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Climate Change and Occupational Safety and Health: Establishing a Preliminary Framework

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The relationship between global climate change and occupational safety and health has not been extensively characterized. To begin such an effort, it may be useful to develop a framework for identifying how climate change could affect the workplace; workers; and occupational morbidity, mortality, and injury. This article develops such a framework based on a review of the published scientific literature from 1988–2008 that includes climatic effects, their interaction with occupational hazards, and their manifestation in the working population. Seven categories of climate-related hazards are identified: (1) increased ambient temperature, (2) air pollution, (3) ultraviolet exposure, (4) extreme weather, (5) vector-borne diseases and expanded habitats, (6) industrial transitions and emerging industries; and (7) changes in the built environment. This review indicates that while climate change may result in increasing the prevalence, distribution, and severity of known occupational hazards, there is no evidence of unique or previously unknown hazards. However, such a possibility should not be excluded, since there is potential for interactions of known hazards and new conditions leading to new hazards and risks.

Keywords biological hazards, climate change, heat stress, UV radiation, worker health

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The findings and conclusions in this report are those of the authors and do not necessarily represent the views of the National Institute for Occupational Safety and Health.

INTRODUCTION

The earth is in a period of climate change characterized by increased average ambient temperatures.(1–3) The most recent Intergovernmental Panel on Climate Change (IPCC) reported that heat waves, heavy precipitation events, and other extreme weather events have become more frequent and intense in recent decades.(1)

In addition, the IPCC identified some evidence of actual human health effects directly affected by climate change (e.g., heat stress, death, or injury in floods and storms) and indirectly through changes in the ranges of disease vectors (e.g., mosquitoes), waterborne pathogens, water quality, air quality, and food availability and quality. The IPCC concluded that the actual health impacts will be largely influenced by local environmental conditions and socioeconomic circumstances and by the range of social, institutional, technological, and behavioral adaptations taken to reduce the full range of threats to health.(1) Will the occupational safety and health of workers be influenced by climate change and these conditions, circumstances, and adaptations?

To date, most of the climate change research has focused on the health of the general population rather than on occupational health and safety outcomes. Because of the lack of appropriate health, climate, and other relevant data, it has been difficult to assess how climate change has affected workers. How is global climate change related to occupational safety and health? Will the effects on workers be different from the general population? Will work potentiate the health effects of global climate change? To begin to address these complex questions, it may be useful to develop a framework for identifying how climate change could affect the workplace, workers, and occupational morbidity and mortality.

The basis for the framework was a review of published peer reviewed scientific literature from 1988–2008. The review focuses on the climate-related health effects, host factors that might enhance susceptibility to climate effects, and the impact of this information on occupational safety and health research and practice. Papers reviewed included those on epidemiologic studies of climate change and health outcomes during 1988–2008. Literature was included if the study had directly pertinent information on workers. Workers are exposed to many types of hazards that depend on their type of work, geographic region, season, and duration of work time.(4)

Where there was no directly relevant information, selective data were included that can be inferred to relate to workers. The National Library of Medicine and the University of Massachusetts Lowell Electronic Library databases were searched using combinations of keywords: climate, climate change, global warming, health, heat, temperature, air pollution, ozone depletion, heat stress, biological hazards, worker health, UV radiation, disaster, extreme weather, vector-borne, and building. A range of databases, websites, and "gray literature" sources (e.g., government funded studies and technical reports) also were accessed. University of Massachusetts Lowell Electronic Library databases included Academic Search Premier, Annual Reviews, American Meteorological Society Archives, Environment Index, IOP Science, ScienceDirect Journals, TOXNET, and Wiley Inter Science. This article describes a framework that includes climate changes or effects, the associated occupational hazards, and their manifestations in working populations.

CONCEPTUAL FRAMEWORK

The potential links between global climate change and occupational safety and health can be visualized in a conceptual model shown in Figure 1. It is derived from two models used by the World Health Organization (WHO) for assessing the relationship between environmental health and policy actions or interventions.[5,6] These models, the "driving forces, pressures, state of the environment, exposure, health effects, actions" (DPSEEA) and the "multiple exposures-multiple effects" (MEME), promote visualization of relationships involving multiple factors. These relationships are influenced by various driving and contextual factors. The models were originally derived to identify where policy interventions could occur and where resources could be allocated, but they can also be considered to identify potential policy implications and research in the field of occupational safety and health.

The impact of climate change on workers' health is affected by other contextual factors, such as population growth, energy policies, and increasing urbanization and deforestation. These factors along with climate change may lead to an increase in the magnitude and severity of known hazards and result in increasing numbers of workers who would be exposed to them.

