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An Overview of Occupational Risks From Climate Change

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Abstract Changes in atmosphere and temperature are affecting multiple environmental indicators from extreme heat events to global air quality. Workers will be uniquely affected by climate change, and the occupational impacts of major shifts in atmospheric and weather conditions need greater attention. Climate change-related exposures most likely to differentially affect workers in the USA and globally include heat, ozone, polycyclic aromatic hydrocarbons, other chemicals, pathogenic microorganisms, vector-borne diseases, violence, and wildfires. Epidemiologic evidence documents a U-, J-, or V-shaped relationship between temperature and mortality. Whereas heat-related morbidity and mortality risks are most evident in agriculture, many other outdoor occupational sectors are also at risk, including construction, transportation, landscaping, firefighting, and other emergency response operations. The toxicity of chemicals change under hyperthermic conditions, particularly for pesticides and ozone. Combined with climate-related changes in chemical transport and distribution, these interactions represent unique health risks specifically to workers. Links between heat and interpersonal conflict including violence require attention because they pose threats to the safety of emergency medicine, peacekeeping and humanitarian relief, and public safety professionals. Recommendations for anticipating how US workers will be most susceptible to climate change include formal monitoring systems for agricultural workers; modeling scenarios focusing on occupational impacts of extreme climate events including floods, wildfires, and chemical spills; and national research agenda setting focusing on control and mitigation of occupational susceptibility to climate change.

Keywords Occupational risks · Climate change · Heat · Ozone · Polycyclic aromatic hydrocarbons · Other chemicals · Pathogenic microorganisms · Vector-borne diseases · Violence and wildfires

Introduction

While susceptibility to the environmental health effects of climate change has received heightened research attention in recent years, susceptibility among workers has received less scrutiny [1, 2, 3••, 4]. This review surveyed the existing empirical evidence to determine: What specific occupational

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exposures are likely to increase as a result of climate change? What occupational sectors will be most susceptible to climate change impacts? What research is needed to protect workers from the predicted health threats from climate change? Unless otherwise noted, this review focuses on threats to US workers but most findings are likely applicable to similar occupational sectors in other countries. Table 1 summarizes the potential effects of global climate change on occupational sectors by exposure source. Detailed below is a description of these sources.

Occupational Exposures Likely to Increase as a Result of Climate Change

Heat

Possibly the greatest risk posed by climate change to workers is heat [5–8]. Climate change-related heat increases (absolute temperature and temperature combined with humidity) are projected to increase over time and pose risks to outdoor and indoor workers across a range of industries, from factory workers to those cleaning up oil spills [9•]. The US Occupational Safety and Health Administration identifies operations involving high air temperatures, radiant heat sources, high humidity, direct physical contact with hot objects, and strenuous physical activities as having a high potential for causing heat-related illness [10]. Workplaces where these conditions are often found include iron and steel foundries, nonferrous foundries, brick-firing and ceramic plants, glass products facilities, rubber products factories, electrical utilities, bakeries, confectioneries, commercial kitchens, laundries, food canneries, chemical plants, mining sites, smelters, and steam tunnels. Limited access to adequate ventilation and no or poor air conditioning exacerbate risks for heat-related illness among indoor workers. Outdoor operations most prone to heat-related illness include farm work, construction, oil and gas well operations, asbestos removal, landscaping, emergency response operations, and hazardous waste site activities [10]. In a review of OSHA heat-related violations in a 2-year period (2012–2013), 20 cases of heat illness or death occurred among 18 private employers and 2 federal agencies. In 13 cases, a worker died from heat exposure, and in 7 cases, two or more employees experienced symptoms of heat illness. Most of the affected employees worked outdoors [11]. Because occupational fatalities and illnesses attributable to heat are not always reported as such, this assessment is likely an underestimate of the actual number of cases.

