 million) of asthma cases in the U.S. (Mudarri and Fisk, 2007) and various aspects of indoor environmental conditions are estimated to result in annual lost productivity of $50 billion to over $100 billion in non-industrial indoor environments (EPA, 1989 and Fisk, 2000).

- **Chapter 1** presents a rudimentary framework for understanding the critical factors that determine the indoor environmental quality of buildings in order to better understand how climate change will affect indoor environments and associated public health consequences.

- **Chapter 2** discusses the impact climate change is expected to have on the outdoor environment, focusing on the aspects most likely to have significant impacts indoors.

- **Chapter 3** discusses how changes in the outdoor environment brought about by climate change will affect the indoor environment and lead to changes in the health, comfort, and productivity of the public as they occupy their residences, schools, and commercial and institutional buildings.

- **Chapter 4** assesses the public health costs of the impacts discussed in Chapter 3.

- **Chapter 5** summarizes the impacts and discusses the implications for public and private actions to protect the public health through improved indoor environmental planning and control.

Chapter 1: Indoor Environmental Quality and Its Role in Protecting Public Health

Chapter Overview

Before assessing potential indoor impacts of climate change in more detail, it is worthwhile to establish the framework for understanding how the interrelationships between the outdoor environment, the building, and occupant activities determine the quality of the indoor environment to which occupants are exposed. This section provides a rudimentary framework for understanding the critical factors that affect indoor environmental quality. It also establishes a framework for understanding methods to mitigate negative impacts. Important features of the indoor environment and factors that affect them are summarized in Table 1-1.

Table 1-1: Critical Factors Affecting Indoor Environmental Conditions

Indoor Environment	Critical Factors
Indoor Climate Indoor Temperature Indoor Humidity	Outdoor Climate Air change rate HVAC systems
Indoor Pollution Chemical Particle Biological	Outdoor pollution Air change rate Ventilation Exhaust Indoor climate Emissions from indoor sources Indoor chemistry Filtration and air cleaning Moisture control

Indoor Temperature and Humidity

Indoor temperature and humidity are important to health. Higher temperatures and increased humidity in buildings (e.g., the high end of the thermal comfort zone) have been associated with increased discomfort and the perception of poor indoor air quality, increased occupant complaints, reduced productivity, and adverse respiratory health symptoms. But prolonged exposure to excessive heat well beyond the comfort zone, as predicted in climate change scenarios, can be a substantial health hazard. The ability of buildings to mitigate the indoor heat and moisture impacts of climate change, particularly for susceptible populations, is therefore a concern. Which buildings are vulnerable and in what regions of the country is a subject worthy of investigation.

Indoor Pollution

General Pollution Processes

The building itself, its furnishings and equipment, and its occupants and their activities produce pollution. In a well-functioning building, some of these pollutants are directly exhausted to the outdoors and some are removed as outdoor air is brought into the building displacing the air already inside. (However, the outside air may also bring in pollutants.) This air exchange is brought about by mechanical ventilation systems, by the natural infiltration and exfiltration of air through the building envelope, and from open windows and doors.

Pollutants inside can travel through a building as air flows from areas of higher atmospheric pressure to areas of lower atmospheric pressure. Some of these pathways are planned and deliberate to draw pollutants away from occupants, but problems arise when unintended flows draw contaminants into occupied areas.

Some contaminants may be removed from the air through natural processes, such as the adsorption of chemicals by surfaces or the settling of particles onto surfaces. Air filtration and cleaning devices also can remove some airborne contaminants.

Outdoor Air Ventilation, Energy, and Health

Ventilating indoor spaces has long been the primary means of removing pollutants generated indoors. By replacing polluted indoor air with outdoor air, contaminant concentrations from indoor sources are diluted.

In a space with a constant outdoor air ventilation rate and clean outdoor air, introducing a pollutant source with a constant emission rate would make the air concentration gradually rise and approach a steady state concentration. The steady state concentration will be proportional to the emission rate and inversely proportional to the outdoor air ventilation rate.4 This rudimentary relationship demonstrates the complementary roles that reducing emissions from indoor sources (source control) and providing adequate outdoor air ventilation play in protecting public health by controlling exposure to indoor air pollutants.

Prior to World War II, buildings were built with envelopes that “breathed,” and operable windows provided additional ventilation to occupants when needed. Opening and closing windows also helped regulate indoor temperatures. Modern buildings, however, are constructed of less porous materials; air conditioning is now widely used and mechanical ventilation has largely replaced operable windows in large buildings.

In the U.S., the American Society of Heating, Refrigeration, and Air Conditioning Engineers (ASHRAE) is the pre-eminent standard-setting authority with regard to ventilation rates for indoor-air-quality purposes. ASHRAE Standard 62, *Ventilation for Acceptable Indoor Air Quality,* is used throughout the building industry and is widely incorporated in state and local building codes.

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[4] The steady state equation is simply Css = S/Q, where Css is the steady state concentration, S is the generation rate of the indoor source (volume or mass per time unit), and Q is the outdoor air ventilation rate (volume per time unit). This equation assumes no sink effects or indoor chemical reactions that would remove the contaminant from the space.

Inadequate ventilation is commonly found to be the primary reason for occupant complaints of poor indoor air quality.

Indoor Chemical Reactions

As ozone and other smog-related reactive chemicals enter a building, they can react with compounds found on the surfaces of commonly used building materials and furnishings and in cleaning products and other surface treatments, air fresheners, and other products to produce carcinogens and irritants such as formaldehyde, acrolein, other aldehydes, acids, and ultrafine particles that are often more toxic than the original constituent compounds (Weschler, 2000, Nazaroff and Weschler, 2004). The impact of these chemicals on public health can potentially be quite significant. It has been suggested that epidemiological studies demonstrating increased mortality and morbidity during smog episodes outdoors may reflect the health consequences of these secondary byproducts that result from indoor chemical reactions (Weschler, 2006). Knowledge in this field is rapidly emerging, but the true health impacts are not yet well understood.

Compared to outdoors, the amount of indoor surfaces available to form reactive byproducts is extremely large relative to building volume, and the residence time for reactions to occur is extended by surface sorption (Morrison, 2008). Furthermore, indoor exposures to reactive byproducts of ozone is estimated to be 2/3 to 6 times higher than exposures to ozone outdoors (Weschler, 2006).

Biocontamination and Other Moisture-Related Pollutants

Indoor biocontaminants include mold, dust mites, and allergens from cockroaches, rodents, and other pests. Biocontaminants can trigger allergies, asthma attacks, and other respiratory conditions. High humidity indoors can condense on cool surfaces and cause mold contamination. This is especially a problem when the condensation occurs in hidden locations such as inside walls. Basements are commonly damp and result in mold growth. Dust mites also require minimum humidity levels to survive, and cockroaches are more likely to be found in damp areas.

There are many sources of excess moisture that can lead to biocontamination. They include high humidity and condensation, wet conditions from spills, flooding, or poor drainage of rainwater; leaks in the building envelope or from water pipes; and poor drainage of HVAC condensate.

The Role of Building Operation and Maintenance

A rigorous and adequately funded building maintenance program is fundamental for maintaining good indoor environmental quality in schools, hospitals, and other institutional buildings and in residential and commercial structures. Inadequate attention to and funding of operation and maintenance (O&M) budgets and poorly trained personnel often lead to malfunctioning or contaminated HVAC systems that result in inadequate ventilation and contaminated ventilation air, poor moisture control leading to biocontamination, or the unintentional introduction of pollutants from sources such as improperly used cleaning products. There is ample evidence of the association between common maintenance shortfalls and reduced health and productivity in buildings (Mendell 2003; Wargocki et al., 2002b; Cole et al., 1994; Raw et al., 1993).

Indoor Environmental Quality and Public Health

Overview[5]

Indoor environmental quality affects individuals' thermal, olfactory, or sensory comfort; health; and work performance. A broad range of health effects may result from exposure to indoor pollutants. Some pollutants (e.g., radon, environmental tobacco smoke [ETS], formaldehyde, benzene, and perchlorethylene) increase the risk of cancers or of other very serious health effects. Some indoor pollutants can cause infectious diseases such Legionnaires' disease, the common cold, and influenza. Allergy or asthma symptoms may result from exposure to indoor pollutants, especially biological contaminants such as mold and plant or pest allergens. Finally, indoor pollutants may contribute to irritation of the eye, nose, throat, or skin; coughing; wheezing; headache; and fatigue, symptoms that are often called sick building syndrome (SBS) symptoms or building-related symptoms (BRS).

Just as indoor conditions affect people's health and comfort, indoor exposures also affect their performance and productivity. The ability to perform mental and physical tasks, rates of absenteeism, performance at school, and productivity at work have all been associated with indoor environmental quality

A quick summary of some indoor environmental issues is provided below. How these issues could be affected by climate change, if at all, is covered in later chapters.

Environmental Tobacco Smoke and Radon

ETS exposure: In 1992, EPA published its ETS risk assessment and declared ETS to be a class A human carcinogen responsible for approximately 3,000 deaths each year from lung cancer and 150,000 to 300,000 lower respiratory tract infections (LRI) in infants and children under 18 months of age, resulting in 7,500 to 15,000 hospitalizations (EPA, 1992). The report did not cover the effects of ETS exposure on heart disease. However, in 2005 the California Air Resources Board (CARB) provided updated information on the health impacts of ETS exposure for both California and the U.S., including estimates for heart disease—among them an estimate of 46,000 premature heart disease deaths each year from ETS exposure, plus other impacts on children.

Radon exposure: Radon is a colorless, odorless radioactive soil gas that enters buildings (mostly homes) through cracks and crevices in the foundation. The surgeon general has warned that radon is the second leading cause of lung cancer in the United States today; only smoking causes more lung cancer deaths. The risk of lung cancer for smokers exposed to radon is especially high. According to EPA (2003), radon is estimated to cause about 21,000 lung cancer deaths per year.

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[5] The U.S. Environmental Protection Agency and the Lawrence Berkeley National Laboratory recently established an *Indoor Air Quality Scientific Findings Resource Bank (SFRB)* that has begun to summarize current knowledge of the public health impacts from indoor environmental conditions. While the subject matter covered thus far is limited to just a few areas, information available from this resource includes the health and economic impacts of building ventilation, the impacts of indoor environments on human performance and productivity, the effect of dampness and biological pollutants on health, and volatile organic compounds and health. This site provides a more detailed summary of some of the information covered in this section. The SFRB is available at http://www.iaqscience.lbl.gov/sfrb.html. Another excellent source of general scientific information on some indoor-air-quality-related topics is Spengler, et al. (2001).

Exposure to Volatile or Semi-Volatile Organic Compounds[6]

Numerous volatile organic compounds (VOCs) can cause sensory irritation symptoms when airborne concentrations are sufficiently high, but, the evidence for sensory irritation at typical concentrations indoors is very mixed and uncertain. However, taken together, mixtures of VOCs from certain products such as water-based paints (Ten Brinke et al., 1998) and photocopiers (Apte and Daisey, 1999) or from typical indoor conditions (Molhave et al., 1986) can cause sensory irritation at levels typically found indoors, but this is not true for all mixtures.

The evidence is stronger that VOCs at concentrations found indoors can cause asthma-like respiratory symptoms (Cal EPA, 2007; Mendell, 2007) though more research is needed. Formaldehyde is a common compound found indoors, and it is not unusual for formaldehyde levels to exceed 8-hour exposure levels for sensory irritation (Hodgson and Levin (2003), particularly in new homes, mobile homes, or portable classrooms—although levels do typically exceed thresholds for asthma-like respiratory symptoms, which are lower .

Cancer: Many VOCs found indoors have been designated by multiple authorities as posing a risk for cancer from long-term exposure. Table 1-2 identifies typical sources of VOCs having the highest estimated cancer risks, which range from 1 in 1,000 to 1 in 100,000 from long-term exposures.

Table 1-2: Typical Sources of VOCs

VOC	**Examples of Indoor Sources**
formaldehyde	some manufactured wood products used as building materials, in cabinets, and in furniture (e.g., medium density fiberboard, particle board, plywood with urea formaldehyde resin; urea-formaldehyde foam insulation [no longer used but still present in some buildings]); tobacco smoking; ozone-initiated chemical reactions with common indoor VOCs, unvented combustion appliances
napthalene	pesticides (moth balls)
paradichlorobenzene	pesticides (moth crystals); toilet bowl deodorizer
chloroform	pesticides; showering; washing clothes and dishes
acidaldehyde	tobacco smoke; water-based paint; unvented combustion appliances; leakage from wood stoves, furnaces, and fireplaces; (outdoor air also an important source)
benzene	tobacco smoke; some furnishings, paints, coatings, wood products, gasoline from attached garages (outdoor air also an important and sometimes predominant source)

Source: LBNL (undated)

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[6] See the IAQ Scientific Findings Resource Bank (SFRB) for a more detailed discussion. Available at http://www.iaqscience.lbl.gov/sfrb.html).

Sick Building Syndrome and Human Performance and Productivity[7]

In addition to specific health endpoints, many characteristics of indoor environments are related to a number of non-specific health complaints generally referred to as Sick Building Syndrome (SBS). These include, for example, nasal and sinus congestion, headache, runny nose, dry or itchy eyes, sore throat, lethargy, and dizziness. These same characteristics are also related to changes in various measures of human performance and productivity. Characteristics of particular interest include ventilation rate, temperature, the presence of indoor sources of VOCs, the presence of particles on surfaces or the degree of cleaning, and maintenance of HVAC systems. While productivity effects may be a direct result of changes in these indoor environmental conditions, it is also likely that some form of degradation of health or comfort acts as an intervening factor affecting productivity. For this reason, issues of productivity are discussed in the same context as SBS in this report.

Ventilation: Since inadequate ventilation increases the concentrations of all contaminants generated indoors, much of the evidence that poor indoor environmental quality increases SBS symptoms and reduces productivity is related to inadequate ventilation rates. The evidence is very strong and repeated in multiple studies. For example, in a major review article, Seppänen et al. (1999) wrote that ventilation studies report relative risks of 1.5 – 2.0 for respiratory illnesses and 1.1 – 6.0 for SBS symptoms when comparing low to high ventilation rates. Almost all studies found that ventilation rates below 10 L/s (20 cfm) per person were associated with statistically significant worsening of health or perceived indoor air quality (IAQ) outcomes. Similarly, Seppänen and Fisk (2006) conducted statistical analyses from a number of studies relating office ventilation rates with performance and found a monotonic relationship between ventilation rate and productivity. In addition, various aspects of schoolwork (Wargocki and Wyon, 2007, 2007a), possibly including test scores (Shaughnessey et al., 2006), have been shown to improve with higher ventilation rates.