The hazards can be considered in seven categories: (1) increased ambient temperature; (2) air pollution; (3) ultraviolet (UV) radiation; (4) extreme weather; (5) expanded vector

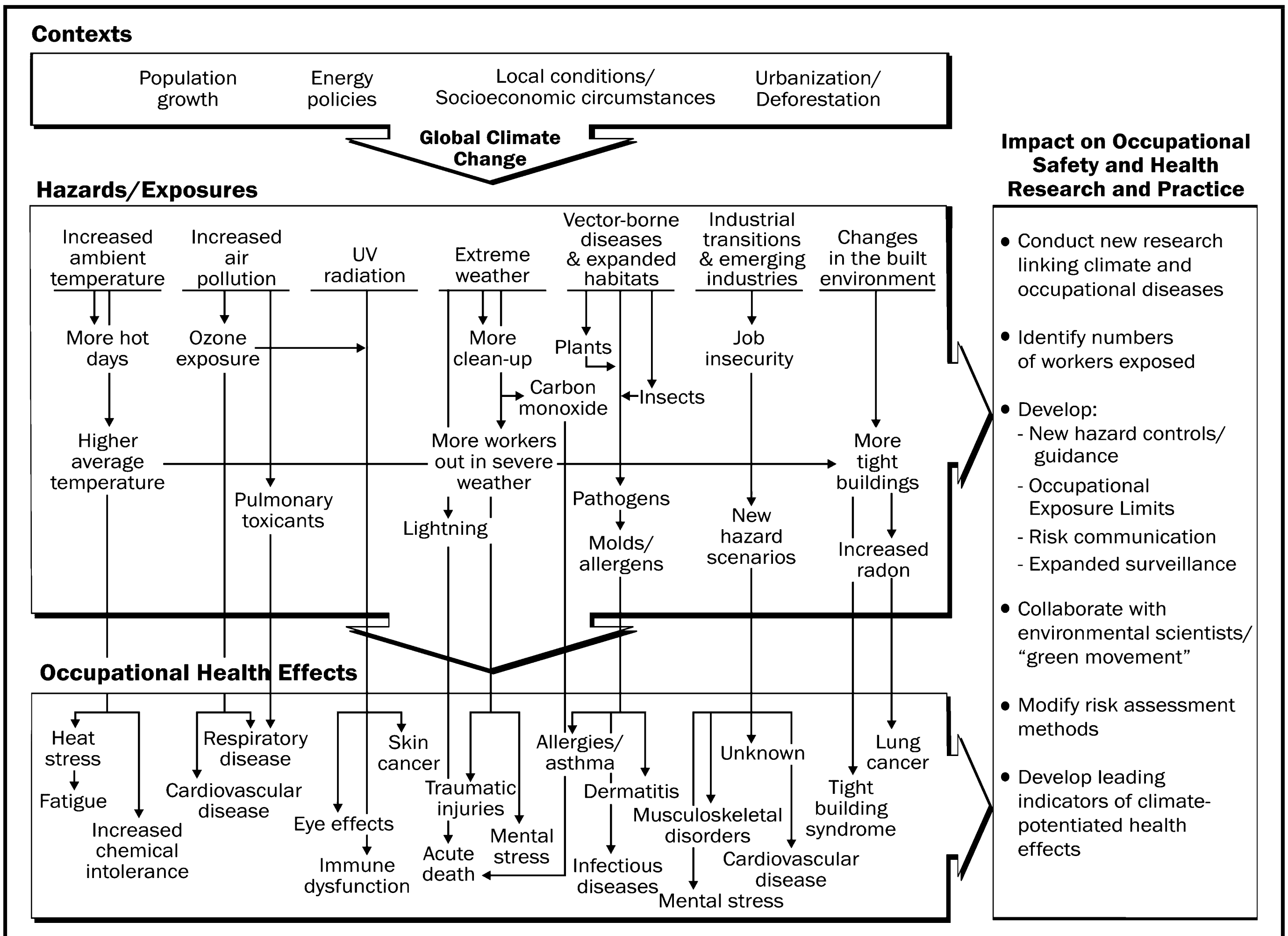

FIGURE 1. Conceptual framework of the relationship between climate change and occupational safety and health

habitats; (6) industrial transitions and emerging industries; and (7) changes in the built environment. Exposures to these hazards can then lead to various health effects. These relationships are discussed in the following section and in Table I.

OCCUPATIONAL HEALTH HAZARDS AND EFFECTS RELATED TO CLIMATE CHANGE

Increased Ambient Temperature

Workers labor in a wide variety of hot environments, and if average ambient temperatures increase, more workers will be exposed to heat stress (in terms of magnitude of temperatures experienced or frequency of heat exposure above a certain threshold). Excessive exposure to a hot work environment can bring about heat-induced disorders, such as dehydration, heat rash, heat cramps, heat exhaustion, heat fatigue, heat syncope/fainting, and heatstroke.[7–9] Work-related factors such as work practices, work/rest cycles, access to water, and access to shade/cooling and other controls can also affect the development of heat-induced disorders.

It is difficult to predict who will be affected and when because of varying individual susceptibility and environmental factors, other than the ambient air temperature, that influence thermal stress (e.g., radiant heat, air movement, conduction, and relative humidity).[8] Factors that could affect susceptibility to temperature-related occupational hazards include age; weight; degree of physical fitness; degree of acclimatization; metabolism; use of alcohol or drugs; a variety of medical conditions such as hypertension or thyroid disease; prior heat injury; and the type of clothing worn.[8] In general, heat-induced occupational illnesses, injuries, and reduced productivity occur in situations in which the total heat load exceeds the capacities of the body to maintain normal body functions without excessive strain.[7,9]

Both outdoor and indoor workers are at risk of heatstroke and heat fatigue. The outdoor occupations most at risk of heatstroke include construction; refining; surface mining; hazardous waste site activities (e.g., those workers required to wear semipermeable or impermeable protective clothing; personal protective equipment [PPE] such as Tyvek suits, gloves, and half-face, powered air-purifying respirators); agriculture; forestry; and fishing.[1,8,10] There also are possible heat implications for indoor workers in such workplaces as greenhouses, glass or rubber manufacturing plants, and for others who work in buildings without air conditioning or proper ventilation systems.[2,7]