US estimates are that five to ten million workers are exposed to outdoor heat exposures beyond safe levels every year [12]. A recent epidemiological review specified outdoor heat risk for construction workers, miners, firefighters, and armed forces personnel and concluded that increasing heat waves caused by climate change would vastly increase the risk of morbidity and mortality in these sectors in a V- or U-shaped curve but could be mitigated with workplace interventions [13•]. On a population level, many epidemiologic studies have demonstrated this V-, U-, or J-shaped relationship between temperature and mortality [14, 15]. A geographic mapping investigation using wet-bulb globe temperature combined with gridded climate maps showed the Southern United States as being particularly vulnerable to occupational heat hazards [16].

Heat adversely affects health through two main pathways: extreme temperature rise leads to heatstroke, while diminished air quality caused by higher temperatures increases cardiopulmonary dysfunction and respiratory illness [17]. Studies of indoor workers demonstrate that fatigue and other self-reported health symptoms [18] and psychological and physical stress increase with heat exposure [19], potentially resulting in decreases in worker safety. Personal protective equipment can increase body temperature and exacerbate health risks to workers [20]. Radiant heat directly affects male reproductive function [21], and occupational settings involving extended periods of heat exposure potentially impact fertility; however, specific job tasks and exposure thresholds are unknown [22]. While there is evidence showing cognitive effects of heat on workers, effect thresholds and the types of tasks most affected are unclear [23]. Heat has been shown to increase conflict in some workplace settings and is discussed in a later section.

Agricultural workers are especially vulnerable to heat-related conditions [24–26]. In the USA, the average annual heat-related death rates among crop workers was 19.5 times the rate in civilian workers between 1992 and 2006 and the rate for crop workers appears to be increasing [27]. Agricultural workers face the acute health effects of heat, which range from cramps to life-threatening conditions such as heatstroke, because the work often requires heavy physical exertion in an outdoor environment with high temperatures and humidity. If physical exertion is held constant, climate change-related temperature increases will increase the burden of heat-related illnesses and deaths among agricultural workers.

To prevent heat-related conditions from increasing, an individual's time spent conducting high-intensity agricultural work should be reduced and carefully monitored. The American Conference of Governmental Industrial Hygienists (ACGIH) recommends that workers' deep body temperature should not exceed 38 °C (100.4 °F) [28]. The ACGIH also developed threshold limit values (TLVs) which recommend that as work strain remains constant, and as temperatures increase, workers should have longer periods of rest each hour.

Working in high temperatures has been associated with reduced productivity [26], and workers are at increased risk of serious work-related injuries [13•]. Even with resting and other heat prevention strategies available, workers face

Table 1 Potential effects of global climate change on occupational sectors by exposure source

Contaminant type	Occupation sectors most likely to be affected	Exposure route	Exposure knowledge level	Health effects	Evidence level	US control	Suspected to increase because
Pesticides	Agriculture, landscape	Dermal, inhale, ingest	High	Numerous	Inconclusive	High	Increase in plant diseases
Veterinary medicines	Veterinary, agriculture	Dermal, inhale	Low	Antimicrobial resistance	Limited	Low	Intensification of livestock production
Ozone	Construction, transportation, energy, agriculture	Inhale	Medium	Asthma, COPD, cardiopulmonary	Inconclusive	Low	Increased temperature
PAHs	Construction, transportation, energy, agriculture	Inhale	Low	Cardiopulmonary, carcinogenic	Inconclusive	Low	Increased dust, forest fires
Pathogenic microorganisms	Fishing, agriculture, sanitation, most outdoor work	Dermal, ingest, inhale	Medium	Infectious disease	Inconclusive	Low	Increased flooding and contamination of soil and water
Vector-borne infectious agents	Food-animal production, most outdoor work	Dermal	Medium	Infectious disease	Limited	Low	Increased range of vectors
Soil dust	Agriculture, most outdoor work	Inhale, ingest				Low	Drier conditions
Industrial processing chemicals	Chemical manufacture, emergency response operations	Dermal, inhale, ingest	Medium	Numerous	Inconclusive	Variable	Floods/wildfires
Wildfire smoke	Fire service	Inhale	High	Respiratory	Inconclusive	Low	Drier conditions

Adapted with permission from Balbus et al. [58•]

challenges to protecting themselves from heat stress in a warmer climate. When agricultural workers are paid by how much they harvest for example, this may incentivize workers to forego employer-provided breaks [24, 26].