Inadequate ventilation has also been shown to increase absenteeism in offices (Milton et al., 2000; Myatt et al., 2002) and schools (Shendell et al., 2004).

Air conditioning: Seppänen and Fisk (2002) reviewed multiple studies and reported that relative to natural ventilation, air conditioning with or without humidification was consistently associated with a statistically significant increase in the prevalence of one or more SBS symptoms. This occurrence is most likely related to the fact that air conditioning involves collecting moisture within the ventilation system, which can foster biocontamination. That conclusion was confirmed by a multidisciplinary team of scientists that also reported increased SBS symptoms with inadequate HVAC maintenance (Wargocki et al., 2002b).

Effect of VOC sources: The presence of known indoor sources of VOCs has been shown to decrease various measures of work performance. They include a 20-year-old carpet from a complaint building (Wargocki et al., 2002a), personal computers equipped with cathode ray monitors (Bako-Biro, 2004), and a 6-month-old particle filter (Wargocki et al., 2004). Although VOCs were not measured in these studies, these items are known sources of VOCs, and the results are consistent with other studies showing improved performance with increased ventilation.

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[7] Ibid.

Moisture-Related Biocontamination

Damp buildings tend to support the growth of mold and bacteria on indoor surfaces. Spores and other fragments released by this microbial growth becomes airborne and subject to being inhaled. The particles often contain allergens, creating adverse health consequences in people who experience an allergic response. In addition, molds and bacteria produce toxic chemicals that have the potential to adversely affect immune or central nervous system functions or produce musty odors.

Dust mites, which are microscopic arthropods, release allergenic particles in the air and feed on skin flakes and other organic material. They are often found in bedding and upholstered furniture. Since dust mites absorb rather than drink water, they depend on a relative humidity above approximately 50 percent to survive (Hart, 1998); Arlian et al., 1999).

Approximately 47 percent of homes are estimated to be sufficiently damp to result in respiratory affects in those exposed and are estimated to be responsible for 21 percent of current asthma cases in the U.S. (Mudarri and Fisk, 2007). Moisture and dampness in schools and office buildings are also associated with respiratory effects in occupants (Mudarri and Fisk, 2007).

Communicable Respiratory Diseases

Building O&M procedures can affect disease transmission in buildings. For example, lower ventilation rates and improper airflow directional control may lead to higher airborne disease transmission particularly in hospitals, schools, and other high-occupant-density buildings such as barracks. Transmission may also occur through contact, either direct contact with infected persons or indirect contact by touching common surfaces such as doorknobs, drinking fountains, phone handles, and computer key boards. Policies that encourage the isolation of infected individuals (e.g., telecommuting when sick) and building maintenance practices (e.g., clean and disinfect common surfaces regularly) can help limit transmission, as can avoidance of overcrowded conditions. The potential for disease vectors (e.g., rodents, insects, arthropods, birds, fungi) to enter and proliferate in buildings can be mitigated by blocking their entry points, minimizing their dispersal potential, removing their access to food and water, minimizing areas of potential harborage, and undertaking similar “integrated pest management (IPM)” maintenance activities.

Chapter 2: Climate Change Impacts on the Outdoor Environment

Chapter Overview

This chapter provides an outline summary of climate change impacts on the outdoor environment, focusing on the aspects that have the greatest implication for altering indoor environmental quality. The chapter covers both gradual and episodic impacts For example, a gradual rise in mean temperature or precipitation will be accompanied by episodic extreme weather events such as heat waves, storms, and heavy precipitation that are expected to be more intense and occur more frequently.

Summary Outline of the Impacts of Climate Change on the Outdoor Environment

A recent U.S. government report (USGCRP, 2009) provides a useful summary of anticipated impacts of climate change. Major findings relevant to indoor environmental quality are paraphrased below.

Mean Temperature Will Rise

- The global warming observed over the past 50 years is due primarily to human-induced emissions of heat-trapping gases.

- Warming over this century is projected to be considerably greater than over the previous century. The global average temperature since 1900 has risen by about 1.5 ºF. It is projected to rise another 2 to 11.5 ºF by 2100. By the end of this century, the average U.S. temperature is projected to increase by approximately 7 to 11 °F under high emissions scenarios and approximately 4 to 6.5 °F under low emissions scenarios.

- The U.S. average temperature has risen by a comparable amount and is very likely to rise more than the global average over this century, with some variation from place to place.

- Increases at the lower end of the range are more likely if global heat-trapping gas emissions are cut substantially. If emissions continue to rise at or near current rates, temperature increases are more likely to be near the upper end of the range

Humidity and Drought Conditions Will Change

- Atmospheric conditions in northern regions will change from very cold and dry to warmer and more humid. Alaska, the Great Plains, the upper Midwest, and the Northeast are beginning to experience such changes for at least part of the year, and it is likely these changes will increase over time.

- Droughts are likely to become more frequent and severe, particularly in the Southwest.

Heat Waves Will Be More Frequent, More Intense, and Last Longer

- Parts of the South that have about 60 days per year with temperatures over 90 °F are projected to experience 150 or more days a year above 90 °F by the end of this century.

- Heat events that now occur once every 20 years are projected to occur about every other year in much of the country by the end of this century.

- In addition to occurring more frequently, at the end of this century these very hot days are projected to be about 10 °F hotter than they are today.

- The number of heat-wave days in Los Angeles is projected to double by the end of this century and the number in Chicago is projected to quadruple if greenhouse gas emissions are not reduced.

Heavy Precipitation Events Will Increase in Intensity

- Precipitation has increased an average of about 5 percent over the past 50 years. Projections of future precipitation generally indicate that northern areas will become wetter and southern areas, particularly in the West, will become drier.

- The amount of rain falling in the heaviest downpours has increased approximately 20 percent on average in the past century, and this trend is very likely to continue with the largest increases in the wettest places.

- Widespread increases in heavy precipitation events have occurred, even where total rain amounts have decreased. These changes are associated with the fact that warmer air holds more water vapor evaporating from the world's oceans and land surface.

- Heavy downpours that are now 1-in-20-year occurrences are projected to occur about every 4 to 15 years by the end of this century, depending on location.

- The intensity of heavy downpours is expected to increase. The 1-in-20-year heavy downpour is expected to be between 10 and 25 percent heavier by the end of the century.

Storms Will Likely Become More Intense

Hurricanes

- The destructive energy of Atlantic hurricanes has increased in recent decades. The intensity of these storms is likely to increase in this century.

- In the eastern Pacific, the strongest hurricanes have become stronger since the 1980s, even while the total number of storms has decreased. However, storms in this region that reach land are rare compared to those that reach landfall along the East Coast and Gulf Coast of the United States.

Snowstorms

- Cold-season storm tracks are shifting northward, and the strongest storms are likely to become stronger and more frequent if that northward shift continues as projected. The stronger, more frequent cold-season storms also are likely to result in greater wind speeds and more extreme wave heights in northern areas (e.g., the Northeast and upper Midwest).

- Lake-effect snow storms in the Great Lakes region are likely to increase (less ice coverage induces greater lake evaporation and hence heavier snow fall) causing potentially heavy snow storms such as that experienced in February 2007 in western New York State.[8]

Sea Level Will Rise

- Global sea levels will rise due to glacier melting and water expansion due to warming. However, geological forces may cause coastlines to sink (subsidence) or rise (uplift), creating differential impacts.

- During the past 50 years, large parts of the Atlantic Coast and Gulf Coast have experienced significantly higher rates of relative sea level rise than the global average due to subsidence. However, portions of the Northwest and Alaska coasts have experienced slightly falling sea level as a result of long-term uplift.

- Assuming historical geological forces continue, a 2-foot rise in global sea level (within the range of recent estimates) by the end of this century would result in a relative sea level rise of 2.3 feet at New York City, 2.9 feet at Hampton Roads, Va, 3.5 feet at Galveston, Texas, and 1 foot at Neah Bay in Washington State.

- Sea level rise will increase risks of erosion, storm surge damage, and flooding for coastal communities, especially in the Southeast and parts of Alaska.

Forest and Grass Fires Will Be More Frequent and More Widespread

- In western United States and Alaska, earlier snowmelt and higher spring and summer temperatures have increased the frequency of large fires and extended the fire season as these conditions reduce available moisture. This trend is expected to continue.

- Deserts and dry lands in the arid Southwest and elsewhere have become hotter and drier, and this trend is expected to continue. Deserts are also projected to expand to the north and east, and upward in elevation.

- Increased drought conditions have and will continue to encourage non-native grasses to invade the Southwest and will provide fuel for fires, which are expected to increase in frequency and intensity.

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[8] However, the heavy precipitation is projected to eventually fall as rain rather than snow with increased warming in the long term.

Pathogenic and Allergenic Diseases May Increase with the Potential for Mass Outbreaks

- Longer and warmer growing seasons with less extreme cold in winter creates opportunities for many parasites and disease-carrying insects to flourish.

- For some species, rates of reproduction, population growth, and biting tend to increase with increasing temperatures. Some parasites' development rates and infectivity periods also increase with temperature.

- Unforeseen ecological changes could result in massive dislocations of species or in pest outbreaks.

- With global trade and travel, disease flare-ups in any part of the world, particularly in poorer nations, brought about by climate change can potentially reach the United States, where extreme weather events could undermine public health infrastructure, creating increased population vulnerability.

- Rising temperatures and carbon dioxide concentrations increase pollen production and prolong the pollen season in a number of plants with highly allergenic pollen, presenting a health risk.

- With stresses on infrastructures related to public health, disease transmission from food, water, and insects is likely to increase.

Outdoor Air Quality Will Worsen

- A warmer climate is projected to increase the natural emissions of VOCs, accelerate ozone formation, and increase the frequency and duration of stagnant air masses that allow pollution to accumulate.

- Increased temperatures and water vapor due to human-induced carbon dioxide emissions have been found to increase ozone more in areas where concentrations are already elevated, meaning that global warming tends to exacerbate ozone pollution most in already polluted areas.

- With constant pollutant emissions, Red Ozone Alert Days (when the air is unhealthy for everyone) in the 50 largest cities in the eastern United States are projected to increase by 68 percent due to warming alone, by the middle of this century.

Infrastructure Will Be Damaged and Adaptation Made Difficult

- The projected rapid rate and large amount of climate change over this century will challenge the ability of society and natural systems to adapt. For example, it is difficult and expensive to alter or replace infrastructure designed to last for decades (such as buildings, bridges, roads, airports, reservoirs, and ports) in response to continuous or abrupt climate change.

- Adaptation will be particularly challenging because society will be adapting to a rapidly moving target, not to a new steady state. Climate change will be continual and occur at a relatively rapid rate, outside the range to which society has adapted in the past.

Chapter 3: Impacts of Climate Change on Indoor Environmental Quality and Implications for Public Health

Chapter Overview

This chapter couples the impacts of climate change on the outdoor environment from Chapter 2 with the factors that influence indoor air quality from Chapter 1 to characterize the likely impacts of climate change on indoor environmental quality. The material covered in Chapters 1 and 2 are delineated in more detail as needed to more fully characterize these impacts of climate change.

Impacts of Climate Change on Indoor Temperature and Outdoor Air Ventilation

Overview

In the absence of a wise policy or other social intervention, it is likely that increased outdoor temperatures, rising energy prices, and the need to reduce greenhouse gas emissions will foster a cycle of self-reinforcing behavior changes that will continually degrade indoor environmental quality. Higher indoor temperatures and humidity will increase use of air conditioning and substantially increase electricity demand. However, increased generation of electricity increases emissions of greenhouse gases, which accelerate the trend toward rising temperatures. Countering this trend toward greater electrical generation are the substantial disruptions to power generation and distribution created by other climate change impacts, particularly during extreme weather events. Both factors—increased demand and interruptions in supply—are expected to raise energy prices and result in unmet needs for cooling indoor environments. Higher energy prices and the desire to limit greenhouse gas emissions will likely encourage individuals and public policy toward greater energy conservation through reduced ventilation in buildings. Less comfort, reduced productivity, and increased SBS symptoms are likely to result.

The Importance of Temperature Control for Good Indoor Environmental Quality

It is well known that exposure to extreme temperatures, especially for extended periods, can have significant health consequences. Less well known is how important temperature control in the mid-temperature range is for comfort and productivity, although complaints of it being “too hot” or “too cold” are the most frequently logged complaints in commercial buildings.

Moderately high temperatures have been associated with poorer perceptions of indoor air quality (Bergland and Cain, 1989; Fanget al, 1998) and with higher rates of unsolicited occupant complaints (Federspiel, 1998). Poor perceived indoor air quality (as well as temperature itself) are in turn also associated with SBS and lost productivity (Seppänen and Fisk, 2005). In addition, there is evidence of increased respiratory effects resulting from higher temperatures. This was a surprising but predominant effect measured in a study of the affect of particles on office workers (Mendell et al., 2002).

The importance of temperature control on productivity is summarized in LBNL (undated), in which a formal statistical analysis of 24 studies (Seppänen et al., 2005) was used to assess the average relationship between temperature and performance of work. While there may be considerable uncertainty in generalizing specific productivity figures, the LBNL analyses show an "inverted U" shaped relationship in which productivity is generally highest when the air temperature is in the midrange of approximately 68 – 72 °F and falls continuously as the temperature deviates from that range in either direction, so that at 59 °F and 87 °F, productivity is diminished by 10 percent from the maximum. Since wages in general are approximately 100 – 200 times building operating costs in office buildings, it makes economic sense to invest in building maintenance or upgrades as needed to maintain occupant productivity.

Thus, it is not only important for public health to protect occupants from extreme heat, it is also important for economic reasons to maintain temperatures at moderate levels where occupants are comfortable and productive. Certainly, any increase in temperatures beyond what is considered comfortable will increase the demand for air conditioning and, consequently, the demand for electricity. While there may be serious questions about the nation's ability to satisfy power needs from increased air conditioning use during extreme heat events (see below), the capacity of air conditioning systems themselves will likely be strained in northern climates such as New England, where air conditioning penetration is still low; these areas may experience the largest indoor environmental problems from the increase in mean climate temperatures.

In addition, VOCs are released from materials and products inside buildings more rapidly at higher temperatures. Thus, if occupants are too warm, it is likely they are also being exposed to higher levels of indoor pollutants.