Heat Stress/Stroke

Heat is an environmental and occupational hazard that can exist in almost any workplace, especially during summer or in warm, moist environments, such as those found in tropical climates.[9,11–13] Most of the epidemiologic studies of the health effects of heat stress have been directed toward short exposures of days or weeks in length and toward acute heat illnesses.[7] Heat waves cause a significant impact on the health of the general population resulting in heat-related deaths.[14–16]

Some of the heatstroke deaths reported have been associated with occupational exposure at construction sites, agricultural settings, and hot industrial jobs requiring heavy work leading to increasing the worker's heat load by generating more metabolic heat.[1,9,17] Industrial heat exposures may be classified as either hot-dry or warm-moist. Hot-dry situations may prevail in a hot desert climate or near any furnace operation, while warm-moist environments are found in industries such as canning, textiles, laundering, and deep metal mining.[9] In addition, outdoor urban workers may be exposed to heat stress as a result of "heat island effect" of urban built environments.

Individuals in thermally stressful occupations or with preexisting illnesses (e.g., cardiovascular disease or chronic respiratory diseases) are vulnerable to heat stress;[2,15,18,19] those unaccustomed to the heat are particularly susceptible.[8] A recent Centers for Disease Control and Prevention (CDC) report identified 423 worker deaths among U.S. agricultural (16% in crop workers) and nonagricultural industries during 1992–2006. The heat-related average annual death rate for the crop workers was 0.39 per 100,000 workers, compared with 0.02 for all U.S. civilian workers.[20]

Decreased Chemical Tolerance

Meteorological conditions such as high ambient temperature and humidity can affect the physiological response to environmental toxicants through their effects on thermoregulation, including skin blood flow, sweating, and respiration.[11] Warm, wet skin promotes the absorption of chemicals.[21] Workers in agriculture, including pesticide applicators and aerial spraying pilots, have potential increased exposure to organophosphate insecticides and reductions in cholinesterase activity when they are heat stressed.[11] Pilot error and crashes may have been exacerbated by hyperthermia and exposure to pesticides.[11,22]

A few studies have indicated an association between high temperature and chemical intolerance, as illustrated by carbon monoxide poisoning among race car drivers during warmer days, and pesticide poisoning among agricultural workers and military personnel in hot environments.[1,12,23] While these associations have been supported by various animal studies and chamber studies with volunteers, the human evidence base is limited.[11,23,24]

Studies also have shown that many workers who labor in hot environments may forgo or misuse available protective clothing and other protective equipment, thereby risking exposure to potentially hazardous chemicals.[11] Adjustment factors for threshold limit values for heat stress have been used to reflect the increased hazard of heat stress imposed by different clothing ensembles.[12]

Fatigue

Prolonged exposure to heat may result in heat cramps and fatigue. Heat exhaustion occurs in conditions of sustained exertion in hot conditions with loss of electrolytes from sweating and dehydration from deficient water intake.[9] At

TABLE I. Health Hazards and Effects Related to Climatic Change

Climate-Related Change	Health Hazards/ Effects	Nature of Evidence
Increased ambient temperature	Heat stress/stroke Decreased chemical tolerance Fatigue Impact on immune function	Heat-related deaths among farm laborers and construction workers.[17,20] Mortality in cities during heat extreme events.[13,130] Outdoor workers and those who work in thermally inefficient buildings without air conditioning or proper ventilation system will be most exposed.[2,7]
Air pollution	Increased pollutants Asthma and other respiratory diseases Allergens - molds	Increased ozone and particulate matter with longer warmer seasons. Possible ozone-related deaths, asthma, and respiratory symptoms among those working outdoors. Rise in allergic disorders prevalence and severity due to increased pollen and spore biomass, earlier flowering, and longer pollen season.[26,30,34,36,131–133]
Ozone depletion leading to increased UV radiation	Increased UV radiation Eye effects and skin cancer Disturbed immune function	Association between the ambient UV exposure, average daily maximum temperature, and the incidence of skin cancer and cortical cataract.[40,47] Suppression of cell mediated immunity, increased susceptibility to infection.[53]
Extreme weather	Flood cleanup Mental stress Lightning Disruption of industrial hygiene services	Association between weather disaster and death, injury, communicable diseases and mental health disorders. Increased frequency or intensity of floods, droughts, and fires; economic disruption, population displacement, and fatalities from sea level rise and flood events.[67,75,134] Exposures to mold, chemicals, biological agents, floodwaters, dust and dried flood sediment, flood debris, and noise were potential health hazards. Safety hazards such as broken glass and skin contact with floodwater posed a risk to disaster relief workers during cleanup operation after Katrina.[64]
Vector-borne diseases/expanded habitats	Pathogens Allergens Plants - poison ivy/oak Insects - ticks, mosquitoes	Increased vector-borne infections such as mosquitoes (malaria, filariasis, dengue fever, and West Nile fever), ticks (Lyme disease and tick-borne encephalitis), sandflies (leishmaniasis), and blackflies (onchocerciasis).[1,4] Outdoor workers are at risk of vector-borne diseases. Outdoor workers include farmers, foresters, landscapers, groundskeepers, gardeners, painters, roofers, construction workers, laborers, mechanics, and any other worker who spends time outside.[10] Forestry workers and firefighters fighting with wildfires develop rashes or lung irritations when poisonous plants are burned and their toxins were inhaled by workers.[10]
Industrial transitions and emerging industries	New industries More nuclear Recycling Job insecurity	Shift in local agriculture and fisheries.[2,135,136] Emerged development of greener technologies.[3] Health effects in nuclear energy production.[98,137] Unemployment risk in fisheries and transport sectors. Different mix of hazards with new technologies.
Changes in the built environment	Tight buildings Radon	Tight buildings for energy efficiency lead to radon build up. Office workers may be exposed to a wide range of indoor air contaminants due to increased indoor activities from more hot days and high air pollution.[120] Occupational radon exposure of miners and indoor workers.[126]

