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# Extreme Heat and Occupational Health Risks

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## Keywords

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## Abstract

Climate change poses a significant occupational health hazard. Rising temperatures and more frequent heat waves are expected to cause increasing heat-related morbidity and mortality for workers across the globe. Agricultural, construction, military, firefighting, mining, and manufacturing workers are at particularly high risk for heat-related illness (HRI). Various factors, including ambient temperatures, personal protective equipment, work arrangements, physical exertion, and work with heavy equipment may put workers at higher risk for HRI. While extreme heat will impact workers across the world, workers in low- and middle-income countries will be disproportionately affected. Tracking occupational HRI will be critical to informing prevention and mitigation strategies. Renewed investment in these strategies, including workplace heat prevention programs and regulatory standards for indoor and outdoor workers, will be needed. Additional research is needed to evaluate the effectiveness of interventions in order to successfully reduce the risk of HRI in the workplace.

## INTRODUCTION

**Heat rash:** skin irritation that occurs when sweat is trapped in the skin

**Heat cramps:** painful muscle spasms that may occur during heavy exercise in hot environments

**Heat syncope:** fainting episode due to heat exposure

**Heat exhaustion:** fatigue, nausea, weakness, dizziness, or headache resulting from heat exposure

**Heat stroke:** overheating to a body temperature of ≥104°F, due to prolonged exposure to or physical exertion in high temperatures. Can cause organ failure and death if not treated promptly

Climate change is increasing average global temperatures as well as the frequency and severity of extreme heat events. While climate change presents challenges for the general public, it also presents a serious threat to those workers whose livelihoods depend on exposure to increasingly hazardous conditions. Occupational injuries and illnesses related to climate change are well documented and may be worsened by socioeconomic factors or precarious working conditions (75). Rising temperatures and heat events are expected to increase the number and types of workers with adverse health impacts from extreme heat. In addition to direct effects, extreme heat has indirect health effects and economic impacts, including increased risk of injuries, mental health impacts, and lost labor productivity (27, 64, 117).

The burden of extreme heat will be unevenly distributed among the workforce. Certain occupations and industries will be at higher risk due to job tasks, working environment, and other factors. For example, occupations that require outdoor work or high levels of physical exertion are particularly vulnerable to extreme heat (126). Individual factors, such as socioeconomic circumstances, may increase worker vulnerability, placing them at higher risk for heat-related illness (HRI) (see the sidebar titled Heat-Related Illness). Furthermore, certain regions of the world are likely to be disproportionately affected by extreme heat. Low- and middle-income countries often have less access to cooling resources, a greater reliance on manual labor, and a higher concentration of vulnerable populations, as compared with high-income countries (17, 119).

Despite their prevalence, heat-related morbidity and mortality are preventable. To mitigate the effects of extreme heat on the most vulnerable workers, multiple strategies should be considered. Investments in adaptation and mitigation measures such as elimination or substitution of localized heat sources, engineering and administrative controls, and regulatory protections can help protect workers from extreme heat. In this review, we examine the evidence on extreme heat and occupational health risks, assess which occupations are at highest risk of HRI, discuss how different regions may be disproportionately affected, identify research needs, and offer solutions to mitigate heat-related impacts in the most vulnerable occupational groups.

## EVIDENCE ON EXTREME HEAT AND OCCUPATIONAL HEALTH RISKS

Exposure to extreme heat can lead to a range of adverse health effects. Most human biological processes function within a narrow temperature range; under normal conditions, the body carefully maintains a core temperature (Tc) of 37°C through thermoregulation. Heat accumulation from the environment and physical exertion is balanced by heat dissipation through mechanisms including sweating and peripheral vasodilation (18).

HRIs occur when the body's adaptive responses to heat are overwhelmed, and heat accumulation exceeds heat dissipation. These responses range from milder conditions, such as heat rash and heat cramps, to more serious conditions such as heat syncope, heat exhaustion, and heat stroke

### HEAT-RELATED ILLNESS

HRI refers to a spectrum of medical conditions that result from exposure to high temperatures. For this review, we are comprehensively defining HRI as the indirect and direct health effects of heat exposure. HRI includes relatively mild conditions, such as heat rash or heat cramps, as well as more severe or life-threatening conditions, such as heat stroke. Indirect effects may include injuries or exacerbation of other cardiovascular or respiratory conditions.

(50). Heat stroke, characterized by a Tc greater than 40°C and central nervous system impairment, results from a breakdown of thermoregulatory processes and leads to multiorgan failure and death without prompt treatment (116).