The impact of heat exposures on agricultural workers' health is expected to affect more than acute heat-related outcomes. Heat may play a role in the workers' development of chronic conditions. For example, in Central America, repeat exposure to heat-related events is thought to be underlying elevated prevalence of chronic kidney disease among sugarcane workers [29]. Other long-term problems have been hypothesized to include mental health, skin, and respiratory problems [5].

Ozone

Temperatures are projected to decrease air quality with particular impacts on ozone. Air quality is predicted to degrade due to changes in air pollution processes including ventilation, precipitation, and increases in anthropogenic and natural sources [30]. It is expected that ozone, an oxidative airborne pollutant formed from temperature-dependent photochemical reactions, will increase in the USA as a result of climate change-related temperature increases [31, 32]. Ambient ozone concentrations have strong diurnal and seasonal patterns with peak concentrations occurring during hours with brightest sunlight. The average 8-h and peak 1-h concentrations are estimated to increase as well as the number of days exceeding the 8-h standard [33]. Outdoor workers may have higher exposure to ozone than the general population with more time spent outdoors as well as from elevated ventilation rates from increased physical activity.

The health impacts of ozone include both acute and chronic effects. Short-term impacts include the induction of respiratory symptoms, such as coughing, wheezing, throat irritation, and difficulty breathing, as well as eye irritation and asthma attacks [34–36]. Chronic exposures to elevated concentrations of ozone have been associated with increased risk for mortality from respiratory diseases such as pneumonia and chronic obstructive pulmonary disease [37]. Several studies have investigated the predicted impact of climate-related increases of ozone on the health of the general public. An increase in acute ozone-related mortality is predicted to increase [38] as well as increases in emergency room visits [39], hospital admissions [40], exacerbation of asthma [41], decreased lung function [42], and chronic obstructive pulmonary disease [30]. Although the impacts of ozone have been shown to be the most detrimental for vulnerable populations such as children [41, 42] and the elderly [43], both acute and chronic impacts occur in healthy adults at concentrations lower than the US ambient (75 ppb, 8 h) and occupational (OSHA, 100 ppb PEL; ACGIH, 50–100 ppb TLV for heavy to light workloads, respectively) standards [42]. The measured impact of exposures to ozone specifically impacting outdoor workers has been the focus of only a few studies: acute reductions to lung function [44–46] and DNA damage at concentrations lower than 75 ppb [47]. Acute respiratory impacts on outdoor workers were found to be non-significantly associated with ozone concentration in Quebec [48]. A recent evaluation of the impacts of ozone exposures using a weight of evidence approach concluded that adequate evidence exists to classify outdoor workers as at risk for ozone-related health effects [49]. Additionally, epidemiological evidence suggests that thermal stress may intensify the toxicity of airborne pollutants including ozone and particulate matter [17].

Ozone exposures among outdoor workers may be associated with productivity. In analyses of a panel dataset of daily farm worker output recorded as part of piece rate contracts merged with data on environmental conditions, farm workers were found to have a 4.2 % increase in worker productivity from a 10 ppb decrease in ozone concentrations, which were below federal occupational standards [50]. Impacts on productivity may lead to increased work hours or reductions in earning potential for workers paid on a piece rate basis such as agricultural harvesters. Occupational sectors other than agricultural workers at risk for increased ozone concentrations due to climate change include construction, fishing, forestry, mining, oil and gas extraction, transport, and landscaping. There will be regional differences in future ozone concentration changes, with the highest increases likely to occur in cities with already high concentrations. Given the well-documented relationship between ozone exposures and respiratory health outcomes and the increased levels of exposures to ozone for outdoor workers in comparison to the general population, climate change is likely to lead to an increase in risk for respiratory impacts for outdoor workers above the current state.