TABLE II. Factors that Could Increase Susceptibility to Climate-Related Occupational Hazards

Factor	Effect
Age	- Older workers may have slower elimination of many toxicants.[9] They are also less able to thermoregulate.
Obesity	- Inherited and acquired differences in heat tolerance and sweat rate: excess body weight raises metabolic heat production.[8]
Pre-existing disease	- Workers with prior heat injury, obesity, or pre-existing illness such as cardiovascular disease or chronic respiratory diseases, elderly, children or others in thermally stressful occupations and who are not acclimatized may be at a greater risk of heat illnesses.[2,8,9,19,15]
Very small body size, lower socioeconomic status	- Those who live in poverty or who have small body size are vulnerable to heat stress because of the potential for multiple exposures, poorer diets, and lack of access to medical care.[69]
Pregnancy	- Some individuals with underlying health conditions (who have weakened immune system by pregnancy, diabetes and autoimmune disease) may be more sensitive to molds.[70]
Immunologic status	- People who have human immunodeficiency virus infection or immunosuppressed as a result of cancer therapy or health hazards are more at risk for serious infections.[9]
Type of work clothing	- Workers required to wear semipermeable or impermeable protective clothing or PPE such as Tyvek suits, gloves, air-purifying respirators are at risk of heat disorders.[1,8,10]
Genetic characteristics	- Genetic host factors (e.g., hemochromatosis gene) that modify pathophysiological effects of particles may play a role in predicting susceptibility to air pollution.[127] Heat shock proteins and some genes (i.e., C-reactive protein, ICAM-1, metallothionein, and cNOS) change expression with heat stress.[11]

higher temperatures, fatigue increases, and both the physical and mental task capacities to work are affected. Increased body temperature and physical discomfort promote irritability, anger, and other emotional states, which sometimes cause workers to divert attention from hazardous tasks making accidents more likely to happen.[8,16]

Increased Air Pollution

Common sources are often responsible for the emissions of both greenhouse gases that influence global warming and air pollutants that have direct health effects on people.[25,26] Elevated temperatures can increase levels of air pollution, which in turn can further harm human health. For example, high temperatures also raise the levels of ozone and other air pollutants, such as particulate matter, that exacerbate cardiovascular and respiratory diseases.[19,26–33]

Some outdoor occupations such as transportation, utility maintenance, landscaping, and construction lead to longer exposures to air pollutants due to the amount of time spent outside and the increased breathing rates involved in the work.[26] Criteria air pollutants such as carbon monoxide, lead, ozone, nitrogen oxides, particulate matter (PM), and sulfur dioxide (SO_2) are linked to asthma and other chronic lung diseases.[9]

There is considerable evidence that season and temperature levels strongly modify the association between air pollutants, such as PM and SO_2, and mortality. Greater air pollutant effects on mortality have been observed during warmer days.[32–35] The combination of high temperature and added heat load by physical exertion increases breathing frequency and, thereby, may increase the total intake of air pollutants.[9,11]

There are many studies suggesting that climate change is associated with increases in air pollution-related diseases, such as respiratory disease, as well as increases in allergic disorders such as heightened lung sensitivity to allergens and irritants caused by air pollutants, pollen, and aeroallergens.[1,36–38]

Recently, a study suggested that the increased length and severity of pollen season; more frequent, heavy precipitation events; and severe urban air pollution episodes are strong risk factors for respiratory allergic disease.[39] People with asthma showed an increased inflammatory response and sensitivity to various allergens following exposure to ozone.[40,41] Increasing asthma prevalence in the general population (and due to workplace exposures) can be expected to translate into increased numbers of workers with asthma, and for this group, exposure to respiratory irritants and allergens is a critical issue.[42]

Ultraviolet (UV) Radiation

Climate change alters the distribution of clouds and thus affects UV radiation levels at the surface. Decreases in the earth's protective ozone layer, due to chlorofluorocarbons, also may increase levels of UV radiation reaching some parts of the earth's surface and, thereby, increase ozone-related exposure and health effects.[1,43] Globally, excessive solar UV radiation exposure caused the loss of approximately 1.5 million disability-adjusted life years and 60,000 premature deaths in the year 2000.[1] It is likely that outdoor workers will have more or higher intensity exposure to UV radiation as the result of climate change.