In addition to these acute heat illnesses, extreme heat exposure can cause a range of adverse health outcomes, such as exacerbation of underlying illnesses and injury to individual organ systems. Heat-related exacerbations of cardiovascular, respiratory, and psychiatric conditions are well documented (116). Extreme heat exposure can cause renal dysfunction and acute kidney injury; repeated episodes of acute kidney injury associated with heat exposure are hypothesized to be an important contributor to chronic kidney disease of unknown etiology (CKDu), which is on the rise in many of the hottest regions of the world (97).

Extreme heat is also associated with indirect health effects. For instance, high ambient temperatures can lead to increased absorption of chemicals through mechanisms such as higher ventilation rates and peripheral vasodilation, which can lead to increased toxicity (19). In addition, hot conditions may lead to fatigue and impaired judgment and coordination; elevated temperatures have been associated with increases in traumatic injuries in workers (13, 22, 105). Heat and other environmental exposures, including air pollution, may have interacting effects that impact morbidity and mortality (109). Extreme heat also results in economic losses, increased health care costs, and lost work time associated with HRIs, as well as decreased productivity under hot working conditions; these losses are borne by individual workers and society as a whole (17, 64).

While HRI can affect all individuals, workers are particularly vulnerable because they typically have little control over working conditions and environments. Personal factors such as age, sex, medical conditions, medication use, and substance use can place individual workers at higher risk of adverse health effects from extreme heat. Workers with medical conditions, such as diabetes, cardiovascular disease, kidney disease, and obesity, and workers who take certain medications, such as diuretics, anticholinergics, or stimulants, are at elevated risk; male workers and younger workers have also been found to have higher rates of HRI (57, 69, 126). Workers may also face job-related risk factors such as strenuous physical activity, use of personal protective equipment (PPE) that impedes heat dissipation, or work in outdoor or non-climate-controlled spaces. Conversely, workplace protections such as access to water, cool spaces, and rest breaks, and gradual acclimatization for new workers to allow for physiological adaptation, can help mitigate the risk of occupational HRI (69). Factors that affect a worker's risk of HRI are presented in **Figure 1**.

While HRI has been well documented in occupational populations, accurately capturing epidemiologic risk is challenging. Milder HRIs are often self-limited and may not result in interaction with the medical system, making their incidence difficult to quantify. In addition, exacerbations of underlying illnesses and traumatic injuries associated with extreme heat may not be attributed to heat exposure and classified as heat related. Finally, even when HRIs are documented, work-relatedness may not be captured, making it difficult to quantify occupational risk. All these factors contribute to underestimation of the true burden of occupational HRI.

**Acute kidney injury:** sudden or abrupt decrease in kidney function or ability to filter waste products from blood

**Chronic kidney disease of unknown etiology (CKDu):** chronic kidney disease that is unrelated to known risk factors such as diabetes and hypertension

**Wet bulb globe temperature (WBGT):** measure of heat stress in direct sunlight, which takes temperature, humidity, wind speed, sun angle, and cloud cover into account

## RISK FACTORS FOR OCCUPATIONAL HEAT-RELATED ILLNESS

### Exposure Assessment

Identifying and characterizing workers at highest risk of HRI require methods of exposure assessment. Surveillance and epidemiologic studies often use occupation or industry as a surrogate measure of exposure. However, environmental or individual measures, or combinations of these approaches, can characterize exposures with more specificity. The wet bulb globe temperature (WBGT), a commonly used environmental index, incorporates measurements of humidity, air movement, radiant heat, and temperature (49). Environmental methods can draw data from


**Figure 1**

Examples of heat-related illness factors. Adapted from NIOSH (69, figure 4–1).

static meteorologic sensors (28) or use model predictions (3, 121). Individual-level worker measurements may include approximation of Tc, physiologic or strain assessments, and hydration status (99). Several worker heat stress indices incorporate some physiologic aspects, including the cumulative heat (47), physiological (92), and perceptual strain index (124). However, not all indices incorporate key environmental and individual-level measurements appropriate for assessing worker exposure. A 2022 review found that only 61 of 167 identified thermal strain indices incorporated active metabolic state, temperature, wind, and other parameters suitable for occupational heat stress and strain (66).