Indoor temperatures are controlled by the HVAC system. How well the temperature is controlled depends on the capacity and operating parameters of the system and on the heat gains and losses in the space being controlled. Indoor humidity conditions are analogous to indoor temperature as they depend on moisture gains and losses and on the HVAC system's capacity to control humidity. Like heat, increased outdoor humidity is also associated with climate change. Unlike heat, however, excess humidity carries the potential for unintended condensation on cooled indoor surfaces, including hidden surfaces within the building fabric, and thereby creates conditions conducive to mold growth and other forms of biocontamination.

All of these considerations raise the issue of whether building O&M in the U.S. will be adequate to maintain appropriate indoor climate conditions. As is discussed below, this issue may be highly problematic given the presence of climate change and the lack of a clear focus on indoor air quality by climate change policy. One encouraging sign is that many buildings in the U.S. may currently be overcooled (Mendel and Mirer, 2009) leaving room for increased outdoor temperature conditions to increase indoor temperatures without extra cooling.

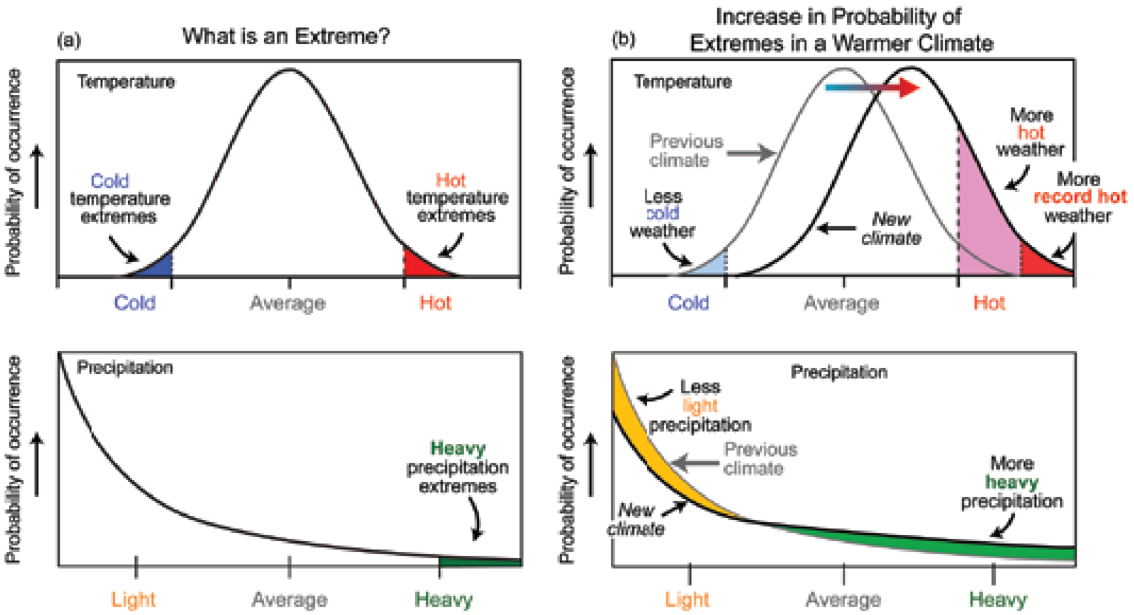
The Impact of Heat Waves on Indoor Environments

Of more acute concern is the likelihood that heat waves will increase in frequency and intensity. The frequency of extremely high temperatures (e.g., above the current 90th percentile) is likely to increase more dramatically than median or average temperatures. This situation is best illustrated by the bell shape of a temperature distribution curve, as shown in Figure 3.1.

Heat waves are an important public health threat. When the body is stressed in its ability to maintain internal thermal control, heat cramps, heat exhaustion, and heat stroke, in order of severity, can be the result. A variety of other adverse health conditions can also result. They include painful muscle cramps, dizziness, fainting, nausea and vomiting, heavy sweating, rapid pulse, high body temperature, and unconsciousness. Mortality rates during heat waves can also increase substantially. Populations that are likely to suffer most from excess heat include the elderly, very young infants, , and those taking certain medications or under the influence of drugs or alcohol. Persons with impaired mobility or mental disabilities may be less able to find coool environments. Low-income individuals are also vulnerable due to the lack of medical services and limited opportunities to keep cool (EPA, 2006).

The number of deaths from extreme heat can be quite high. For example, during the 2003 heat wave in Western Europe, France alone experienced over 15,000 deaths. In the United States, Philadelphia experienced 120 deaths from the 1993heat wave in, while 700 deaths in Cook County Illinois were attributed to the 1995 heat wave.

Figure 3.1: Impact of Gradual Temperature Increases on Extreme Temperature Events



Source: U.S. Climate Change Program. Synthesis and Assessment Product 3.3, June 2008

The data also suggest that people in the Northeast and Midwest appear to be more vulnerable than those in the Southeast and South, presumably because people in southern regions are more acclimatized and buildings are more equipped to deal with extreme heat (EPA, 2006). Thus, as extreme heat events move northward into areas where air conditioning is not widely used, people living in those areas will be most vulnerable in the short term. Over time, greater use of air conditioning in these areas can be expected.

Recommended Public Health Responses to Heat Waves

The generally agreed upon recommended public health response to extreme heat events is a notification and response program. Recommendations include establishing air-conditioned public spaces, establishing a public notification and education system to warn and advise the public of the risks and appropriate actions to take, and identifying and targeting at-risk individuals for interventions (EPA, 2006).

These recommendations do not address the structural issues of equipping indoor environments to shelter the population during such events. Serious disruption to people's lives and to the economy will likely result as a consequence of the inability of buildings to perform their most basic function: to shelter people from the outdoor environment and to provide healthy and productive living environments. Cooling indoor environments from excessive heat is a public health issue that will call for increased use of air conditioning, but there are serious problems that the nation will likely face in trying to satisfy that public health need.

Ability to Satisfy Increased Demand for Air Conditioning May Be Severely Constrained

Impact of Mean Temperature Rise on Electricity Demand and Supply

The gradual increase in outdoor temperatures, which are expected to rise by 4 – 11 °F by the end of the century, will call for substantial increases in air conditioning. How much of an increase can be measured in part by changes in the number of cooling degree-days expected in different regions.

A recent U.S. government report (USGCRP, 2009a) provides a useful summary of research in this area[9]. Figure 3.2, taken from that report, shows how cooling degree-days are expected to increase, while heating degree-days are expected to decline as a result of climate change. Since cooling uses electricity while heating uses mostly natural gas and little electricity, the demand for electricity is expected to increase.

Research on the impact of climate change on energy use suggests that the demand for cooling energy increases from 5 percent to 20 percent—and the demand for heating energy drops by 3 percent to 15 percent—for every 1 °C (1.8 °F) increase in outdoor temperature. This change would translate to a 10-percent to 120-percent increase in electricity use by the end of the century, assuming current technology. These studies do not account for the increase in energy used by air conditioning to remove the excess moisture that is also expected to accompany climate change, so that this is a conservative estimate. On the other hand, it is highly likely that greater efficiencies will be achieved over time and that some "natural conditioning" using different construction techniques to keep buildings cool will be employed. Nevertheless, significant increases in electricity demand for cooling can be anticipated, which in turn will create a corresponding demand for increased electric power generation and increased power generation capacity. The demand for electricity to power air conditioning will exceed the capacity to generate that electricity in areas where the ability to maintain cool indoor temperatures is particularly problematic.

Stresses on power generation could be substantial. For example:

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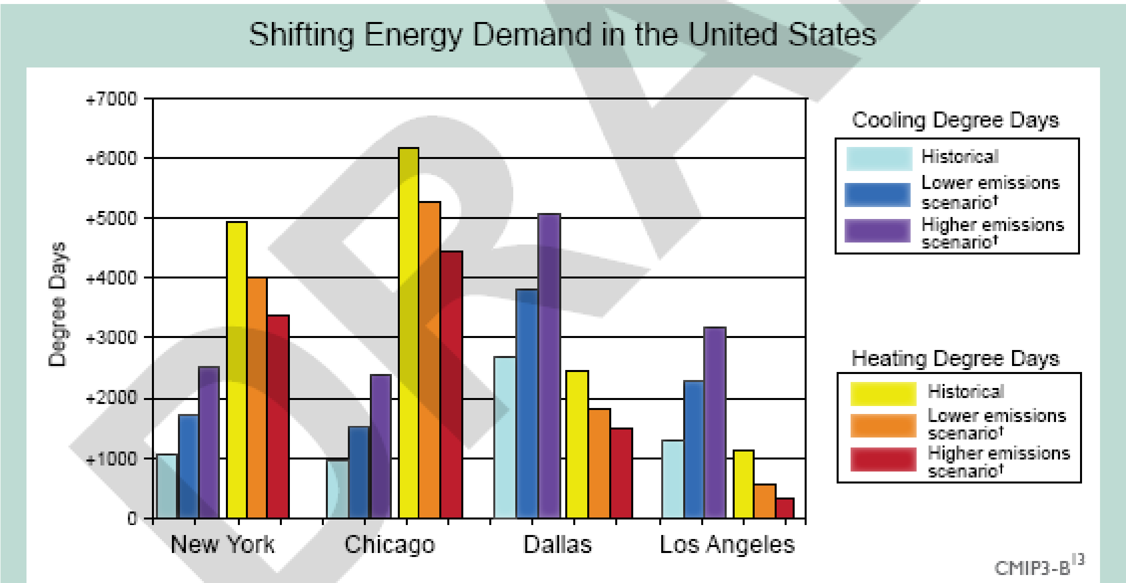
[9] This section borrows heavily from the analysis in this report.



"Degree days" are a way of measuring the energy needed for heating and cooling by adding up how many degrees hotter or colder each day's average temperature is from 65°F over the course of a year. Colder locations have high numbers of heating degree days and low numbers of cooling degree days, while hotter locations have high numbers of cooling degree days and low numbers of heating degree days. Nationally, the demand for energy will increase in summer and decrease in winter. Cooling uses electricity while heating uses a combination of energy sources, so the overall effect nationally and in most regions will be an increased need for electricity. The projections shown in the chart are for late this century.

Source: USGCRP (2009a)

Stresses from water shortages: It is likely that water shortages will limit power production in many regions. Electricity production uses almost as much fresh water as irrigation in the U.S. Water shortages in parts of the South (Florida, Louisiana, Georgia, Alabama), parts of the Southwest (Arizona, Texas), and the West/Northwest (Utah, California, Oregon, and Washington State) are expected to constrain electricity production. These and other areas where demand for water increases due to drought, expanding populations, or other reasons may also find it difficult to increase electricity production. Energy will also be needed to move and manage water resources during these scarcities, further straining the availability of electric power to satisfy air conditioning demands.

Hydropower generation is sensitive to the amount of water available and the timing of its availability. Changes in water availability patterns from climate change could therefore significantly hinder hydropower generation and affect areas such as the Northwest, where hydropower is a significant source of electricity. Changes in the timing and amount of flow have already been experienced due to reduced snowpack, melting glaciers, and earlier peak runoff. This trend is expected to continue. In addition, warming is expected to cause more rapid evaporation of reservoirs, particularly in sunny arid areas. Thus, the availability of electricity to fully satisfy indoor environmental needs in these areas is problematic.

Stresses from sea level rise: A good deal of the U.S. energy infrastructure is located in coastal areas, particularly along the East and Gulf Coasts. These areas are particularly vulnerable to sea level rise because of their topography., They also are subject to hurricanes. Electric power plants in these areas are vulnerable, as plants that process natural gas, which is used for electricity generation. Approximately 20 percent of natural gas production is located in the Gulf Coast region. Sea level rise in the Gulf is expected to reach as high as 2 – 4 feet by the end of the century. In addition to sea level rise, major hurricanes and storm surges can wreak havoc on these facilities, as was experienced during Hurricane Katrina.

Stresses from extreme weather events: Extreme weather events could lead to dramatic increases in peak demand for electricity that result in long-lasting supply interruptions. For example, as the average temperature increases, the frequency of what are currently considered extreme temperatures increases dramatically. These are the times of peak demand,[10] when existing energy infrastructure is strained to meet demands for cooling. It is expected, therefore, that the frequency of events where power is not available to satisfy indoor environmental quality needs will dramatically increase.

In addition to extreme temperatures, heavy rains and local flooding can interrupt coal transport to power plants via rail that often follow riverbeds in the Appalachian region. Extreme weather events including heavy rains and snowstorms, which are predicted to increase in intensity, can damage the power grid over large areas of the country. For example, the number of significant weather-related disturbances in the U.S. electric grid has increased tenfold since 1992. These disturbances do not include local disturbances from downed power lines, which cause the majority of power interruptions to end users and may also be expected to increase.

The Shift from Heating to Air Conditioning Increases Greenhouse Gas Emissions

The residential and commercial building sectors' use of energy accounts for approximately 38 percent of the carbon emitted to the atmosphere in the U.S. (9 percent of global fossil fuel-related emissions). These emissions are predicted to rise by 50 percent by 2030, absent any impact from climate change. However, climate change will exacerbate this trend, as the major energy needs in buildings shift away from heating, where natural gas is the major fuel source, to air conditioning, which uses electricity generated to a large extent by burning coal. Since about 50 percent of electricity is generated by burning coal, a high-carbon fuel, and since it takes over 3Btu of energy input for every Btu of delivered electric energy (including transmission losses), the shift in energy usage toward electricity will increase CO_2 emissions in what amounts to a potentially destructive negative feedback loop.

Pressures for Reduced Ventilation to Reduce Energy Use are Likely

Given the large role that buildings play in greenhouse gas emissions and the potential for climate change itself to foster even greater emissions, there is little doubt that the building sector will be called upon to reduce energy usage. This, too, will likely place great stress on indoor environmental quality with significant public health consequences, as described below.

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[10] Increases in peak energy demand would require a disproportionate increase in energy infrastructure investment (Scott, et al.). Linder and Inglis (1989) predicted that between 2010 and 2055, climate change could require investments of $200 billion – $300 billion ($1990).

Reducing Ventilation Saves Energy

While there are some important misconceptions about the energy cost of ventilation, there is no denying that reducing ventilation rates can significantly reduce energy use during outdoor temperature extremes because of the expense of treating outdoor air to satisfy indoor thermal requirements. The opposite may be true, however, during mild weather when the outdoor air is closer to the desired indoor conditions than is the existing indoor air.11

Historically, the challenge to reduce energy use in buildings has been met, in part, by reducing outdoor air ventilation rates. For example, as energy prices rose during the 1970 Arab Oil Embargo and the desire to save energy became widespread, building envelopes were tightened, much more energy efficient windows were introduced, and ventilation was curtailed to avoid having to use energy to "condition" the ventilation air. In 1981, ASHRAE significantly reduced the required ventilation rates in buildings in response to energy conservation needs. The result was a wave of occupant complaints and litigation about building-associated illnesses.