Eye Effects

Outdoor workers may be at increased risk of adverse eye effects from UV radiation. There is evidence that solar UV radiation increases risks of several diseases of the eye, including cortical cataract, conjunctival neoplasms, and ocular melanoma.[44] Studies indicate that individuals with blue or gray eyes and light hair and skin color are at elevated risk of ocular melanoma.[44,45]

Recently, a report by the United Nations Environment Program (UNEP) suggested that sunlight-associated pterygium occurs in people of all skin colors; all outdoor workers regardless of skin color would thus benefit from eye protection.[46] McCarty and Taylor[47] reviewed 22 epidemiologic studies and found that in 15 of the studies there was a significant association between UV exposure and cortical cataract.

Skin Cancer

Similarly, UV radiation may increase the risk of skin cancer in outdoor workers. There is sufficient evidence to establish UV radiation as a human carcinogen.[4,46] Excessive exposure to UV radiation can increase risk of cancer of the lip, basal cell carcinoma, squamous cell carcinoma, and malignant melanoma.[9,42,48–51] Epidemiologic studies indicate that individuals with light skin, hair, and eye color are at elevated risk of cutaneous malignant melanoma.[44] In addition, certain drugs (e.g., chlorpromazine, tolbutamide, and chlorpropamide) can increase susceptibility to skin damage from UV radiation.[9]

Disturbed Immune Function

Little is known about the link between climate change and the dysfunction of the immune system. However, high temperature and increased UV radiation from ozone layer depletion have been demonstrated to suppress certain aspects of cell-mediated immunity in mice.[52] There is a possibility that UV radiation-related immunosuppression may blunt cell-mediated immunity and affect risks from various infectious agents.[9,46,53] Consequently, outdoor workers may be at increased risk of developing immune dysfunction from increased UV exposure.[1,44,54–56]

Extreme Weather

Extreme weather events such as floods, landslides, storms, droughts, and wildfires have become more frequent and intense in recent decades, as temperatures and climatic variability change.[1] The impact of recent hurricanes and heat waves shows that even high-income countries are not well prepared to cope with extreme weather events.[1] There is a substantial body of literature on the association between weather disasters and death, injury, communicable diseases, malnutrition, famine, and mental health disorders.[2,10,57–62] Workers involved in rescue and cleanup efforts could have more exposure to risky conditions as the frequency and severity of extreme weather events increases.

Flood Cleanup

Flooding is the most frequent weather disaster.[2,63] Potential health or safety hazards associated with flooding are exposures to mold, chemicals (e.g., carbon monoxide and hydrogen sulfide), biological agents, venomous snakes, fire ants, floodwaters, dust and dried flood sediment, flood debris, noise, electrical hazards, confined spaces, musculoskeletal hazards, drownings, blood-borne pathogen infection, eye injury, falls, and motor vehicles.[4,64]

During Hurricane Katrina investigations, exposure samples obtained from workers during cleanup operations revealed carbon monoxide levels above the National Institute for Occupational Safety and Health (NIOSH) ceiling limit.[64] Carbon monoxide exposures occur when internal combustion engines of cleanup equipment are used indoors or in circumstances that impede safe dispersion of exhaust gases.

In addition, safety hazards such as broken glass and skin contact with floodwater posed a risk to workers. Heat stress was also a potential health hazard for crews who worked on a hot day or were wearing PPE to clean up spoiled food (such as maggot-infested meat) and flood debris.[64] After Hurricane Katrina, wound-related *Vibrio* illnesses were reported, which were likely a result of floodwaters infecting a wound.[65]

Firefighters and police personnel reported both physical and mental health symptoms related to their relief efforts during Hurricane Katrina in New Orleans.[62,66,67] Studies showed that new onset respiratory symptoms such as sinus congestion, throat irritation, cough, and skin rash were common among aid workers and emergency responders.[67,68]

Environmental studies showed a strong association between the outbreak of pulmonary hemosiderosis and flooding of homes with inadequate mold remediation.[69] Floods and increased temperature may lead to situations where relief, emergency response, and cleanup workers are exposed to increased levels of molds and allergens.[4,70]

Mental Stress

If climatic changes lead to increased frequency of adverse weather events such as hurricanes, tornadoes, floods, and fires, more workers involved in rescue and cleanup operations may be exposed to mental stressors. After Hurricane Katrina, firefighters and police personnel reported mental health symptoms related to the event.[61,62] Symptoms of depression were twice as likely among relief services workers with other comorbidities, such as lower respiratory tract symptoms or skin rash.[61] Risk factors associated with post-traumatic stress disorder include recovery of bodies, crowd control, assault, and injury to a family member.[61] Studies showed that symptoms of depression in response workers were associated with rare family contact, uninhabitable homes, low supervisor support, and injury to a family member.[61,62,68]

Lightning

If climate change increases the frequency of storms, workers may encounter more exposures to lightning. Most work-related lightning deaths and injuries involve outdoor workers in construction; agriculture (driving tractors, farm equipment, and heavy road equipment, etc., and picking crops located under trees); recreation; and in the fishing industry.[4,71,72] Construction workers, laborers, machine operators, engineers, roofers, and pipefitters have been struck by lightning most often on the job.[4,71] Although rural areas were one of the most common locations for lightning victims early in the 20th century, according to recent storm data, there are now many more injuries in urban than rural settings.[72,73] Numerous injuries have involved recreation (fishing in a boat, boating, being near the beach or water, and mountain climbing) and sports (playing soccer, swimming, golfing, and riding a bike); ball parks and playgrounds were the most frequent locations for lightning encounters during 1959–1994.[72,74]

Disruption of Infrastructure

The increase in both frequency and intensity of extreme weather events may cause extensive damage to infrastructure and buildings.[75] Service networks such as power, roads, and transportation may fail, increasing risk of exposure to disaster damage and hazards to workers. As a result of disruption of infrastructure, workers could be put in new or unfamiliar circumstances leading to a high risk of traumatic injury. If infrastructure disruption involves information technology systems that have critical occupational safety and health data, the workers could be at increased risk because of standard controls not being applied or the inability to recognize hazards. In addition, in disruption scenarios where citizens face severe restriction of mobility, electric power, food, and shelter, various workers may be at increased risk of violence.