## Individual and Work Arrangement Factors

New workers, meaning those who are new or returning to a job and lack acclimatization to heat, are at risk for occupational heat illness because they may not be accustomed to the physical activity and environmental conditions of their job. Acclimatization, or physiological adaptation to heat, occurs gradually over several days of heat exposure (126). Reviews of HRI investigations by the US Occupational Safety and Health Administration (OSHA) have found that more than 70% of heat-related fatalities occurred during the first week on the job (127), and some deaths occurred on the worker's first day (7). A retrospective cohort study of US Army soldiers found that heat illness events peaked during the second month of military service and substantially declined thereafter (96). In addition to lacking the opportunity for physiological adaptation, new workers may be unaware of heat illness signs and symptoms or prevention measures such as hydration and taking breaks in cool areas. Without protections such as acclimatization programs and HRI prevention education, new workers are vulnerable to extreme heat.

Migrant workers have high overall rates of occupational injuries; they often have extended work hours, poor working conditions, and limited safety trainings in comparison to native counterparts (88, 94). For example, a study of heat perception among construction and agricultural workers in Italy found that migrant workers were more likely to be informed of risks via informal written or oral communications, whereas native workers received training on heat illness issues through formal courses (5, 6, 88, 108). Migrant workers can be subjected to exploitative workplace practices, including late or nonpayment of wages (5), and may be temporary, seasonal, or undocumented, often facing difficulties accessing benefits such as workers' compensation (WC) or health insurance (94). They may tolerate dangerous working conditions and be reluctant to report symptoms due to financial pressure and fear of employer retaliation or disclosure of immigration status (94). Language barriers can also interfere with health and safety training (94).

## Outdoor Work

Occupations at highest risk of heat illness include those with outdoor labor in hot climates, such as workers in agriculture, construction, mining, and landscaping, as well as those in non-climate-controlled indoor settings, such as production workers. These workers are typically at risk due to their exposure to hot environments, labor-intensive tasks, and lack of access to cooling resources, such as shade, air conditioning (AC), and fans.

Agricultural workers are at elevated risk of heat-related mortality compared with workers in other industries (7, 53) (**Table 1**). In addition, elevated risk of nonfatal HRI among agricultural workers has been documented through analysis of WC claims data (57). Farmworkers are often paid per output, which can be a strong financial incentive to increase work effort and avoid taking breaks despite high temperatures (30, 104). Agricultural work that requires hand harvesting and minimal mechanical equipment may place workers at higher risk for HRI (104, 136). For example, sugarcane harvesters perform physically demanding work with machetes to cut and pack sugarcane on fields that have been burned prior to harvest (16, 32). Sugarcane harvesters from Thailand, Costa Rica, Nicaragua, and El Salvador have reported HRI symptoms (14, 16, 31, 74). Moreover, sugarcane workers are a subset of agricultural workers with a higher-than-expected rate of CKDu, which some researchers hypothesize is related to extreme heat exposure and chronic dehydration (72).

Construction workers are also at high risk for HRI as identified in the United States, India, China, Japan, Taiwan, and Australia (36, 40, 56, 82, 129, 137). Several factors may increase risk, including physical exertion from labor-intensive tasks, protective clothing, and frequent and direct exposure to sunlight and high outdoor temperatures. While construction workers make up 6% of the US workforce, they accounted for 36% of occupational heat-related deaths from 1992 to 2016 (36). Specific construction occupations at high risk for HRI include cement and brick masons, roofers, helpers, and laborers, as well as heating, AC, and refrigeration mechanics (36). These occupations require heavy manual labor, including assembling scaffolding, loading materials, and using heavy machinery and power tools (36, 136). While protective clothing can shield construction workers from sun exposure, it may also prevent sweat evaporation and trap heat, increasing workers' risk of HRI. Landscaping workers are also at high risk of HRI due to physical exertion from carrying heavy equipment and working long hours in direct sunlight (11, 60).

Other outdoor workers at risk for HRI include first responders, such as firefighters, and those in extraction industries. Wildland firefighters perform physically demanding work, including hiking and constructing firelines, containment areas near the perimeter of an uncontrolled wildfire, by using equipment or hand tools to clear flammable material. A study using individual Tc