Polycyclic Aromatic Hydrocarbons

Polycyclic aromatic hydrocarbons (PAHs) are molecules composed of two to seven fused benzene rings formed during the combustion of carbon-containing materials such as coke, petroleum-based fuels, and biomass materials such as crops and forests. The chemical class of PAHs contains hundreds of compounds which vary from extremely volatile to non-volatile. As such, the US EPA has identified 16 priority PAHs that are most commonly included in health studies. Generally, PAHs are considered to be mutagenic and carcinogenic. Outdoor workers with the highest exposures to PAHs commonly work in close proximity to combustion sources such as traffic police, tunnel construction workers, garage workers, taxi drivers (particularly those who keep their windows down), and wildland firefighters.

Health impacts associated with exposures to PAHs have been shown in only a handful of studies focused on occupations with high exposures such as foundry, asphalt, and coke oven workers. Increased exposures are associated with higher risk for cancer [51] and ischemic heart disease [52].

Unlike the other pollutants discussed, the impact on PAH exposures due to climate change may be varied. Friedman et al. estimated a decrease in atmospheric concentrations globally with a small increase in volatile PAHs and a decrease in non-volatile PAHs [53]. Cai et al. predicted climate change-related increases in atmospheric PAHs as well as water concentrations in a study limited to Korea [54]. Both studies reported emissions of PAHs as a primary factor in predicted future concentrations. It is likely that exposures to workers will be more directly impacted by local sources. For example, outdoor worker exposures to PAH concentrations may be improved through the use of cleaner-burning fuels and electric vehicles in transportation sectors. However, firefighters, discussed below, may have increased exposures due to a predicted increase in the frequency of forest fires.

Other Chemicals

Exposures to environmental chemicals are predicted to increase as a result of climate change through various routes including increased pesticide use, changes in transport pathways such as dust proliferation, increased chemical dispersal from storm runoff, and increases in chemical spills from floods and fires [55, 56, 57•, 58•].

A key transport pathway for particulate dust and particle-bound contaminants present in the atmosphere is through agricultural tilling and harvesting. Soil dust has been linked to a number of human health impacts. Increased dust concentrations during hot dry conditions will create both particulate and potential chemical exposures [57•, 59]. Both transport pathways and fate processes for chemicals and pathogens will likely be affected by changes in climate conditions, and this will affect the exposure level depending on chemical properties (hydrophobicity, solubility, volatility) and the form of the contaminant (particulate, particle associated, dissolved) [57•, 60]. Transport of contaminants to water bodies will increase with extreme precipitation events. Climate change is anticipated to result in the increased use of pesticides and biocides as farming practices intensify [61], which may also lead to increased occupational exposures. The increased use of veterinary medicines to counteract temperature-related increases in livestock outbreaks is also predicted [57•], which will differentially expose veterinary professionals and food-animal producers [62]. Extreme weather events will mobilize contaminants from soils and fecal matter, potentially increasing their bioavailability [60]. Farmers and farming communities could be differentially susceptible, as would emergency response and disaster management workers.

Thermoneutrality is the temperature between where the body must increase perspiration to reduce core temperature or increase metabolic rate to increase core temperature. Temperatures higher than thermoneutral temperatures exacerbate the action of most air pollutants, insecticides, and other chemicals [17]. Raising ambient temperature to thermoneutral and above temperatures increases the rate of toxicant clearance but also exacerbates toxicity. Sweating and skin blood flow elevation during hyperthermic conditions speed up the dermal uptake of some insecticides in humans [17, 63]. Animal studies demonstrate that lowering body temperature reduces chemical toxicity but slows down excretion rate, and the lethal toxicity of many chemicals is exacerbated by heat stress [17, 64, 65]. Increased release of contaminants combined with increased temperature represents a confluence of excess risks to workers in a range of occupational sectors including agriculture, energy, construction, hazardous waste, and emergency management.