Pollutant emissions indoors increase with the number of occupants because of the bio-effluents of occupants and because of the emissions from the products that occupants use. Therefore, the ventilation rates required for indoor air quality in buildings rises with increased occupant densities. Thus, schools and other high-occupant-density buildings require higher ventilation rates than office buildings or homes, and the per-square-foot energy costs for ventilation to maintain adequate indoor air quality in these buildings will be considerably higher (Mudarri et al., 2000).

Economic and Public Policy Pressures to Reduce Ventilation Will Develop

The response to the energy crisis in the 1970s stands to be repeated in response to climate change unless the public health consequences of indoor environmental quality receive far more attention. Because the energy costs of ventilating high-occupant-density-buildings are high, schools and similar buildings are particularly vulnerable to pressure to reduce ventilation rates. They also have the greatest financial incentive to do so. This situation could create serious problems for school children. Climate change policy would be wise to include provisions to reduce energy use while maintaining adequate ventilation for indoor environmental quality.

Outdoor Air Ventilation and Public Health

In an occupied enclosed space without any ventilation, the concentration of pollutants emitted from indoor pollutant sources, including people themselves, will continually rise to dangerous levels. This is why outdoor air ventilation is so important to public health.

As discussed elsewhere, ventilation dilutes contaminants generated indoors so that, in general, pollutant concentrations from indoor sources are inversely proportional to the outdoor air ventilation rate. This fundamental fact is likely behind the previously described historical experience of the United States and Europe, where reducing building ventilation rates in an attempt to save energy led to a sharp increase in occupant complaints. Subsequent studies confirm the adverse effect of low ventilation rates on occupants. For example:

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[11] The economizer operation of commercial HVAC systems uses the cooler outdoor air to help cool the indoor environment without using air conditioning. This technique typically is called "free cooling."

In homes, low ventilation rates are associated with increases in formaldehyde and VOCs (Emenius et al., 2004), increased risk of bronchial obstruction caused by other conditions such as dampness (Oie et al., 1999), increased allergy symptoms (Bornhag et al., 2005), and asthma (Emenius et al., 2004; Norback et al., 1995).

In offices and schools, low ventilation rates are associated with degraded perceptions of indoor air quality (Wargocki et al., 2000; Seppänen et al., 1999), increased symptoms of sick building syndrome (Seppänen et al., 1999; Wargocki et al., 2002; Mendell,et al., 2005; and Fisk et al., 2009), increased absences (Shendell et al., 2004; Milton et al., 2000), decreased performance and productivity (Wargocki et al., 2002a, 2004; Bako-Biro et al., 2004; Seppänen et al., 2006), and decreased performance in school work (Wargocki and Wyon, 2007, 2007a), possibly including reduced test scores (Schaunessey et al., 2006).

In high-occupancy buildings (nursing homes, barracks, jails), low ventilation rates are associated with higher rates of respiratory illnesses (Seppänen et al., 1999; Brundage et al., 1988; Hoge et al., 1994; Drinka et al., 1996) and, in hospitals, with increased transmission of infectious diseases (Li et al., 2005, 2007).

While scientific documentation of these effects is still emerging, taken together, available evidence provides a compelling case for maintaining ventilation rates in buildings as a matter of public health.[12]

Ventilation Strategies to Protect Indoor Environmental Quality Are Needed

Unless adaptation strategies are implemented, the warming and increased humidity brought about by climate change will increase the energy cost of ventilating buildings, which is critical to maintaining good indoor environmental quality. Such strategies could include increasing the energy efficiency of equipment, employing ventilation strategies that use less energy (e.g., separating outdoor air delivery from heating and cooling airflow requirements, or employing more natural ventilation[13]), adopting ventilation strategies that are more efficient in removing contaminants (e.g., displacement ventilation, increased exhaust ventilation), or strategically integrating more air cleaning into the ventilation system. In addition, a major effort to reduce pollutant emissions from products and materials used in a building would go a long way in reducing the need for ventilation in order to maintain adequate indoor air quality to protect public health.

Some of these strategies, such as using displacement ventilation or natural ventilation, might be feasible only in new building construction, while others, such as separating the outdoor air flow from heating and cooling air flow requirements and more strategic use of exhaust ventilation, might be feasible through expensive remodeling efforts. Still other strategies, such as increasing the energy efficiency of equipment or incorporating ERVs or air cleaning devices might be implemented by retrofitting existing equipment. Each of these strategies becomes more cost-effective as energy prices rise.

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[12] See the IAQ Scientific Findings Resource Bank (SFRB), for a useful summary of this evidence. Available through http://www.epa.gov/iaq/largebldgs/index.html or directly at http://www.iaqscience.lbl.gov/.

[13] Natural ventilation makes building occupants particularly vulnerable to outdoor air pollution. This topic is discussed separately in this report.

Reducing Outdoor Air Ventilation during High Pollution Episodes

As indoor air is exchanged with outdoor air, the indoor concentration of a pollutant will eventually equal the outdoor air concentration plus contributions from indoor sources. For this reason, it is often stated that in the long run, the outdoor air acts as the background for indoor air pollution, to which emissions from indoor sources are added. Thus, if climate change results in increased outdoor pollutant concentrations over extended periods, this increased pollution will ultimately find its way indoors, unless the outdoor ventilation air is cleaned prior to entering the building. Cleaning the air, however, will require additional energy, so the relationship between ventilation, air cleaning, indoor air quality, and energy use may become extremely important in developing strategies to protect public health from climate change.

If outdoor pollutant levels rise in episodic events, it is possible to lower the outdoor air ventilation rates temporarily to protect the indoor environment. This strategy would take advantage of the fact that the indoor concentration from indoor sources takes time to rise toward a new higher steady state level as the ventilation rate is reduced.[14] If the episode is brief, this strategy could be useful. The only other alternatives would be to reduce indoor source emissions and provide additional air cleaning for both indoor air and outdoor air. Additional air cleaning and reduced source emissions would each allow for reduced ventilation rates while protecting indoor air quality.

Some outdoor contaminants have greater public health consequences than others. Ozone, for example, can have particularly significant public health consequences indoors for a variety of reasons. But temporarily reducing outdoor air ventilation to reduce ozone exposuremay not be advisable, as discussed below in the section on indoor chemistry.

Indoor Chemistry Effects from Outdoor Ozone

Overview

Tropospheric ozone is the product of atmospheric chemistry in which reactive VOCs interact with oxides of nitrogen in the presence of sunlight to produce photochemical smog, including ozone. Higher temperatures contribute to this process by increasing the levels of ozone produced. Thus, climate change is expected to increase tropospheric concentrations of ozone.

Ozone is known to react with many VOCs found indoors to create a variety of chemical byproducts that have potentially troubling adverse health consequences. Emerging research suggests that with increased ozone concentrations outdoors, the adverse health consequences from indoor chemical reactions could present a significant unanticipated public health issue.

Increased Ozone from Climate Change

In a recently published study (EPA, 2009), EPA summarizing results from several modeling studies and reported the following:

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[14] Levels of outdoor pollution will ultimately become background levels of indoor pollution to which indoor generated pollutants are added. If outdoor levels are constant, and the indoor emission rate is constant, and the indoor air starts out with a zero contaminant level, the indoor air concentration of the contaminant will gradually rise toward its steady state value, achieving 95 percent of the steady state value in h=3/ach where h = hours and ach is the air change rate (see Mudarri, 1997). In a typical home with an air change rate of 0.5, 95 percent of steady state is achieved in 6 hours. By lowering the ventilation rate so that ach is 0.33, the time is extended to 9 hours.

- Climate change has the potential to produce significant increases in near-surface ozone concentrations throughout the United States.

- For nearly every region of the country, at least one (and usually more) of the modeling groups found that climate change caused increases in summertime ozone concentrations.

- Where these increases occur, the amount of increase in the summertime average Maximum Daily 8-hour Average (MDA8) ozone concentrations across all the modeling studies tends to fall in the range of 2 − 8 ppb.[15]

- These results suggest a possible extension of the ozone season into the late spring and early fall in some regions of the U.S.

- Climate change has the potential to push ozone concentrations in extreme years beyond the envelope of current natural year-to-year variability

- A subset of results also suggests that climate change effects on ozone grow continuously over time.

- The largest increases in ozone concentrations in these simulations occur during peak pollution events. (For example, the increases in the 95th percentile of MDA8 ozone tend to be significantly greater than those in summertime-mean MDA8 ozone.)

That last point is particularly important. There is a strong relationship between temperature and the conditions that produce high ozone levels. Thus, the severity of a particular ozone episode will depend strongly on temperature and other meterological conditions (e.g., sunlight), many of which also tend to correlate strongly with temperature. Thus, long periods of summer heat and drought will likely produce high ozone concentrations, along with elevated levels of particulate matter, exacerbated in some regions by pollution from forest fires, from higher levels of pollen, and from elevated carbon dioxide. Since the rise in peak ozone levels is expected to be considerably more pronounced than the average rise, and since high ozone concentrations also tend to occur when concentrations of other pollutants are high, episodic events of high ozone concentrations will be of particular concern.

Indoor Chemical Reactions with Ozone

Recent studies have shown that indoors ozone can interact with chemical compounds in indoor air and on surfaces to produce elevated levels of many toxic compounds, including formaldehyde, and of fine and ultrafine particles that could potentially have profound impacts on public health. These reactions decrease the indoor level of ozone, while simultaneously increasing the levels of these secondary byproducts. This decrease in indoor ozone levels explains why indoor levels may be considerably less than those outdoors. But from a public health standpoint, the reduction in indoor ozone signals potentially more toxic byproducts. Indeed, the secondary byproducts from indoor chemistry resulting from elevated outdoor ozone levels may be partially responsible for elevated health consequences commonly associated with outdoor ozone and particulate matter during air pollution episodes (Weschler, 2006). Levin (2008) has called this situation “the big threat” to public health from climate change.

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[15] This represents 2 percent – 13 percent of the current (2008) NAAQS of 0.075 ppm.

Recent studies[16] indicate that ozone reacts with the constituents of carpet, cleaning products and air fresheners, paints (particularly the low-VOC paints which use linseed oil), building materials, and a variety of surfaces, including HVAC surfaces, to produce stable and unstable byproducts. Among the stable byproducts are compounds that are irritating and toxic. Formaldehyde and other aldehydes, acid aerosols, and fine and ultrafine particles are among the commonly found secondary byproducts. Of particular concern is the prolific use of cleaning products and air fresheners, in which selected terpenes (e.g., a-pinene, limonene, and isopropene) readily react with ozone. Studies suggest that such reactions produce substantial quantities of these secondary byproducts.

The unstable byproducts, such as the OH radical, can set off a cascade of chemical reactions that, depending on the indoor and outdoor air constituents, can produce further stable and unstable byproducts. The potential impact of these reactions on the public health is just beginning to be appreciated (Weschler, 2006).

Indoor Chemistry and Public Health

The adverse health effects of ozone are well known. When inhaled, ozone can damage the lungs. Relatively small amounts can cause chest pain, coughing, shortness of breath, and throat irritation. Ozone may also worsen chronic respiratory diseases such as asthma and compromise the body's ability to fight respiratory infections.[17] This is why health authorities advise the public to go inside during days of high ozone concentrations. But outdoor pollution generally acts as background pollution indoors unless the outdoor pollutants are captured (e.g., with an air cleaner or filter), adsorbed on indoor surfaces,[18] or transformed through chemical reaction. Since ozone is highly reactive, a number of different reaction sequences can produce other irritating and reactive byproducts, as well as a number of other chemical compounds that are harmful to building occupants. Thus, while ozone levels are lower indoors due to chemical transformations, occupants may be worse off as a result of exposure to secondary byproducts of ozone's reactivity.

Ventilation Strategies under High Outdoor Ozone Conditions

As described previously, when outdoor pollution levels are temporarily high, it may be advisable to reduce the outdoor air ventilation rate in order to protect the indoor environment. But if ozone is elevated outdoors, reducing the outdoor air ventilation rate will not only temporarily reduce indoor ozone levels but also increase the time for ozone reactive chemistry to take place indoors, potentially increasing the overall formation of byproducts while decreasing their dilution through ventilation (Weschler, 2001). Public health could therefore suffer adverse consequences from this strategy. More study of these issues is needed.

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[16] See for example Weschler (1992,2000,2004,2006,2007), Weschler and Shields (1997, 2004), Nazaroff and Weschler (2004), Morrison (2008), and Levin (2008).

[17] See for example EPA's publication *Ozone and Your Health* available at http://www.epa.gov/airnow/brochure.html.

[18] Many VOCs are adsorbed on indoor surfaces, particularly fleecy or porous materials. A major problem can occur when these VOCs are later emitted back into the indoor air as conditions change (e.g. during warm weather).

The movement toward green buildings has led to increased interest in natural ventilation. In general, natural ventilation has the potential to save energy and improve the health and comfort of building occupants. It thus becomes an attractive alternative to mechanical ventilation in response to climate change. But when outdoor ozone levels are elevated, natural ventilation increases the potential for high ozone levels indoors and elevated public health risks from indoor chemical reactions. Natural ventilation strategies will necessarily have to deal with problems of outdoor ozone levels in order to avoid these public health risks.

Mitigation of Indoor Chemistry Pollution is Feasible

Fortunately, the potentially significant impact of ozone on public health, both from direct exposure to ozone and from exposure to the byproducts of chemical reactions with ozone indoors, may possibly be avoided. One important strategy would have manufacturers change their product formulations to reduce the use of VOCs that readily react with ozone.

Other potential strategies include the use of air-cleaning systems to remove ozone and particles from ventilation air and from indoor air. However, filters used in HVAC systems may be a cause of concern when ozone levels are elevated. Filters continually collect dust particles containing VOCs that may react with ozone to create undesirable byproducts such as formaldehyde that is then delivered into the indoor spaces. In fact, formaldehyde has been shown to be a common product of reactive chemistry on filters (Hyttinen et al., 2006). Such phenomena also highlight the need for elevating building maintenance as part of the climate change strategies to protect public health in buildings.