**Table 1 Select research on occupations and industries at high risk for adverse effects of extreme heat**

| Worker group | Hazards | Proxy for exposure | Findings | Location | References |
|---|---|---|---|---|---|
| Agriculture | Ambient heat, physical exertion | Industry | 35-fold risk of heat-related death versus all other industries | United States | 53 |
| | | I/O | Crop production and support activities for agriculture and forestry industries had high HRI WC claims case numbers and rates | California, USA | 57 |
| | | NA[a] | Large proportions of outdoor farmworkers report symptoms of heat illness | Georgia, North Carolina, USA | 8, 45, 89 |
| | | Tc, hydration status, WBGT | Dehydration observed among 28 northern Mexico farmworkers; elevated Tc (37–38°C) >80% of workdays | Mexico | 132 |
| Construction | Ambient heat, heavy equipment, physical exertion | Occupation | Construction workers account for 6% of the US workforce but accounted for 36% of occupational heat-related deaths 1992–2016 | United States | 36 |
| | | I/O | High HRI WC claims rates in the construction industry and roofing occupations | Washington, USA | 15 |
| | | I/O | From 2006 to 2017, the construction industry comprised more than 25% of WC claims | Washington, USA | 58 |
| | | Maximum daily humidex | Near-linear relationship between humidex (a measure of apparent temperature) and risk of traumatic injury among construction workers | Washington, USA | 22 |
| | | WBGT, skin temperature, Tc, metabolic rate | Strong relationships between WBGT and both Tc and skin temperature among construction workers; no relationship between WBGT and metabolic rate of construction workers | Spain | 65 |
| Firefighting | Ambient heat, heavy equipment, physical exertion, PPE | NA[a] | 74.8% of firefighters experienced HRI; 5% experienced HRI symptoms ≥20 times a year | Korea | 76 |
| | | I/O | Firefighters had the highest HRI WC claims rate compared with other occupations | California, USA | 57 |
| | | NA[a] | 86% of wildland firefighters reported perceived heat strain (higher heart rate, sweat rate, body temperature) or reported witnessing the impact of heat strain among colleagues | Spain, Italy, Portugal, Argentina, Brazil, Chile, Mexico | 24 |

(*Continued*)

**Table 1 (*Continued*)**

| Worker group | Hazards | Proxy for exposure | Findings | Location | References |
| --- | --- | --- | --- | --- | --- |
| Mining | Ambient heat, heat-generating and heavy equipment, physical exertion | Tc, WBGT | 78.3% of open cut miners had Tc above safety thresholds; 78.4% of underground miners and 69.6% of open cut miners reported moderate heat illness | Tanzania | 87 |
| | | NA[a] | 87% of surface miners and 79% of underground mining workers reported heat illness symptoms | Australia | 61 |
| | | NA[a] | Average cost per OHI WC claim in the mining industry exceeded that of most other industries | Australia | 138 |
| Military | Ambient heat, heavy equipment, physical exertion | NA[a] | 488 incident cases of heat stroke and 1,864 cases of heat exhaustion among US Army, Navy, Air Force, and Marine Corps members in 2021 | United States | 134 |
| Indoor | Heat-generating equipment, poor ventilation, lack of cooling | NA[a] | Work-related hospitalizations for heat-related acute kidney injury identified among workers at manufacturing facilities (glassware, metals, plastics, explosives, food), restaurants, paper mills, bakeries, smelting facilities, greenhouses, barns, warehouses, supermarkets, and ships undergoing repair | United States | 114 |
| Athletics | Ambient heat, physical exertion | NA[a] | 48% of track and field athletes competing in world championships experienced symptoms of exertional heat illness | In Beijing with varied country representation | 107 |
| | | NA[a] | Among a cohort of long-distance runners, 10 serious events related to heat stroke for every cardiac adverse event | Israel | 139 |
| Landscaping | Ambient heat, heavy equipment, physical exertion | Maximum daily temperature and heat index | Mean maximum daily temperature for landscape and horticultural services HRI claims was 95°F<br>17% of HRI WC claims within agriculture and forestry sectors occurred in landscaping and horticultural services industries, with landscaping, groundskeeping, and logging workers as the most represented occupations | Washington, USA | 118 |

Abbreviations: HRI, heat-related illness; I/O, industry and occupation; NA, not applicable; OHI, occupational heat illness; PPE, personal protective equipment; Tc, core body temperature; WBGT, wet bulb globe temperature; WC, workers' compensation.

[a]Refers to studies without proxy for heat exposure, for example cross-sectional studies with self-reported or perceived heat-related outcomes.

monitors in wildland firefighters found occupational exposure to physical exertion increases Tc and subsequent risk of HRI (133). Structural firefighters are also at risk for HRI due to exertion; cadets and instructors were found to be at increased risk for rhabdomyolysis, a serious condition where muscle breaks down, which can lead to kidney damage (42). Risk of HRI among first responders can be exacerbated by the use of PPE, which can increase Tc and prevent sweat evaporation (24, 76). While PPE such as flame-retardant coats, pants, gloves, boots, hoods, and self-contained breathing apparatuses protect firefighters from burns and smoke inhalation, its weight can increase workload, exacerbating risk of HRI. PPE affects other first responders similarly; one study found a significantly stronger association between heat exposure and HRI among oil spill response workers using PPE compared with workers who did not use PPE (44).