Vector-Borne Diseases and Expanded Habitats

Changing temperatures can affect vector, pathogen, and host habitats.[14,15] Shifting rainfall levels have mixed effects on the potential for infectious diseases, such as malaria and dengue fever.[76] A growing number of studies present evidence of the effects of climate change, such as temperature, humidity, and a rising sea level, on widespread infectious diseases.[77,78] Outdoor workers are at risk of biological hazards (e.g., venomous wildlife, insects, and poisonous plants) and vector-borne diseases (e.g., malaria and Lyme disease transmitted by the bite of infected arthropod species).[1,10,60,79]

The classification of "outdoor workers" includes such occupations as farmers, foresters, landscapers, groundskeepers, gardeners, painters, roofers, construction workers, laborers, mechanics, and any other worker who spends time outside. Industry sectors with a substantial number of outdoor workers include the agriculture, forestry, fishing, construction, mining, transportation, warehousing, utilities, and service sectors.[4]

Pathogens

Increasing ambient temperatures may favor growth of various pathogens.[2,14,15,80] Some occupations have exposure to pathogens, and an increase in the prevalence and distribution of them may further affect workers in those occupations. Exposure to water-borne and food-borne pathogens can occur via contaminated drinking water (from human waste or agricultural runoff), seafood (due to natural microbial hazards or toxins), or fresh produce (grown or processed with contaminated water).[9,81] Workers may acquire water-borne or food-borne diseases if they have direct contact with water or food that has been contaminated by microorganisms (e.g., *Salmonella, Shigella, Giardia lamblia*, or others).[9]

Water-borne pathogens (protozoa, bacteria, and virus) are associated with other serious conditions, including hepatic, lymphatic, neurologic, and endocrinologic disease.[81] Emergency responders and health care workers are at risk of various infectious diseases (e.g., vector-, water-, food-, and airborne diseases).[4,9] Workers who perform necropsies of infected birds or rodents or who handle infected tissues or fluids are at risk of infection if their skin is penetrated or cut.[4]

Allergens and Molds

Outdoor workers are most likely to be at increased risk of exposure to elevated levels of allergens. There is evidence to suggest that climate change is affecting the seasonal distribution and concentrations of some allergenic pollen species.[1,36,82,83] The impact of elevated atmospheric carbon dioxide (CO_2) concentrations on allergenic plants or aeroallergens includes: changes in pollen amount; pollen allergenicity; pollen season; plant and pollen distribution; other plant attributes; and other aeroallergens, such as mold spores.[36] High temperatures raise the levels of pollen and other aeroallergens that trigger allergenic diseases, such as allergic rhinitis.[1,84,85]

There are suggestions that the abundance of a few species of airborne pollens have increased due to climate change.[1,86] Climate change leads to increased pollen and spore biomass, earlier flowering, and longer pollen season via higher temperatures and CO_2 levels, and results in increased prevalence of molds and allergens.[26,36] Molds are indoor and outdoor air hazards for workers, occurring as a result of excessive moisture or poor building maintenance.[68,70,87] Increasing numbers of hurricanes and floods could lead to more houses with mold and more remediation and construction workers exposed to molds.

Plants—Poison Ivy/Oak

Elevations in temperature and atmospheric CO_2 increase plant metabolites, photosynthesis, growth, and population biomass of poison ivy.[1,88,89] Poisonous plants can cause allergic reactions if the leaves or stalks are damaged and come in contact with workers' skin.[4] They are also dangerous if burned and their toxins inhaled by workers. A study by NIOSH showed that nearly one-third of forestry workers and firefighters who battled forest fires in California, Oregon, and Washington developed rashes or lung irritation from contact with poison oak, which is the most common poisonous plant in those states.[10] In addition to firefighters, electrical utility workers, landscapers, farmers, and road workers may be at increased risk of exposure to an expanded poison ivy habitat.

Insects—Ticks, Mosquitoes

Elevations in temperature have affected increased rates of extrinsic incubation in insect vectors (e.g., ticks and mosquitoes), extended vector transmission seasons, and expanded distribution seasonally and spatially.[1,14,15,76,90–92] Outdoor workers may also be at increased risk from exposure to ticks and mosquitoes in enlarged habitats. When a mosquito or tick bites a worker, it may transfer a disease-causing agent, such as a parasite, bacterium, or virus.

Mosquito-borne diseases include West Nile Virus, St. Louis encephalitis, eastern equine encephalitis, western equine encephalitis, and dengue, malaria, and LaCrosse encephalitis.[4] Tick-borne diseases include Lyme disease, babesiosis, ehrlichiosis, Rocky Mountain spotted fever, southern tick-associated rash illness, tularemia, tick-borne relapsing fever, anaplasmosis, Colorado tick fever, Powassan encephalitis, and Q fever.[4] Work sites with woods, bushes, high grass, or leaf litter are likely to have more ticks, and work sites with standing water are more likely to breed mosquitoes.