The synthetic media of the filters themselves also appear to be a problem, as evidenced by analysis of EPA's data on commercial buildings. From 1994 to 1998 EPA collected comprehensive data on 100 randomly selected office buildings to foster analysis of indoor air quality problems' causes, consequences, and solutions. Analysis of these data by Lawrence Berkeley National Laboratory showed a relationship between air filter materials, ozone, and adverse health symptoms of building occupants (Buchanan et al., 2008). Relative to conditions of low ozone and a fiberglass filter medium, the use of polyester synthetic filter medium or high outdoor ozone was significantly associated with fatigue/difficulty concentrating. However, the combination of both high outdoor ozone and polyester/synthetic filter medium had a significant association with lower and upper respiratory irritation, cough, eye irritation, fatigue, and headache. These results suggest the possibility that proper filter medium selection could reduce adverse health symptoms from ozone. Further study is underway.

Charcoal or other chemical sorbents are currently being used to remove ozone within filtration systems, and the practice is suggested for use in high ozone areas. These systems require careful monitoring and diligent maintenance, also stressing the need for improvements in maintenance of buildings in the future.

Experiments with the use of ultra-violet photocatalytic oxidation (UVPCO) air-cleaning systems show promise for removing VOCs from indoor air and offer the opportunity to reduce outdoor air ventilation rates. These systems use ultra-violet light to promote indoor chemical transformations on the filter media . Experiments by Lawrence Berkeley National Laboratory demonstrate that such systems have the potential to significantly reduce VOC concentrations at relatively low cost (Hodgson et al., 2005). However, as with ozone transformations, incomplete oxidation of VOCs in this system was shown to produce formaldehyde and acedaldehyde byproducts. It was later shown that adding a scrubber with a chemisorbent to the system effectively removed the unwanted byproducts and, combined with the VOC removal rate of the UVPCO system, could potentially afford the opportunity for a 50-percent reduction in outdoor air ventilation (Hodgson et al., 2007).

Moisture-Related Impacts on Indoor Environments from Climate Change

Much of the dampness and mold problems in buildings result from inadequate control of moisture flows from rain, snowfall, or groundwater and inadequate control of humidity and condensation in the occupied spaces and within the building fabric. Given current building construction methods and level of maintenance, dampness and mold problems in buildings are already quite significant. Mudarri and Fisk (2007) report that almost half of U.S. homes have dampness and mold problems of the type that have been associated with respiratory symptoms. Girman et al. (2002) report that 85 percent of office buildings have had water damage in the past, while 45 percent report having current leaks.

These problems can have significant health consequences. For example, Fisk et al. (2007) conducted a meta-analysis of a number of studies concerning the relationship between dampness and mold in homes and respiratory symptoms. They concluded that damp and mold conditions in homes are associated with increases in respiratory and asthma-related health outcomes of approximately 30 percent to 50 percent. That the analysis was limited to studies in homes, in part, reflected the limitations of studies in other building types for such a meta-analysis. However, Mudarri and Fisk (2007) reviewed available studies in office buildings and schools and concluded that, while not sufficiently robust to draw definitive conclusions as was done in homes, the studies tend toward supporting the hypothesis of a strong association. Mudarri and Fisk (2007) estimate that dampness and mold in homes accounts for approximately 21 percent of asthma prevalence in the U.S.

Increased relative humidity from climate change will increase the moisture content of materials indoors and thus increase the risk of mold growth. These conditions will be exacerbated as periodic heavy rainfalls will likely stress the ability of buildings of all types to adequately manage excess water flow. The current prevalence of dampness and mold conditions in U.S. buildings already suggests a lack of proper building defenses against excess moisture flows. In the absence of increased maintenance and retrofit activity in the U.S. to control moisture, these problems could easily grow exponentially in the face of increased humidity, heavy rainfall, storms, and flooding. Local flooding along streams and rivers and flooding along the coastline in the East and Gulf Coast regions from storm surges and sea level rise will create additional problems. The rampant mold problems caused by flooding during Hurricane Katrina (Hamilton, 2005) provide ample evidence that mold issues could be a significant problem related to climate change.

Damage caused by flooding plus the abundance of water available to pests will likely increase opportunities to harbor them and increase the capacity of buildings to support pest infestations. (Cockroaches, for example, are primarily attracted to water sources and food debris.) This development could increase exposure to pest allergens, infectious agents, and to pesticides.

Some products have been shown to decompose in the presence of water, causing both health effects and the decomposition of building materials (Levin, 2008). For example, the decomposition of plasticizers commonly used in vinyl flooring and adhesives generates byproducts that may be associated with asthma (Norback et al., 2000).

Among other consequences of flooding are increased exposure to VOCs and formaldehyde in the temporary housing provided in flooded areas (DHHS, 2007). These houses have high levels of formaldehyde and VOCs from surface emissions, and their significantly higher surface-to-volume ratio increases indoor concentrations.

Given the variety of potentially serious bio-contaminants and other building pollution problems associated with heavy rains and flooding, a careful analysis of regional vulnerability to moisture intrusion into existing buildings, and an analysis of building practices to prevent such intrusions in new construction, would be worthwhile. In addition, widespread dissemination of guidelines for correcting dampness and mold problems in buildings, integrated pest management techniques, and revised specifications for temporary housing could help mitigate moisture-related public health consequences of climate change in buildings.

Ecological Shifts, Disease Vectors, Pests, and Increased Occupant Vulnerability to Indoor Environmental Conditions

Changes in the ecological balance brought about by climate change can alter the geographical distribution and biological cycle of many disease vectors, allowing the establishment of new breeding sites and bursts of disease carriers, thus posing significant disease risks to people. For example, the 1993 hantavirus outbreak in the southwestern U.S. resulted from the tenfold increase in the rodent population from May, 1992, to May, 1993, after rodent predators had suffered through six years of drought and the heavy spring rains that followed resulted in an abundance of rodent food (Epstein, 1995). Similarly, outbreaks of West Nile virus between 2001 and 2005 are correlated with increasing temperature and rainfall during that period, leading to the expectation that such outbreaks will accelerate with climate change. Girman et al. (2002) also draw attention to possible outbreaks of diseases such as dengue fever and possibly malaria as possible consequences of climate change (Hales et al., 2002; Rogers and Randolph, 2000).

There are three important indoor environmental quality issues associated with the spread of communicable diseases in buildings. All of them relate importantly to building maintenance. The first highlights the importance of maintaining adequate ventilation control. Lower ventilation rates and the improper directional control of airflow affects airborne transmission and are associated with higher disease transmission rates (Li et al., 2005, 2007). This is important in all buildings, but particularly in hospitals, schools, and other high-occupant-density buildings such as barracks and prisons where increased respiratory ailments have been associated with decreased ventilation rates (Seppänen et al., 1999; Brundage et al., 1988; Drinka et al., 1996; Hoge et al., 1994). Related to ventilation is the control of airflow from contaminated areas (especially in hospitals) that needs to be directed away from uninfected occupants.

The second environmental quality issue relates to transmission through contact, either direct contact with infected persons or indirect contact by touching common surfaces such as door knobs, drinking fountains, phone handles, and computer key boards. Policies that encourage the isolation of infected individuals (e.g., telecommute when sick), and building maintenance practices (e.g., clean/disinfect common surfaces regularly) can help limit transmission, as can the avoidance of overcrowded conditions.

Third is the potential for disease vectors (e.g., rodents, insects, arthropods, birds, fungi) to enter and proliferate in buildings. Reducing the pest-carrying capacity of buildings through proper maintenance reduces the potential for disease transmission from these vectors. Blocking entry points, minimizing their dispersal potential, removing access to food and water, minimizing areas of potential harborage, and similar IPM maintenance activities would reduce disease vectors indoors.

In addition to considering disease-carrying pests, Quarles (2007) provides a useful summary of potential impacts of climate change on populations of structural pests, crop pests, and forest pests. For example:

- Milder and shorter winters could increase the population and geographic distribution of pests such as ants, flies, wood-boring beetles, and termites.

- Increased population density and range of crop pests could create serious challenges. For example, increased temperature could extend the range of pink bollworm from Arizona and Southern California into the Central Valley of California, causing considerable crop damage.

- Higher nighttime temperatures will likely accelerate the growth rates of caterpillars such as the cabbageworm and increase damage from pest nematodes and the diamondback moth.

- Warmer winters will increase the survival rate of plant pathogens, and increased plant growth will likely increase pathogen density.

- The mountain pine beetle produces one generation per year compared. The range and extent of damage has already greatly increased in the Canadian pine forest. This beetle also populates the Rocky Mountains.

- As lower mountain slopes and peaks get warmer, plant, animals, and pests have migrated upwards, so that insects and insect-borne diseases are now being reported at higher elevations.

- Poison ivy is expected to grow more rapidly and with more potent toxin as carbon dioxide levels increase.

Increased Pesticide Exposure is Likely

An expected response to the proliferation of pests, particularly those that carry diseases that seriously affect human health or the health of plants and animals important to agriculture, is the increased use of pesticides and herbicides. In urban areas, for example, eradication programs are used to control pest infestations (e.g., mosquitoes that carry the West Nile Virus; Gypsy Moths). In agriculture, the spraying of pesticides is already common. Pesticides sprayed outdoors can find their way indoors through air exchange or can be brought in on clothing, skin, and especially on shoes. People living close to agricultural operations may be at particularly high risk. Urban dwellers where pesticides are commonly used may also be at elevated risk. Children are particularly vulnerable because they play in the dirt and on the floor (EPA, 1990). Building owners will likely respond to increased infestation (e.g., of rodents, ants, cockroaches) with the use of pesticides, adding to occupant exposure.

It is not clear what the long-term implications of increased human exposure to pesticides would be exactly, but it must be considered an important concern. The increased application of IPM techniques, which minimizes pesticide use in buildings (and in agriculture), would be an important avenue to pursue.

Potential Increased Population Vulnerability to Disease

Climate change is expected to deplete the upper stratospheric ozone layer and thereby increase exposure to ultraviolet (UV) radiation. This eventuality raises the potential for such exposures to suppress immune responses to various diseases and to vaccinations (de Gruijl et al., 2003), and it could leave the general population more vulnerable to disease outbreaks.

Implications

In general, buildings will be used as shelters to avoid exposure to disease vectors outdoors, to avoid excessive exposure to UV radiation, and to avoid extreme environmental events such as heat waves. This fact presents a particular challenge. If indoor environments are to be relied upon to protect the public, a paramount concern would be whether the indoor environment itself will be able to provide environmental conditions conducive to supporting the health and well-being of populations made more vulnerable by disease, UV radiation, and other environmental stressors, particularly in light of the stresses on building structures and building equipment capacity discussed in this chapter. A systematic review of this issue should be of primary concern to those planning strategies for adapting to climate change. Design strategies for new buildings in vulnerable locations, as well as the improved maintenance of existing buildings would be critical subjects of interest.

Chapter 4: Public Health Cost of Climate Change Resulting from Changes in Indoor Environments

Overview

This chapter provides a very rough estimate of the economic value of the public health impacts of climate change on indoor environments as described in Chapter 3. The estimates are limited to the economic value of the impacts on public health; they do not account for expenditures or other adaptations that may occur as society attempts to adjust to such impacts.

Purpose of a Quantitative Economic Assessment

The impact of global warming on the outdoor environment is reasonably robust in qualitative terms, but quantitative estimates are much more problematic. Similarly, while it is possible to describe in qualitative terms how climatic changes might affect indoor environmental quality, attempts to quantify those changes are destined to yield highly uncertain results. Therefore, the assessments provided here are of a very coarse grain. Their purpose is only to help determine whether the anticipated changes to indoor environmental quality are likely to be minor or major public health concerns, or somewhere in between, in order to help policy makers and researchers set priorities for further research and planning.

Methodology

The economic value of changes in public health, comfort, and productivity are estimated in terms of percentage increments to baseline public health costs of the current inadequacies of indoor environmental quality. The assessments are made first by establishing baseline public health costs and then by estimating a likely percentage change from that baseline due to specific climate change effects on the indoor environment. The total public health cost is estimated by summing the public health cost of specific climate change effects. Further, the public health costs that are calculated are limited to those solely related to the cost of public health impacts resulting from changes to indoor environmental quality; they do not include costs of mitigating or adapting to those changes.

Time Frame

Various government publications on climate change use different time frames to predict environmental impacts, but generally seem to adopt a perspective of somewhere between 50 years and the end of this century. This assessment uses the same general time frame.

Discounting

Since public health costs are evaluated over time, it is appropriate to discount future costs. There are three time frame issues to consider for this analysis. The first relates to situations in which a given health impact from exposure is delayed after an initial climate change effect occurs. The second relates to situations where exposure in the absence of climate change is expected to change over time. And the third relates to the fact that climate change itself does not happen all at once, but is expected to evolve.

- **Health impacts that are delayed:** Most health effects discussed below occur shortly after climate change alters exposure. The one exception for this analysis is the increase in premature deaths caused by long-term exposure to environmental tobacco smoke (ETS). Generally, premature death estimates are based on lifetime exposure, which for the purpose of this analysis is assumed to be 70 years.

- **Exposure that is expected to change independent of climate change:** The incidence of smoking is declining in the U.S., so it is assumed that exposure to ETS in the absence of climate change would gradually decline to 40 percent of its current level over a 25-year period.

- **Climate change effects evolve over time**. Climate change and its impacts are not expected to occur all at once but rather to evolve over time. For this analysis, a 75-year time frame is used to account for this effect.

The basic estimates of public health cost are first presented without discounting. Discounted values and adjustments for the final estimates are then made using discounts rates of 3 percent and 7 percent.

Estimating Baseline Public Health Costs of Current Indoor Environmental Quality Conditions

Some quantitative relationships between specific indoor environmental conditions and various measures of health, comfort, and productivity have been reported in the scientific literature. A few studies have also attempted to evaluate the economic cost of these impacts. Some of these studies, along with independent analyses, are used here to establish baseline effects of indoor environmental quality on public health and the associated economic costs. These baseline public health costs represent current conditions, absent any impact from climate change. It is assumed that baseline conditions in the absence of climate change would remain constant—except for exposure to ETS, which is expected to decline. These baseline impacts serve as the basis for assessing the incremental effects of climate change resulting from increased indoor exposure to risk factors for health, comfort, and productivity-related effects.

Considerations Related to Environmental Tobacco Smoke and Radon

ETS: As discussed below, recent estimates of the impact of ETS on a variety of health endpoints are substantial. However, public attitudes toward smoking and ETS exposure have been changing over the past decade, and smoking is becoming less prevalent. Smoking restrictions in public and commercial buildings also have served to reduce exposure to ETS. These trends are expected to continue to some extent. Therefore, it is assumed that the prevalence of smoking will decline in equal decrements over the next 25 years, from current levels of approximately 25 percent to 10 percent, and remain constant after that. In other words, it is assumed there will always be some minimum proportion of the population that smokes (in this case 10 percent) and ETS exposure will decrease in proportion to the decline in smoking.