Pathogenic Microorganisms

Workers who are likely to be at increased risk of exposure to pathogenic microorganisms will be those who interface closely with the natural environment or who have contact with contaminated soil, water, animals, and infrastructure. Most studies have found a positive relationship between rainfall levels and the incidence of infectious diseases, such as enteric infections [66]. A variety of occupational sectors could be affected by increases in extreme rain events. The incidence of Legionnaires' disease, caused by *Legionella*, has been found to increase during warmer months and is associated with rainy, humid weather. *Legionella* could affect workers in buildings with poorly maintained cooling systems and hot water tanks as well as individuals who work on plumbing and water systems. With increased extreme rain events, workers who operate and maintain septic systems or sewerage systems—which are susceptible to flooding—could face increased exposures to human pathogens in sewage [67]. This may be especially important in coastal areas, where septic and sewerage systems are especially vulnerable to rising sea levels.

A warming climate could affect the expansion of different animal species and food-animal production practices, changing the animal-human interface and creating new conditions for the emergence of infectious diseases. The workers most likely to be affected will be those in forestry, agriculture, animal husbandry, and meat handling industries. These risks could include tick-borne encephalitis, tularemia, brucellosis, leptospirosis, rabies, and anthrax. Furthermore, studies have highlighted that the warming of the sea surface can increase the concentration and distribution of *Vibrio* spp., which increases the risk of human infections among people working in fisheries [68]. In 1996, a major outbreak of *Vibrio vulnificus* caused severe soft tissue infections and bacteremia in Israeli fish market workers as well as the broader population. Subsequent research found significant correlations between temperature and hospital admission for *V. vulnificus* infections [69].

Vector-Borne Infectious Agents

Individuals working in areas where poor water drainage exists—providing breeding sites for mosquitoes—could be negatively affected by increased extreme rain events [70]. Vector-borne diseases, including Rift Valley fever, yellow fever, malaria, dengue, and chikungunya, are sensitive to changes to the climate, and research suggests that many of these diseases will expand their geographical range, increasing their toll on human health [71]. This is especially a risk for animal agricultural workers, meat processors, and veterinarians, given that Rift Valley fever in animal populations can lead to human infections. A significantly higher prevalence of infection with Rift Valley Fever has been found in abattoir workers, cattle farmers, and veterinarians who have regular contact with animals [72, 73]. Changes in vector-borne diseases are likely to affect a wide variety of worker populations.

Workplace Violence

Generally speaking, climate change is expected to exacerbate conflict. A large meta-analysis that included 60 empirical studies concluded that deviations from normal rainfall and moderate temperatures systematically increased conflict across major regions of the world through time [74]. The study included domestic violence, violent crime, civil conflict, and war. An increase in conflict will increase the risk of injury and mortality for various occupations such as law enforcement, security personnel, armed forces, disaster response personnel, emergency medicine, firefighters, homeland security, and border security as well as aid organizations like the Red Cross.

The US Department of Defense predicts that climate change will pose immediate defense and national security risks [75]. The potential for refugees fleeing into other countries from either the lack of resources or from increasingly destructive weather will strain resources in many areas of the world. This context poses specific risks of injury to humanitarian aid, law enforcement, and medical workers.

The strongest correlation between increased temperatures and conflict is seen in interpersonal violence. Violent crime, rape, and violent intergroup retaliation are all generally positively correlated with increased temperature [74], although specific relationships vary across studies. The observations of uncomfortable heat and human aggression can be seen in both experimental and natural experiments such as aggression among players at sporting events and from domestic violence reports [74]. One example is the aggression of police officers as a function of elevated temperatures during training exercises. It was observed that officers were more likely to become aggressive or draw their weapon on an assailant in training rooms where the temperatures were higher [76]. A study in Greater Manchester showed a positive correlation between sexual assault and maximum temperature [77]. Violent crime is expected to disproportionately increase in economically disadvantaged populations. One study predicts that 20 % of the most disadvantaged neighborhoods in St, Louis, MO, will experience over half the climate-related increased violence in the city [78].

Wildfires

Climate change alterations to wind patterns, temperature, and levels of moisture around the globe will alter the likelihood and magnitude of wildfires, whether started by natural activity (e.g., lightning strikes) or human activity [79]. Considerable effort is expended around the globe to fight wildland fires, and fighting these fires carries the potential for occupational injury or death [80–83]. If there are increases in the number or magnitude of wildland fires, a concomitant increase in vulnerability to occupational morbidity and mortality can be expected.