**Rhabdomyolysis:** muscle injury from heavy use or trauma causing muscle breakdown; toxic by-products can damage the kidneys

Mining workers are at risk of HRI due to ambient heat as well as heavy workload activities, including drilling and blasting (37). For example, virgin rock temperatures increase with depth and expose underground mining workers to hot and humid conditions (136). Decades-old research from South Africa and Australia indicate that muscle cramps and heat exhaustion were common among underground mining workers (61, 37). More recent research indicates that HRI remains a concern among open cut miners and underground mining workers (61, 87, 100).

Professional athletes are at risk for exertional HRI, particularly when motivated to perform at maximum effort during competitions (106). Athletes perform physical activity for varying durations of time, from brief spurts of explosive strength, such as sprinting, to longer durations, such as long-distance running (107). These activities can raise Tc and cause thermal strain leading to HRI (107). For example, Hollander et al. (59) found that about one-quarter of all illnesses at outdoor athletic championships were classified as HRI, with the greatest risk among elite marathon runners and race walkers.

Military personnel often engage in strenuous physical activity with heavy equipment during training exercises and military operations (106), which can lead to HRI. The youngest and least experienced members of the military are the most at risk for HRI (134). A review of heat stress in Australian workplaces found that the highest peak Tc occurred during military-related activities, even when carried out in cooler environments (70).

## Indoor Work

Research on HRI among indoor workers remains limited. Indoor workers who utilize heat-generating equipment, particularly in poorly ventilated settings, or work in non-climate-controlled environments, such as warehouses, may be at risk of HRI. Most existing studies on indoor workers and HRI have focused on production settings with heat point sources, such as factory workers in foundries, steel plants, glass and automobile manufacturing, and food production facilities (9, 46, 48, 51, 54, 113, 120). Studies of WBGT indices found that indoor food production workers may be exposed to excessive indoor heat (62, 113).

## Incarcerated Workers

Last, incarcerated workers are vulnerable to heat stress yet are often not afforded the same protections as other workers. Incarcerated workers perform indoor and outdoor jobs, including firefighting, construction, cooking, cleaning, laundry, and manufacturing (91), many of which are known to be at high risk for HRI. The extent to which incarcerated workers are impacted by extreme heat is unknown; incarcerated workers are not typically captured in data sources used to characterize occupational heat illness, as these sources are limited to noninstitutionalized populations.