Climate change alone may not explain the changes in insect-borne infectious diseases. Other factors associated with mosquito-borne disease include host factors such as population susceptibility, insecticide resistance, primary health care, land use patterns, and subtle alterations in microenvironments.[76,81,93] It has been observed that nonclimatic factors such as forest clearance, urbanization, changing agricultural practices, and deficient disease control activities have caused substantial shifts in the pattern of malaria and other diseases.[93] Nonetheless, the potential impact of climate change and other factors may require increased pesticide and herbicide use, which potentially could increase workers' exposure to these toxicants.[94]

Industrial Transitions and Emerging Industries

Climate change may result in extensive shifts in industrial investments leading to deterioration of some industries.[95–98] There is a wide range of government and private reports that describe potential impacts on various industries, but there are very few peer reviewed publications of actual deterioration. Increases in frequency and intensity of extreme weather events, floods, and destruction and damage of infrastructure and buildings may have negative impacts on economic activity and employment.[98] Job insecurity has been associated with detrimental health outcomes, such as cardiovascular disease and musculoskeletal disorders.[99–101]

In contrast to the deterioration of some industries, others may grow. The IPCC summarized key mitigation technologies and practices by sectors and indicated that climate change is stimulating the development of "greener" technologies, hence, sources of new employment. For example, current technologies that are commercially available for the energy supply sector are those leading to improved supply and distribution efficiency; fuel switching from coal to gas; nuclear power; renewable heat and power (hydropower, solar, wind, geothermal, and bioenergy); fuel cells; hydrogen; combined heat and power; and early applications of carbon capture and storage.[78] In addition, technologies such as more fuel-efficient vehicles, hybrid vehicles, cleaner diesel vehicles, biofuels, modal shifts from road transport to rail, and public transport systems are occurring in the transport sector. Each of these may have inherent occupational hazards as well.

Emerging Industries

The emergence of new "climate-friendly" industries may result in the reduction of some hazards and the introduction of others. For example, there is a growing awareness of hazards and risks involving wind generation.[102,103] The American Society of Safety Engineers has announced initiation of work on a new standard to protect workers in wind generation construction and demolition. The standard will address working at heights, long strenuous ladder climbs, mechanical assembly of large components, medium voltage electrical safety, and working in exposed environments.[104]

Solar energy materials manufacturing, construction, maintenance, and demolition may also present various hazards known in construction and manufacturing, with notable exceptions that illustrate the nature of both solar electric and solar hot water equipment; that is, exposure to sunlight creates stored energy not present in other construction trades.[105,106] Another emerging energy source, biodiesel, may also have various hazards, such as caustic, volatile, and flammable chemicals leading to burns, fires, explosions, and toxic exposures.[107,108] New technologies will require the anticipation, recognition, and control of known hazards in new settings.[65] There also are health hazards involving other renewable energy industries, such as with nuclear power (mining, reprocessing, and disposal) and hydroelectric power.[102,103]

Increased Production of Nuclear Energy

Health effects associated with the nuclear power industry are variable across the industry. Occupational deaths can arise from occupational exposure at the mining, milling, and generation stages. Routine radiation during generation, decommissioning, reprocessing, low-level waste disposal, high-level waste disposal, and accidents can be the source of injury or illness.[109]

Recycling

Enhanced recycling may be one response to climate change. Recycling is an integrated system that starts with the collection of materials by individuals, businesses, and municipalities; involves processing the recycled materials; and leads to the manufacturing of new products with recycled content. Though the health and safety hazards of recycling have not been widely studied, there have been reports of exposures to lead and other metals, and ergonomic and biological hazards among recyclers.[110–112]

Job Insecurity

If economic activities are slowed down to reduce energy consumption or carbon emissions, many jobs in energy, construction, and transport sectors may be at risk. In addition, sectors such as agriculture, forestry and fishing, the finance-insurance industry, and tourism could be affected directly.[14] For example, in coastal areas, sea level rise will have negative impacts on employment due to the loss of land in agriculture and tourism.

Previous epidemiologic studies showed an association between job insecurity (or workplace psychosocial factors) and adverse health outcomes.[100,113,114] Some deterioration in health status of workers was seen during the period of job loss anticipation that preceded actual organizational restructuring.[100] In job insecurity studies, cardiovascular disease and musculoskeletal disorders are the occupational hazards that occur most often.

Changes in the Built Environment

High temperatures increase the need for climate-controlled buildings. Occupants of buildings (particularly workplaces with air conditioning) have higher rates of building-related health symptoms than occupants of naturally ventilated buildings. Building-related illness can occur in water damaged buildings as well as in energy-efficient "tight" buildings with microbially contaminated humidifiers or air handling units that use biocides.[115]

Tight Buildings

Workplace indoor air quality can be affected by many different factors: temperature and humidity; biological, chemical, and particulate pollutants; quality of the heating, ventilation, and air conditioning system; noise; light; and odor.[116] There is some evidence that reactions between ozone and indoor contaminants, such as volatile organic mixtures, may influence health and indoor air quality.[117–120] Biologic aerosols containing mold spores and bacteria are important pollutants.[9,70]