Radon: According to current estimates, exposure to radon is responsible for 21,000 premature deaths each year (EPA, 2003). Radon is a colorless, odorless radioactive soil gas that enters buildings (mostly homes) through cracks and crevices in the foundation. How much radon enters a building depends on the radon concentration in the soil, the available paths for entry (e.g., cracks in the foundation), and the pressure difference between the indoors and the soil beneath the foundation. A negative pressure indoors relative to the soil will tend to draw radon gas into the building. The main potential impact on radon exposure from climate change is a reduction in ventilation, which would tend to increase concentrations of indoor contaminants. However, the impact of ventilation reductions on the pressure difference between the indoors and the soil are uncertain and could well neutralize or even reverse radon exposure. Therefore, climate change's impact on radon exposure is assumed to be negligible and is not included in this analysis.

Baseline Cost Categories

The categories of public health impacts from indoor environmental exposures for which baseline costs are estimated are exposures to ETS, heat waves, and exposures resulting in public health impacts related to sick building syndrome, allergies and asthma, and communicable respiratory illnesses. These are discussed below.

Baseline Public Health Costs from ETS Exposure

Baseline Rates of Mortality from ETS Exposure

In 1992, EPA published its risk assessment of ETS and declared it to be a class A human carcinogen responsible for approximately 3,000 deaths from lung cancer each year, and 150,000 to 300,000 lower respiratory tract infections (LRI) in infants and children under 18 months of age, resulting in 7,500 to 15,000 hospitalizations (EPA, 1992). The report did not cover the effects of ETS exposure on heart disease.

In 2005, the California Air Resources Board (CARB) provided updated information on the impacts of ETS exposure and health for California and the U.S. (CARB, 2005). The report included estimates of the effects of ETS exposure on heart disease and other impacts on children. It leaves the EPA estimate for LRI unchanged, updates the cancer impact to 3,400 deaths a year, and adds 46,000 (22,700 – 69,600) deaths from ischemic heart disease, 430 deaths from sudden infant death syndrome (SIDS), and 202,300 excess asthma episodes each year. These and other impacts reported by CARB are presented Tables 4-1a and 4-1b.

Table 4-1a: Attributable Chronic Mortality Effects Associated with ETS Exposure

Cardiac death (Ischemic heart disease deaths)	46,000 (range: 22,700 – 69,600)	Updated 2005
Lung cancer death	3,400	Updated 2005
SIDS	430	Updated 2005

Baseline Public Health Cost of Mortality from ETS Exposure

Economic valuation of increases or decreases in the risk of death associated with some activity are customarily based on the “value of a statistical life” (VSL). The VSL is derived from the value that the market places on a unit risk of death. The range of values from a number of meta-analyses is $1 million to $10 million per statistical death. The Office of Management and Budget recommends a default value of $5 million, although most agencies tend to use higher values.[19] EPA, for example, uses $7.4 million as a default value, although some EPA offices may use higher or lower values.[20] This analysis uses the EPA value of $7.4 million per statistical life.

Using updated figures from CARB (2005), premature deaths each year from cancer, heart disease, and SIDS associated with ETS exposure total 49,830, which when valued at $7.4 million each comes to $368.7 billion. By the end of the century, however, this amount would be reduced to 40 percent of that level, $147.5 billion, to account for the estimated decline in smoking.

Baseline Annual Mortality Costs from ETS Exposure: $369 billion (current) / $148 billion (future).

Baseline Public Health Cost of Morbidity from ETS Exposure

The chronic and acute morbidity effects of ETS exposure estimated by CARB (2005) are provided in Table 4-1b.

Table 4-1b: Attributable Chronic & Acute Morbidity Effects Associated w/ ETS Exposure

Outcome	Annual Excess #	Comment
Pregnancy		
Low birth weight	24,500	Updated 2005
Pre-term delivery	71,900	Updated 2005
Asthma (in children)		
# Episodes	202,300	Updated 2005
# New cases	8000 – 26,000	Conclusion in 1997
# Exacerbations	400,000 – 1,000,000	Conclusion in 1997
Lower respiratory illness	150,000 – 300,000	Conclusion in 1997
Otitis media visits	790,000	Updated 2005

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[19] See, for example, Department of Transportation Memorandum RE: Treatment of the Economic Value of a Statistical Life in Departmental Analyses, (http://ostpxweb.dot.gov/policy/reports/080205.htm) accessed 5/26/2009.

[20] See US EPA. Frequently Asked Questions on Mortality Risk Valuation. (http://yosemite.epa.gov/ee/epa/eed.nsf/pages/Mortality%20Risk%20Valuation.html#WhyDoesEPAPlaceVSL National Center for Environmental Economics. Accessed 5/26/2009.

EPA has estimated unit costs for some acute and chronic symptoms of illness. Of significance for this analysis is the estimated lifetime unit cost of approximately $145,000 for low birth weight (EPA, 2002) and approximately $41,000 for chronic asthma (new cases of asthma) (EPA, 1999), in 2008 dollars. Using these figures and ignoring the acute health effects identified above, the baseline annual cost of low birth weight is approximately $3.6 billion. Using the midpoint of 17,000 excess new cases of asthma, the annual baseline cost is approximately $0.7 billion, for a total of approximately $4.3 billion in 2008 dollars. Adjusting this for reduced smoking prevalence yields a baseline cost of $1.7 billion.

Baseline Morbidity Cost from ETS Exposure : $4 billion (current) ($2008) / $2 billion (future) ($2008)

Baseline Public Health Costs of Heat Waves

A large number of health effects are related to extreme heat. This analysis focuses on the number of heat-related deaths. Unfortunately, there is a great deal of uncertainty on the overall number of deaths from extreme heat events. For example, EPA (2006) suggests that an examination of multiple extreme heat events in different regions indicates that extreme heat events result in approximately 1,700 – 1,800 excess deaths per summer, roughly an order of magnitude greater than the national annual average of 182. On the other hand, using death certificates on which the causes of death is recorded, the Centers for Disease Control and Prevention (CDC) estimates that 3,442 deaths between 1999 and 2003 (annual mean of 688 deaths) resulted from exposure to extreme heat, including deaths where hypothermia was recorded as a contributing factor. Using the more conservative CDC estimate of 688 deaths annually from extreme heat events, and $7.4 million value for a statistical life, the baseline public health cost of premature deaths from heat waves each year is estimated to be $5.1 billion.

Baseline Mortality Cost from Heat Waves: $5 billion

Baseline Public Health Cost of Sick Building Syndrome, Heat Waves, Allergies and Asthma, and Communicable Respiratory Illness

Fisk (2000) estimated the economic value of health and productivity gains that could be attained by taking actions in buildings to prevent and mitigate poor indoor environmental quality. The study covered issues associated with communicable respiratory illness, allergies and asthma, and sick building syndrome.

Ideally, the true economic cost of these health impacts would use a market-based value of what people are willing to pay to avoid having an illness, or the amount that would make people indifferent as to whether they did or did not have an illness. These values are much less readily available for acute illnesses. Therefore, the health care costs (direct costs) of such illnesses plus work time (or productivity) losses (indirect costs) are often used. The direct and indirect costing methods, however, can grossly undervalue the true economic costs, especially for severe illnesses, because they imply that society has no interest in preventing such illnesses other than saving the productivity and health care resources involved.

The cost estimates in Fisk (2000) used the direct and indirect costing methodology for illnesses, and, in this way, may be considered conservative. In addition, the study estimated costs of the direct impact of building factors on human performance (productivity) independent of illness, but many of these direct impacts are related to lighting, which is not likely to be affected by climate change. Therefore, these direct productivity impacts are not included here.

The purpose of the Fisk (2000) study was to determine the public health impact reductions and economic savings that could be attained if preventive and mitigation actions were taken. The discussion below draws from that analysis the health and productivity costs associated with current indoor environmental quality conditions that were used in the current analysis.

Sick Building Syndrome

Sick building syndrome, or SBS, is a constellation of cold or flu-like symptoms experienced by building occupants that improve when they leave the building. These symptoms include irritation of the eyes, nose, and skin; headache; fatigue; and difficulty breathing. Approximately 23 percent of office workers regularly experience at least two such symptoms. Various SBS symptoms are statistically associated with a number of building factors, such as the type of ventilation system, outdoor air ventilation rates, chemical and biological contaminants, and particles on surfaces. Associations of SBS symptoms with low ventilation rates are particularly common.

The main economic impact of SBS is the reduced productivity of those affected. Given the prevalence of SBS, even a small reduction in productivity could represent a substantial economic burden. EPA estimated productivity losses from office workers due to SBS were 3 percent, or $60 billion in 1989 dollars, (EPA, 1989), approximately $104 billion in 2008 dollars. Fisk (2000) more conservatively estimated these losses at 2 percent,or $60 billion in 1996 dollars, approximately $82 billion in 2008 dollars. This estimate is conservative in that it does not include losses in non-office environments.

Baseline Public Health Cost: $93 billion ($82 billion – $104 billion) annually ($2008)

Allergies and Asthma

Fisk (2000) estimated that 16 percent to 50 percent of allergies and asthma cases are associated with building-related risk factors such as moisture problems and bio-contamination, irritating chemicals such as ETS, and exposure to pets, pest allergens, and pollen. This accounts for approximately $2 billion to $8 billion annually in medical cost and lost ore severely restricted work days. In a related study, Mudarri and Fisk (2007) estimated that exposure to dampness and mold in homes accounts for approximately 4.6 million cases of asthma at an annual cost of approximately $3.5 billion, which falls within the Fisk (2000) estimate.

Baseline Cost: $5 billion ($2 billion to $8 billion) annually ($2000) / $6 billion (2008)

Communicable Respiratory Illness

Fisk (2000) estimated that 9 percent to 20 percent of respiratory illnesses are associated with building-related factors such as ventilation, air cleaning, air re-circulation, and crowding. This translates to approximately $6 billion to $14 billion in annual costs: $3billion to $7 billion in health care costs, plus $3 billion to $7 billion in lost work or severely restricted work days. Between 16 million and 37 million cases of the common cold and influenza are estimated to be associated with building-related indoor environmental factors. However, communicable disease outbreaks can be more serious than is indicated here because of the potential premature mortality of vulnerable populations. Because premature death may be a serious climate change issue, the baseline cost in this category is thought to be greatly underestimated.

Baseline Cost:$10 billion ($6 billion – $14 billion) annually ($2000) / $13 billion (2008)

Table 4-2 summarizes the baseline annual cost estimates associated with poor indoor environmental quality.

Table 4-2: Baseline economic cost of health, comfort, and productivity impacts

Health or Exposure Category	**Approximate Annual Cost (Billions)**	**Comment**
ETS exposure mortality	$369 (current) $148* (future)	49,830 premature deaths from cancer, heart disease, and SIDS (from CARB, 2005)
ETS exposure morbidity	$4 (current) $2* (future)	Includes 24,500 cases of low birth weight and 17,000 new cases of asthma only (CARB, 2005)
Heat waves	$5	688 premature heat-related deaths including hypothermia as a contributing factor (CDC, 2006)
SBS	$93	Midpoint of productivity loss of $73 billion from SBS (Fisk, 2000) and $87 billion (EPA, 1989), adjusted for inflation to 2008 dollars
Allergies and asthma	$6	Midpoint of $2 billion – $8 billion (Fisk, 2000), adjusted for inflation to 2008 dollars
Communicable respiratory illnesses	$13	Midpoint of $6 billion – $14 billion (Fisk, 2000), adjusted for inflation to 2008 dollars
Total Baseline Annual Cost	**$490 billion (current)** **$267 billion (future)**	

***** Adjusted to 40 percent of the dollar value to account for declining smoking prevalence.

Public Health Cost Impact Categories

Consolidated Cost Impact Categories

The baseline costs in Table 4-2 are consolidated below under public health cost impact categories useful for this analysis. The cost impact categories, and what they include, are summarized in Table 4-3. Since only the economic value of health effects resulting from indoor environmental changes is being evaluated, the cost impact categories describe the health effects being estimated.

Table 4-3: Consolidated Cost Impact Categories

Category	**Source**
(1) Sick building syndrome (SBS)	Increased indoor temperatures and pollution from VOCs, pesticides, and formaldehyde
(2) Heat waves	Extreme heat events
(3) Allergies, asthma, and respiratory symptoms	Moisture-related contaminants such as mold, dust mites, cockroaches, and rodents, plus symptoms from fine particles resulting from indoor air chemistry involving ozone
(4) Communicable diseases	Ecological shifts that increase disease vectors and from reduced immunity due to ultraviolet radiation
(5) All health effects except heat waves	Reduced ventilation, which increases all indoor air contaminants. Includes all the effects in Table 4-2 except heat waves

Level of Impact

Given the great uncertainty in quantifying public health effects and cost impacts, only a very rough estimating procedure was attempted. For each cost impact category, reasoned judgments were used to assign a percentage change impact, as follows:

- Low-level impact (1 percent – 20 percent)
- Medium-level impact (21 percent – 35 percent)
- High-level impact (36 percent – 50 percent)

For heat waves, however, a specific estimate available in the literature was used. The economic value of each cost impact category was then summed to estimate the total cost.

Despite their imprecision, these assessments may be useful for suggesting where major public health costs are likely to be. The assessments also may help policy makers determine whether the climate change impacts on indoor environmental quality are of major or minor concern compared to other types of public health impacts.

The rationale for the individual estimates is described more fully below. No attempt was made to estimate the economic expenditures likely to occur as the public adjusts to indoor environmental changes (e.g., the cost of increased air conditioning systems to cool buildings, mold remediation expenses, etc.), though preventing those costs or reducing them through research and recommendations of the most cost-effective alternatives would be worthwhile.

The climatic changes and associated indoor environmental and health-related effects discussed in Chapters 2 and 3 are summarized in Table 4-4, along with the applicable cost impact category. Quantitative estimates of the level of impact and the associated economic costs of the public health, comfort, and productivity losses follow.