Predicting wildfire risk is challenging [84] and even more difficult when accounting for changes in climate. In addition to the right physical conditions, fires also need a source. In focusing on the physical conditions, which will be affected by climate change, most research suggests that some areas will see changes in conditions that favor fires while others will see a decreased risk [85–87]. Brown et al. found that some areas of the Western United States are predicted to have increases in fire risk while other areas will see little change [85]. In looking globally, Flanigan et al. reported "To date, research suggests a general increase in area burned and fire occurrence but there is a lot of spatial variability, with some areas of no change or even decreases in area burned and occurrence" [86]. To examine the uncertainty in these predictions, Moritz et al. used output from 16 different global circulation models as inputs to fire models to predict changes in fire likelihood and size [87]. They find that the models do not agree on the direction (higher or lower) of fire risk across 50 % of the globe [87]. In addition, changes in human behavior will be important in wildfire risk. Flannigan et al. remind us "we need more research on the role of policy, practices and human behaviour because most of the global fire activity is directly attributable to people" [86]. If climate change leads to alternations in human activity, such as increased time in wilderness areas (where campfires can start wildfires), increased criminality and arson, or greater proximity of people and forests, the human factor in wildfires may change too.

In the USA, an average of 10.4 wildland firefighters have lost their lives each year between 1910 and 2014, according to the National Interagency Fire Center [88]. Deaths can occur due to exertion from fighting fires (e.g., heart attack), vehicle accidents including trucks and helicopters, and being trapped in the fire, among other causes. Exposure to smoke from wildfires may have significant health effects, too [89]. On average, more than 250 wildland firefighters suffered non-fatal injuries in the USA each year between 2003 and 2007 [80]. The complexity of a fire situation and firefighter experience and training can affect the likelihood of non-fatal injuries [82]. A simple model, assuming that changes in conditions that alter the number or size of wildfires will proportionally change mortality and morbidity associated with firefighting, suggests that climate change may alter the risks of occupational injury or death in wildland firefighters. Increases in heat and air particulate exposures will also increase disease risks to firefighters.

Recommendations and Conclusions

This article has provided an overview of climate change-related exposures and occupational sectors most likely to be affected. In light of projected temperature increases and resulting atmospheric effects, evidence to date suggests that workers will need enhanced protections to reduce exposures to heat, ozone, PAHs, other chemicals, pathogens, wildfires, and violence. Occupational health research agenda setting is needed that takes these climate predictions into account. There remains a need to better characterize the population of workers at risk for climate change effects in different job sectors as well as the nature and context of their work within different geographic regions. This information will support in-depth exposure assessment work that can measure occupational climate change impacts.

Surveillance programs are needed to better track changes in occupational exposures and patterns of injury and illness in relation to changes in climate by an occupational sector. Worker protection strategies can include administrative controls such as altering workday schedules to reduce exposures to hazards with strong temporal patterns, increasing the frequency and length of breaks, as well as developing methods to incentivize workers to use breaks. Workplaces may also require additional training that identifies how climate-related changes to environmental conditions can exacerbate or cause hazards not previously experienced. Jobs requiring personal protective gear need special attention to counteract the dual risks of injury or infection and hyperthermia due to heat-inducing body ware. Gear made of light, heat-dissipating materials, adequate ventilation, and limits on how long a heat-inducing gear is worn all need to be examined to keep workers protected while, at the same time, working under acceptable temperature conditions.

Given the rapid expansion in the use of personal data collection and monitoring sensors, an opportunity exists to leverage these technologies to quantify worker risks in response to changing climate-related hazards, and heat is one exposure ideally suited for monitoring [90]. Small sensor-based technology could be used to pre-warn workers about exposures approaching excessive levels and could also be used to reinforce protective practices.

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Compliance with Ethical Standards

Conflict of Interest Katie M. Applebaum, Jay Graham, George M. Gray, Peter LaPuma, Sabrina A. McCormick, Amanda Northcross, and Melissa J. Perry declare no conflicts of interest.

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•• Of major importance

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