Other factors associated with building-related health symptoms include heat island effect, high occupancy load, video display terminal use, female gender, job stress, and allergies.[9,121] Office workers, school teachers, and students who inhabit inadequately ventilated buildings; factory workers exposed to industrial chemicals; and those residing in areas polluted by toxic substances, groundwater contamination, radon, or aerial pesticides are at risk of tight building syndrome.[70,115,122]

Radon

If warming climates and demand for energy efficiency lead to increased numbers of tight buildings, workers in those buildings could be at increased risk of exposure to radon. Exposure to radon is the second leading cause of lung cancer in the United States and the number one cause among nonsmokers. The U.S. Environmental Protection Agency estimates that radon causes more than 20,000 lung cancer deaths in the country each year.[122,123]

Radon is a naturally occurring radioactive gas released in rock, soil, and water from the natural decay of uranium. An elevated radon level inside tight buildings or in drinking water may affect workers' health.[122,124] According to the National Radiological Protection Board (NRPB), in the U.K. there are 16,000 workplaces located in affected areas with radon levels in excess of the Action Level®. Recent NRPB estimates of radon exposure of employees in the 2 million U.K. workplaces are that radon causes between 90 and 280 lung cancers every year.[125]

Generally, significant radon exposure occurs to workers who labor in cellars, basements, and poorly ventilated ground floor rooms and are less likely to exist in larger workshop-type workplaces, such as engineering works and large bakeries, often because the nature of the process requires enhanced ventilation. However, buildings that are tight for energy efficiency can lead to radon buildup in work areas. Smaller rooms, storage areas, and offices may have high radon levels.[125,126]

SUSCEPTIBILITY FACTORS

Table II summarizes host factors that could increase susceptibility to climate-related occupational hazards. These include age, weight, obesity, degree of acclimatization, metabolism, use of alcohol or drugs, and a variety of medical conditions (e.g., pregnancy and hypertension) or pre-existing diseases (e.g., cardiovascular disease or chronic respiratory diseases).

Other predisposing factors include the type of clothing worn, immunological status, and genetic factors. These issues could influence occupational health policy and planning, such as development of emergency response systems, climate effect-related health management plans, energy efficiency and building code guidelines, and education on occupational health and safety.

For example, regarding heat exposure, the host factors that affect a worker's sensitivity to heat need to be considered when setting up occupational guidelines. Because studies have suggested that workers who are not acclimatized or who have had prior heat injury may be at a greater risk of heat illnesses,[8,9] both the use of acclimatization or adaptation programs (e.g., use of air-conditioners, additional intake of fluids, change in work hours, better building insulation and design, etc.), and occupational health and safety training for hazardous environments may merit consideration as preventive actions.

IMPACT ON OCCUPATIONAL SAFETY AND HEALTH RESEARCH AND PRACTICE

In response to the impact of climate change, adjustments in occupational safety and health research and practice could include alteration of standards, modification of hazard controls, development of acclimatization procedures, new research directions, development of new hazard control guidance and hazard communications, development of early warning systems and surveillance, and increased emphasis on prevention through design. Standards for hazards that might be increasing as a result of climate change may need to be reviewed to determine if they are still adequate or need to be modified to reflect more frequent exposures. Moreover, risk assessment methods may need to be adapted to address a mix of risks not usually considered in occupational standards (e.g., exposure to ticks, poison ivy, mosquitoes, and water-borne diseases).

One area of growing concern is that transition to more environmentally safe products or chemicals, i.e., "green" materials as a means to mitigate climate change may be misinterpreted in terms of their safety for workers. For example, recent neurologic cases involving 1-bromopropane illustrated that what is considered environmentally safe is not necessarily worker safe.(128,129) Occupational safety and health practitioners will need to participate in decisions to recommend environmentally safer materials.

The next step in developing the framework is to assess the relative magnitude and frequency of climate-related hazards and the number of workers exposed. This probably needs to be done on a regional basis, with attention to what industries or occupations might be most affected. Ultimately, there may be the need for a research and prevention agenda as well as a prioritization scheme.

CONCLUSION

A review of the literature shows that the effects of climate change on workers' health and safety are likely to increase the prevalence, distribution, and severity of their exposure to known hazards and result in increased incidence of morbidity, mortality, and injury. There is no evidence at this time of unique or previously unknown hazards that will result from climate change, but such a possibility should not be excluded because there is potential for interaction of known hazards and conditions leading to new hazards and risks. Uncertainty remains in attributing the expansion or resurgence of diseases to climate change, due to the lack of long-term, high-quality datasets, as well as the large influence of socioeconomic factors and changes in immunity and drug resistance.(130)

Although considerable uncertainties exist in linking climate change to workers' health, it has been suggested that WHO pay more attention to this issue, and international institutions such as the Organization for Economic Cooperation and Development examine and publicize the potential impacts of climate change on employment.(98) Workers' health is determined not only by occupational risks but also by employment status, income, and access to health services.

The conceptual framework for identifying how climate change could affect the workplace and occupational morbidity, mortality, and injury may help decision makers to assess occupational health policy and recommendations within the broader public health framework. Surveillance may need to be augmented to identify climate-related occupational effects and might include attention to sentinel effects (e.g., heat stress) and various leading indicators, such as the climate vulnerability index.(131) Current knowledge is limited in many areas. Anticipation, recognition, evaluation, and control of occupational hazards related to new "green" jobs are required. More research on how changes in climatic conditions affect a range of occupational health concerns is needed.

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