Table 4-4: Effects of Climate Change (Global Warming) on Indoor Air Quality

Climatological Effect and Adaptations	Indoor Environmental Effect		
	Effect on indoor climate and indoor pollution	**Effect on health, comfort & productivity**	**Value (cost) of health, comfort, & productivity change***
Outdoor Temperature Mean rise in outdoor temperature rise	Indoor temperature rises.	Sick Building Syndrome (SBS) increases from temperature rise.	Percentage increase in SBS (1)
	Increased use of air conditioning Potential for increased off-gassing of VOCs.	Potential increase in respiratory symptoms	Percentage increase in SBS (1)
Increased frequency and intensity of heat waves	Inability of air conditioning to condition indoor air		
	Extreme heat stress	Multiple effects	Percentage increase in respiratory symptoms (2) Percentage increase in premature death (2)
Outdoor Pollution Increased outdoor pollution (especially particulates and ozone)	Increased particulates and ozone come indoors	Increased respiratory ailments	Percentage increase in respiratory symptoms (3).
	Increased ozone reaction byproducts (indoor chemistry)	Increased SBS and respiratory symptoms	Percentage increase in SBS (1)

Climatological Effect and Adaptations	**Indoor Environmental Effect**		
	Effect on indoor climate and indoor pollution	**Effect on health, comfort & productivity**	**Value (cost) of health, comfort, & productivity change***
Moisture and Water Events			
Increased mean outdoor humidity	Increased indoor relative humidity, condensation, and mold growth	Asthma, allergies, and respiratory symptoms	Percentage increase in allergies, asthma, and respiratory symptoms (3)
Increased frequency and intensity of extreme precipitation episodes, with flooding in inland areas Higher intensity of storm surges and sea level rise in coastal areas, with increased flooding in East and Gulf Coast Regions	Increased wet, damp conditions, building damage, and mold	Asthma, allergies, and respiratory symptoms.	Percentage increase in allergies, asthma, and respiratory symptoms (3)
Increased harborage of rodents	Increased rodent infestation indoors due to rodent migration from outdoors to indoors and possible cockroach infestation due to dampness	Allergies, asthma, and respiratory symptoms.	Percentage increase in allergies, asthma, and respiratory symptoms (3)
	Increased use and exposure to pesticides		Percentage increase in SBS (1)
Temporary housing provided in flooded areas	Increased formaldehyde and VOC exposures	SBS from pesticides, formaldehyde, and VOC	

Climatological Effect and Adaptations	**Indoor Environmental Effect**		
	Effect on indoor climate and indoor pollution	**Effect on health, comfort & productivity**	**Value (cost) of health, comfort, & productivity change***
Outdoor Air Ventilation Pressure to reduce energy use to lower GHG; because of the cost of increased air conditioning results in reduced outdoor air ventilation	All existing indoor pollutants rise in inverse proportion to reduced ventilation	Increases in all existing indoor air health, comfort, and productivity effects	Percentage increases in all categories except heat waves (5)
Ecological Shifts and UV Radiation Changes in population and geographical distribution of disease pathogens, vectors, and hosts	Increases in disease outbreaks	Disease transmission in indoor environments	Percentage increase in communicable diseases (4)

*The numbers in parentheses correspond to the cost impact category in Table 4-3

Estimates of Public Health Costs from Climate Change Impact on Indoor Environments[21]

(1) Estimated Increase in Public Health Cost from Sick Building Syndrome (SBS)

Estimated SBS increase from increased indoor temperature: Higher temperatures have been associated with poorer perceptions of IAQ (Bergland and Cain, 1989; Fang et al., 1998) and with higher rates of unsolicited occupant complaints (Federspiel, 1998). Temperature and perceived IAQ are also associated with SBS and productivity (Seppänen and Fisk, 2005). In addition, there is evidence of increased respiratory effects resulting from higher temperatures. This was the predominant effect measured in a study of the impact of particles on workers (Mendell et al., 2002). In addition to higher temperatures, higher levels of SBS have been associated with air-conditioned buildings (Seppänen and Fisk, 2002).

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[21] Numbers in parentheses below correspond to the numbers in Tables 4-3 and 4-4.

It is not clear how pervasive these effects will be because air conditioning will lower indoor temperatures and mitigate the temperature effect, while the use of air conditioning will itself contribute to increasing adverse health effects. Further, the impact of air conditioning has only been shown when comparing buildings with and without air conditioning, not buildings with different levels of air conditioning use. For the purpose of this analysis, and for simplicity, only SBS affects are considered. Further, because of the counteracting effects (air conditioning lowers temperature) and the uncertainty about the air conditioning effect, the impact of rising temperature and the increased use of air conditioning is not expected to be large.

Estimated SBS increase from increased outdoor pollution: Higher outdoor temperatures enables the air to absorb more moisture, leading to a longer time to saturation and, thus, less frequent light rainfalls resulting in an increase in drought and forest fires. The forest fires will increase outdoor pollution. In addition, an increase in temperature will increase the chemical reaction of ozone primary and precursor pollutants from motor vehicles and industrial emissions such as VOCs and oxides of nitrogen (NO_x) to produce increased levels of ozone. This increase in outdoor pollution will increase ozone and particulates indoors, and it will also likely cause people to spend more time indoors[22].

Higher indoor ozone levels will create reactive byproducts, such as fine and ultrafine particles, formaldehyde, acetaldehyde, acetone, glycolaldehyde, formic acid, and acetic acid, particularly in the presence of terpenes which are common in cleaning products (Weschler, 2006, 2006a; 2007, 2007a; Nazaroff and Weschler, 2004; Levin, 2008). Reactive byproducts, along with outdoor pollutants entering the indoors, contribute to increased SBS.

EPA (2009) estimates that the increase in summertime average Maximum Daily 8-hour Average (MDA8) ozone concentrations across all the modeling studies tends to fall in the range of 2 − 8 parts per billion (ppb), which represents about a 2 percent to 13 percent increase. However, peak levels are expected to rise considerably and could be a matter of serious concern. Taken together, the impact on SBS indoors from increases in the average and peak ozone level rise outdoors is assumed to fall in the middle of the low impact category.

Estimated SBS increase from the use of temporary housing: Earth's rising temperature along with an increase in the frequency and intensity of extreme precipitation events and flooding, is expected to continue. As temperatures rise, thermal expansion of the oceans and melting glaciers contribute to the intensity of precipitation events, sea level rise, and thus the flooding of streams, rivers, and coastal areas that will create the need for temporary housing. Temporary houses have high levels of VOCs from surface emissions and their significantly higher surface-to-volume ratio, which increases indoor concentrations. Flooding is also expected to increase the harborage of pests and the use of pesticides. An important consequence of flooding, therefore, is the increased exposure to VOCs and formaldehyde of persons in temporary housing, which is assumed to increase the prevalence of SBS symptoms.

Because flooding and the use of temporary housing is mostly limited to flooded areas, on average this impact is considered to be in the low end of the low impact category.

Overall economic cost of increased SBS: Given the analysis above, the percentage increase in SBS is assumed to fall within the low-level impact category of 1 percent – 20 percent.

Baseline annual costs of SBS = $93 billion (Table 4-2).
A *low-level impact assumption* (1 percent – 20 percent) is used.

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[22] Currently, most jurisdictions recommend that people stay indoors during high outdoor pollution episodes.

Estimated annual cost impact = approximately $1 billion – $19 billion.

(2) Estimated Increase in Public Health Costs from Heat Waves

Estimated increase in morbidity from heat waves. Increased morbidity from heat waves includes heat cramps; heat exhaustion with symptoms such as intense sweating, thirst, fatigue, fainting, nausea, and headache; and heatstroke, a severe illness that can lead to serious long-term impairment. While these are important health impacts, data on their public health cost are not readily available. They are therefore not included in this analysis.

Estimated increase in mortality from heat waves: Ebi and Meehl (2007) report on a study (Hayhoe et al., 2004) that assumes a linear increase in heat-related mortality with increase in temperature. The study estimates, a 2-to-7-fold increase in heat-related mortality in California. This is consistent with reports from research at King's College London, where it is suggested that the increase in heat-related deaths in London from climate change may reach four times the current level[23]. Ebi and Meehl (2007) project only a 70-percent increase in extreme heat days by the end of the 21st century and argue that projections of extreme heat conditions are not sufficient to predict increases in morbidity and mortality. In addition to extreme heat conditions, other factors such as the changing characteristics of the population, the ability to acclimatize to high temperatures, and adaptation strategies that may be implemented are also important (Ebi and Meehl, 2007).

For the purposes of this analysis, a simple linear relationship between the number of extreme heat days and heat-related mortality is assumed. The 70-percent increase in extreme heat days would therefore translate to a 70-percent increase in the baseline cost. To be consistent with providing a range of impacts, an assumption of ± 10 percent was used, yielding an increase of 60 percent – 80 percent.

Baseline annual public health costs of heat-related mortality = *$5 billion*
A 60-percent to 80-percent increase assumed
Estimated annual cost impact from heat waves = approximately $3 billion – $4 billion

(3) Estimated Increase in Public Health Cost from Allergies, Asthma, and Respiratory

Symptoms

Estimated increase from humidity, dampness, and mold: Damp conditions caused by increased indoor humidity and condensation, along with heavy rainfall and flooding due to climate change, create an optimum environment for mold growth, which contaminates indoor environments. As described previously, dampness and mold are associated with asthma and asthma-like respiratory symptoms. However, condensation and dampness are functions of relative humidity (RH), not just absolute humidity. It was previously noted that with climate change, indoor temperatures are likely to rise along with outdoor temperatures. This rise in indoor temperatures will, to some extent, counter the rise in absolute humidity and tend to mitigate against the rise in RH. Thus, the impact of increased humidity is assumed to be relatively minor.

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[23] See news article from Mail; Online, Jan 25, 2010. Science and Tech. Heatwave Deaths will Quadruple in Cities like London, say Climate Experts. http://www.dailymail.co.uk/sciencetech/article-1160959 . Accessed on 1/24/2010.

On the other hand, the increase in heavy rains and flooding previously described will be accompanied by dampness and mold that will last long after the heavy rain and flood conditions have passed. Areas where dampness and mold are already present are likely to experience a substantial increase in those problems, while some areas where mold is not currently a problem will begin to experience problems for the first time. Because electric power outages frequently accompany heavy rains and flooding, efforts to pump water out of buildings or use air conditioners or dehumidifiers to assist in drying can be greatly impeded, and this development will extend the likely time of mold growth and exposure well beyond the flooding or heavy rain events. Further, once it infests a building, mold can be a chronic and continuous problem unless thoroughly mitigated. Mold within walls and framing elements is often extremely difficult or expensive to remove. Thus, this impact is assumed to be in the medium impact category.

Estimated increase from pest infestations: Damage caused by flooding plus the abundance of water available to pests, along with other ecological shifts previously described, will likely increase pest harborage opportunities, and building damage caused by heavy rains and flooding may be expected to increase the carrying capacity of buildings for pests. This will likely increase exposure to pest allergens. Once it occurs, an infestation can last for a long period. However, unlike communicable diseases where an initial increase can be multiplied several fold as the disease spreads, the impact of allergens is likely to be limited to the proportional increased infestation. This impact, therefore, is assumed to be in the low impact category.

Total estimated public health cost from allergies, mold, and respiratory symptoms: Overall, it is assumed that mold infestations will dominate the impacts on allergies, asthma, and respiratory conditions which are in the medium impact category, and the contribution of pest infestation and humidity will not be sufficient to raise that level. The overall impact, therefore, is assumed to remain in the medium impact category.

***Baseline annual costs* of allergies, asthma & respiratory symptoms = *$6 billion* (Table 4-2).**
A medium-level impact assumption (21 percent – 35 percent) used
Estimated annual cost impact from allergies, asthma, and respiratory symptoms = approximately $1 billion – $2 billion

Estimated Increase in Public Health Cost from Communicable Diseases

As previously described, alterations in the ecological balance brought about by climate change will vary the geographical distribution and biological cycle of many disease vectors, allowing the establishment of new breeding sites and bursts of disease carriers, thus posing significant disease risks to humans. Episodes such as the hantavirus outbreak in the southwestern U.S. in 1993 and the West Nile virus outbreak between 2001 and 2005 are expected to accelerate with climate change.

The fact that communicable diseases have the potential to spread throughout the population increases the potential impact of this problem, which could easily multiply several fold from current conditions. There also is some concern that increased exposure to UV radiation due to climate change could make the population more vulnerable to infection.

Since people spend the vast majority of their time indoors, the degree to which indoor environments are maintained (e.g., adequate ventilation, cleaning contact surfaces) can reduce the potential for disease transmission. Maintenance in hospitals, schools, and high-occupant-density buildings is particularly important. The behavior of occupants (e.g., frequent hand washing, staying home if sick) is also a critical variable. These issues were addressed in previous chapters.

Assuming that building O&M practices remain the same as they are today, the impact of climate change on communicable diseases could be quite large (i.e., medium- to high-level impact). However, a major portion of building operation practices is ventilation, which is expected to decrease thus raising the potential for disease transmission. Since the impact of reduced ventilation is estimated separately (see below), the impact of climate change on communicable diseases is assumed to be in the medium impact category.

Baseline annual cost for communicable disease = approximately $13 billion
A *medium impact assumption* (21 percent – 35 percent) used
Estimated annual cost impact for communicable diseases[24] = approximately $3 billion – $5 billion.

(5) Estimated Economic Cost for All Health Effects Due to a Reduction In Outdoor Air Ventilation

The Earth's rising temperature will increase use of air conditioning, which in turn will increase the amount of greenhouse gases pumped into the atmosphere from burning fossil fuels to generate electricity to power air conditioners, further perpetuating the temperature rise. To reduce the anthropogenic effect on the Earth's climate, a number of policies will likely be put in place to reduce energy use and, therefore, reduce greenhouse gas emissions. Among the likely actions to be taken to reduce greenhouse gas emissions and energy use are tightening building envelopes and reducing mechanically driven outdoor air ventilation to maintain indoor air temperatures. Since outdoor air ventilation is used to "dilute" indoor contaminants, its reduction will cause an increase in indoor exposures to airborne contaminants generated indoors. Thus, with the exception of heatwaves, all the baseline economic costs associated with health, comfort, and productivity as previously described are expected to increase as a result of reduced ventilation.

Indoor concentrations of pollutants that are generated indoors are roughly inversely proportional to outdoor air ventilation rates, and indoor concentrations of pollutants generated outdoors are directly proportional. Thus, reductions in outdoor ventilation rates would increase indoor concentrations of pollutants generated indoors and temporarily reduce the indoor levels of pollutants generated outdoors.[25] During the energy crisis of the 1970s, ventilation standards were effectively reduced from 15 to 5 cubic feet per minute (cfm) per occupant, a 66-percent reduction. Were a similar scenario to occur, it would constitute a high-level impact. Most commercial buildings, schools, and multistory apartment buildings are mechanically ventilated, so reduced ventilation can easily be achieved through operational changes. However, single-family residences rely almost exclusively on natural ventilation. The most significant ventilation reductions in single-family homes would be achieved by increasing insulation, replacing windows, or performing other retrofits that likely would occur over many years. Since people spend more time at home than in other buildings, the overall reduction in ventilation is tempered by the difficulty of doing so in homes. A medium impact rather than a high impact assumption for ventilation reduction is therefore used.

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[24] Because the baseline cost of this category does not include mortality estimates, this is likely to be a gross underestimation of this impact.

[25] The decrease in exposures to outdoor pollutants is true in the short run; however, the tendency for outdoor pollutant levels to also be achieved indoors as background levels (steady state condition) would remain.

Since these cost impacts represent conditions that would occur after 75 years, or toward the end of the century, all the ETS-related ventilation impacts are adjusted to reflect the decrease in smoking prevalence to 40 percent of its current value.

Baseline Annual Economic Cost of All Health Effects from Reduced Ventilation

ETS mortality = approximately $148 billion
ETS morbidity = approximately $2 billion
All other = approximately $112 billion

A medium impact ventilation reduction assumption (21 percent – 35 percent) is used. Corresponding increase in pollutant concentration becomes 27 percent – 54 percent[26]

Estimated Annual Cost Impact

Ventilation ETS mortality = approximately $40 billion – $80 billion
Ventilation ETS morbidity = approximately $1 billion – $1 billion
Ventilation Other* = approximately $30 billion – $60 billion

Total Public Health Cost from Climate Change Impact on Indoor Environmental Quality

Undiscounted and Unadjusted Costs

Table 4-5 presents the total undiscounted and unadjusted costs of climate change's effects on indoor environmental quality

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[26] Indoor concentrations are inversely proportional to the ventilation rate. The generic equation is $C = S/V$, where C is the concentration, S is the emission rate indoors, and V is the ventilation rate. Thus, if V is decreased by x %, i.e., $V_1 = (1\text{-}x\%)V_0$, then C_1 becomes $C_0\ (1/(1\text{-}x\%))$. Accordingly, assuming that ventilation rate is reduced by 21% – 35% (i.e. x = 21% – 35%), then C is increased by 27% – 54%.

Table 4-5: Undiscounted Public Health Cost Impact Estimates

Category	**Annual Public Health Cost (billion$)**	
	Low	**High**
Sick Building Syndrome	1	19
Heat Wave Mortality	3	4
Allergy, Asthma, and Respiratory	1	2
Communicable Disease	3	5
Ventilation ETS (mortality)	40	80
Ventilation (morbidity)	1	1
Ventilation (other)	30	60
Total	**79**	**171**
Approximate Range	**75 – 175**	

It is thus concluded that the total undiscounted public health cost of climate change impacts on indoor environments are potentially between the high tens of billions of dollars up to perhaps two hundred billion dollars per year, with the largest impact coming from reduced ventilation rates. This estimate represents the annual cost burden that will eventually be experienced toward the end of the century, valued in current dollars.

Discounted Costs

A change in climate is not expected to occur all at once, but rather will evolve over time. For this analysis, it is assumed that the full impact estimated above will occur in equal annual increments over a 75-year time frame. This assumption applies to all the health effects estimated.

When estimating costs that occur over a time period, it is appropriate to discount future cost streams. Future costs are thus discounted using discount rates of 3 percent and 7 percent to achieve a present value, which is then converted to an "annual equivalent" cost.

When estimating the future cost stream of premature deaths from ETS exposure, two additional factors are assumed to alter the future cost stream. The annual estimates of premature death from ETS exposures provided in Table 4-1a represent calculations of a steady state population exposure based on mortality risks from individual lifetime exposures of 70 years. Therefore, when an incremental change occurs in the population exposure due to climate change, a new steady state condition will ultimately result in a different annual rate of premature death, and this new rate is assumed to evolve in equal increments over the assumed lifetime of 70 years.

In addition, as previously described, the current baseline population exposure which is assumed to result from smoking prevalence of approximately 25 percent is not expected to remain constant, given current trends away from smoking. For this analysis, it is assumed that smoking prevalence will gradually diminish in equal decrements to 10 percent in 25 years and remain constant thereafter. Since this reduction will take place over time, its effect on the future cost stream of premature deaths from ETS exposure is also incorporated into the discounting procedure.

Table 4-6 provides the discounting factors when using a social discount rate of 3 percent or 7 percent. The public health cost calculations presented in Table 4-5, multiplied by the appropriate "annual equivalent" factors in Table 4-6, represent the discounted public health cost. The discounted public health cost of climate change impacts on indoor environments is presented in Table 4-7 using discount rates of 3 percent and 7 percent. It is generally thought that a 3 percent rate is most appropriate for long-term analyses of societal impacts.

Table 4-6: Discount Factors for Annual Equivalent Impact Estimates

	3%	**7%**
	Annual Equivalent	**Annual Equivalent**
Delayed premature death (70 yrs)	0.425	0.216
Incremental climate change (75 yrs)	0.405	0.202
Smoking prevalence reduction from 25 percent to 10 percent in 25 yrs	0.568	0.701
All effects combined	0.115	0.038

Table 4-7: Discounted and Adjusted Annual Equivalent Public Health Cost of Climate Change on Indoor Environmental Quality ($billion)

	3%		**7%**	
	Low	**High**	**Low**	**High**
Sick Building Syndrome	0	8	0	4
Heat Wave mortality	1	2	1	1
Allergies, asthma, respiratory disease	1	1	0	0
Communicable respiratory disease	1	2	1	1
Ventilation ETS mortality	11	23	4	8
Ventilation ETS morbidity	0	0	0	0
Ventilation other*	12	24	6	12
Total	**27**	**60**	**12**	**26**
Approximate Range	**10 – 60**			

*Excludes heat waves

The rough estimates presented here suggest that the public health cost impact of climate change on indoor environmental quality would be in the range of $10 billion – $60 billion per year. This range represents the current value of a varying future stream of annual costs that would occur into the indefinite future, converted to an annual equivalent. The cost estimates take into account the gradual nature of changes in climate over time, the delay of onset of mortality from ETS exposure, and the declining prevalence of smoking in American society. Given the uncertainties and the rough nature of these estimates, it is perhaps more appropriate to conclude that the discounted and adjusted public health costs are in the low-to-mid tens of billions of dollars per year, but could be in the high tens of billion of dollars per year if all health impacts were included.

Chapter 5: Summary and Conclusions

Overview

This chapter summarizes the major findings and arguments presented in this report and discusses the implications for public and private actions to protect the public health through improved indoor environmental planning and control.

Warmer Temperatures

- Warmer outdoor temperatures caused by climate change are expected to increase indoor temperatures.
- While partly mitigated by increased use of air conditioning, overall, the rise in indoor temperatures can be expected to have some health impact, including perceptions of poorer indoor air quality, increased SBS symptoms, and some increase in respiratory symptoms. Greater use of air conditioning will likely increase carbon emissions, which in turn will accelerate the warming effect.
- Temperature extremes are expected to experience proportionally higher increases than mean temperatures, and extreme temperature events will occur more often. This will greatly increase peak electricity demand, perhaps beyond the capacity to meet the increased demand for air conditioning, and this will exacerbate the health effects from indoor exposure.
- Heat waves will result in a host of health effects, including increased deaths of vulnerable populations from indoor heat exposures.

Implications

- Significant unmet needs for cooling through air conditioning will require greater attention to alternative cooling strategies in building design (e.g., building orientation, roofing and window systems) and operational practices (e.g., night cooling). This is consistent with the "green building" movement, which may be further encouraged in response to climate change.
- The generally agreed upon recommended public health response to heat waves is a notification and response program. This approach does not address the likelihood that many buildings, including many that are relied upon in these programs to be available to cool sensitive populations, may not be capable of doing so due to disruptions in energy supplies and building damages from other climate change events. Further consideration of this issue is needed.

Reduced Outdoor Air Ventilation

- Non-industrial buildings account for almost 40 percent of the energy consumed in the United States. The rise in energy demand for air conditioning combined with the need to reduce carbon emissions is expected to result in reduced outdoor air ventilation of buildings. Since ventilation is a primary means of controlling concentrations of pollution generated indoors, this is expected to have a potentially profound affect on all categories of health impacts associated with exposure to indoor pollution.

- Outdoor air ventilation was significantly reduced during the energy crisis of the 1970's. Complaints of building sickness brought about the recognition that indoor air pollution can be a major public health threat and that adequate ventilation is important for acceptable indoor air quality.

Implications

- A major effort to install more energy-efficient ventilation equipment and more effective and efficient ventilation strategies may be needed. These changes would reduce the energy used for ventilation and mitigate the need to save energy by reducing ventilation rates. Such strategies could include more reliance on natural ventilation or greater ventilation efficiency (e.g., displacement ventilation).

- Efforts to increase control of indoor pollution sources and promote the use of advanced filtration and air-cleaning technologies could allow ventilation rates to be modestly reduced without affecting indoor air quality.

Elevated Ozone

- Elevated levels of outdoor ozone due to climate change are expected to increase ozone levels indoors where people spend most of their time, and where the public is traditionally advised to go when outdoor ozone levels are high.

- Ozone indoors is known to react with a host of commonly used chemicals and produce toxic byproducts to which people indoors are exposed. The byproducts include fine and ultrafine particles, formaldehyde and other aldehydes, acrolein, and other chemicals. Other byproducts are unstable compounds that stimulate additional chemical reactions.

- While elevated ozone is rapidly emerging as an important indoor air concern, the specific health impacts are not well understood. Nevertheless, it is thought that the often-cited health impacts from ozone and particulate pollution outdoors may in fact reflect exposures to toxic compounds indoors from ozone reaction byproducts.

- With ozone levels expected to increase, this issue may be one of the most important indoor environmental impacts on public health due to climate change. Important chemicals of concern indoors because they react readily with ozone include terpenes, which are natural oils increasingly used in fragranced products and cleansers (including many "green" cleaning products). The rapid growth of fragranced products and air fresheners may be of particular concern in view of climate change. This issue is worth further study.

Implications

- Fortunately, it may be possible to mitigate the potentially significant public health impacts from direct exposure to ozone and from exposure to byproducts of chemical reactions with ozone indoors.

- Strategies to reduce direct exposure to ozone indoors could include the use of air cleaning systems to remove ozone from outdoor ventilation air and from indoor air. Charcoal and other chemical sorbents are used to remove ozone within filtration systems and are suggested for use in high ozone areas. That these systems require careful monitoring and diligent maintenance emphasizes the need for improvements in building maintenance. Further research into improved gas phase air-cleaning systems may prove to be highly beneficial.

- The most direct strategy to reduce exposure to ozone-reaction byproducts is to have manufacturers change their product formulations to reduce the use of those VOCs that readily react with ozone. Filters typically found in HVAC systems may also be a cause of concern when ozone levels are elevated. Filters continually collect dust particles that containing VOCs that may react with ozone to create undesirable byproducts such as formaldehyde that is then delivered into the indoor spaces. In fact, formaldehyde has been shown to be a common product of reactive chemistry on filters (Hyttinen et al., 2006). The synthetic media of the filters themselves also appear to be a problem (Buchanan et al., 2008). This suggests the possibility that proper filter medium selection and alternative filter media or treatments could reduce adverse health symptoms from chemical reactions with ozone.

Extreme Water Events

- Extreme water events from heavy rainfall, flooding of interior rivers and streams, and flooding in coastal areas caused by sea level rise are expected to put great strains on the building stock, increasing infestations of molds, rodent, cockroach and dust mites.

- Allergy, asthma, and respiratory effects from these problems are expected to increase substantially. Problems are likely to be made worse by power outages and infrastructure damage caused by extreme weather.

- Providing temporary housing for displaced populations is expected to increase in areas susceptible to flooding. Exposure to formaldehyde in temporary housing has been a problem and will likely become a far greater problem unless provisions are made for removing formaldehyde-laden materials from these units. Problems caused by inadequate ventilation and poor drainage have also been experienced in some of these structures.

Implications

- Delays in the ability to pump out water and dry buildings will likely extend exposures well beyond the events themselves, and these exposures may become endemic if the time needed for recovery extends beyond the time between extreme water events.

- Areas where buildings are perpetually wet or very damp from extreme water events may become uninhabitable and abandoned, leaving large swaths of economically depressed areas and causing significant population relocation.

- Research to identify vulnerable areas could provide advanced warning and time for the development of mitigation strategies. Codes, standards, and the widespread dissemination of guidelines to protect buildings from damage where possible, and to mitigate dampness and mold problems, may be useful.

Ecological Shifts

- Ecological shifts are expected to alter the breeding cycles and geographic distribution of many disease vectors, and this trend raises the potential for major disease outbreaks in the United States. The globalization of commerce and increased international travel adds to this threat. The increase in UV radiation from climate change also has the potential to compromise a person's immune system, making the population more vulnerable to disease.

Implications

- Reduced ventilation in buildings could expand the potential for disease transmission.

- Building O&M practices could be critical elements of control, particularly in hospitals, medical centers, schools, and other high-occupant-density buildings.

- Cultural attitudes in the building community that consider maintenance to be an expense to be minimized rather than an investment to be made in building environmental quality may need to be addressed through educational and training programs. A change in attitude and a move toward more scientifically based maintenance and cleaning practices would be needed.

- Policies and guidelines specifically addressing disease transmission may need to be developed, widely disseminated, and promoted.

- The improved design and construction of temporary housing would help protect the health of displaced occupants housed in these facilities.

Economic Costs

- The undiscounted public health costs of climate change impacts on indoor environments appear to between the high tens of billions and two hundred billion dollars per year. These are annual costs that would occur toward the end of this century valued in current dollars. Using social discount rates of 3 percent and 7 percent, the public health costs appear to be in the low-to-mid tens of billions of dollars per year, and would likely be in the high tens of billions of dollars per year if the full range of health effects were included in the estimate. These ranges represent the current value of discounted annual costs that are expected to occur indefinitely into the future.

Implications

- From a public policy standpoint, the impact of climate change on indoor environments and public health appear to be at levels that would warrant more attention. Focused study is needed to determine how best to ensure that policies, building practices, and technologies are implemented to prevent the degradation of indoor environments and ensure that buildings can fulfill their primary role of providing indoor spaces that are supportive of occupant health, comfort, and productivity in the face of climate change.

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