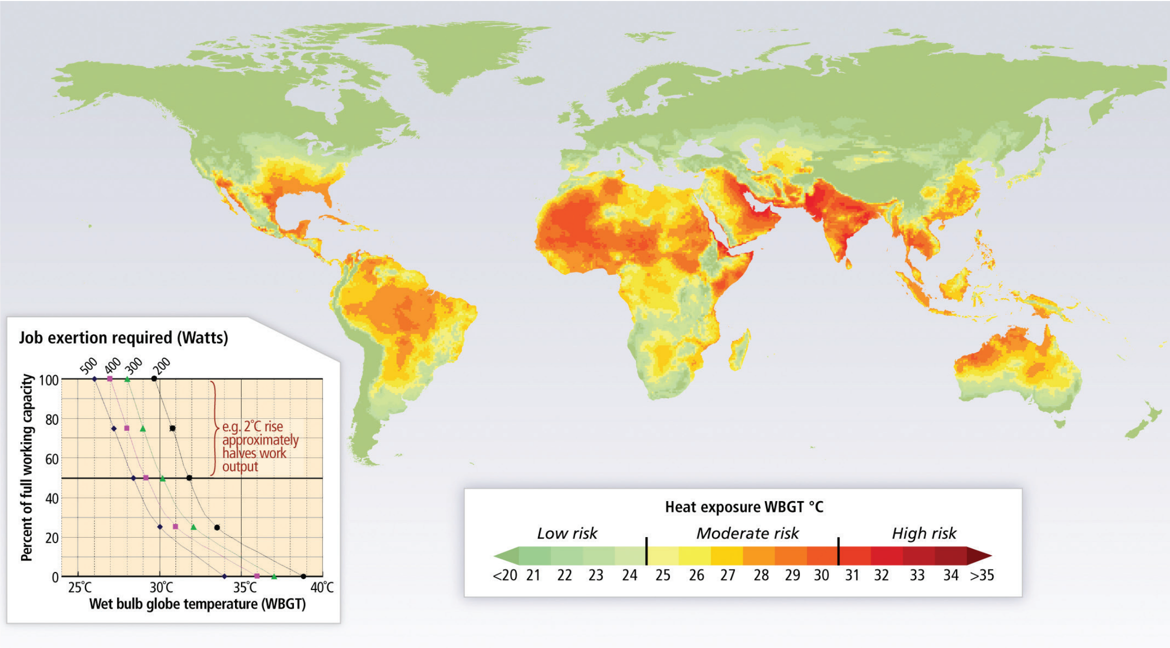


**Figure 2**

Worldwide average temperatures, 1980–2009. IPCC figure caption: The 1980–2009 average of the hottest months globally, measured in web bulb globe temperature (WBGT), which combines temperature, humidity, and other factors into a single index of the impact on work capacity and threat of heat exhaustion. The insert shows the International Organization for Standardization standard (ISO 1989) (68) for heat stress in the workplace that leads to recommendations for increased rest time per hour to avoid heat exhaustion at different work levels. This is based on studies of healthy young workers and includes a margin of safety. Note that some parts of the world already exceed the level for safe work activity during the hottest month. In general, with climate change, for every 1°C that Tmax goes up, the WBGT goes up by about 0.9°C, leading to more parts of the world being restricted for more of the year, with consequent impacts on productivity, heat exhaustion, and need for air conditioning to protect health [Lemke and Kjellstrom (81)]. Copyright © Intergovernmental Panel on Climate Change, figure 11–5 from Human health: impacts, adaptation, and cobenefits. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (115).

## REGIONAL DISPARITIES

Geography, gross domestic product (GDP), distribution of industries, conflict, and urbanicity can modify how heat affects working populations. In recent years, extreme heat has disproportionately affected low-income regions, including sub-Saharan Africa and Southeast Asia, in comparison with wealthier regions of the world (**Figure 2**). Projections from climate models predict excessive increases in WBGT in these regions as well (98). Low-income regions experienced greater than 30% more heat wave days compared with high-income regions in the 2010s (4), and densely populated low-income regions, including India and Bangladesh, have experienced an undue share of heat waves (4). Despite contributing the least to climate change, low-income countries often bear a higher burden of heat stress yet have more limited access to resources, including cooling infrastructure, health care, and workplace safety regulations to mitigate heat's impact on working populations. Moreover, the regions at greatest risk of heat wave frequency and severity are least represented in the literature (23). An estimated 5.6 billion people live within 40° of the Equator (77), where projected maximum WBGT is centered. The global working population (**Table 2**) is estimated to grow to 6.6 billion by 2030, distributed unevenly across regions (63). Moreover,

**Table 2 Worldwide regional summary of key heat and employment characteristics**

| Region | Mean Annual Temperature Change Range[a] | Climate Classifications[b] | 2021 Share of Global Labor Force[c] |
|---|---|---|---|
| Africa | 1–2°C | Arid desert, to savannah and rainforest | 13% |
| Middle East and Arid Asia | 1–2°C | Semi-arid and desert | 3%[d] |
| Australia and Pacific Islands | 1°C | Arid, tropical, and temperate | 0.5% |
| Asia | 1–2°C | Tropical monsoon to deserts | 49% |
| Europe | 1–2°C | Semi-arid to highland | 6% |
| Americas | 1–2°C | Polar to tropical | 7% |
| Antarctic and Arctic | 2°C | Polar | - |

[a]Change between mid-century projections (2040–2059) and historical (1986–2005), under moderate emissions with median probability assumptions (29). Projections are based on the World Climate Research Program's Sixth Coupled Model Intercomparison Project (102).

[b]Defined by Köppen climate classification system (10, 63).

[c]Does not sum to 100%; labor force participation data are missing for some countries.

[d]Includes North Africa.

labor force migration due to climate change or conflict is an ever-growing risk factor for HRI, given a lack of acclimatization combined with more frequent heat waves worldwide. Heat waves and rising temperatures demonstrate the importance of focusing on disproportionately affected regions and the urgency of implementing protections for workers to minimize heat stress inequities across the globe.

## Africa

Based on the Intergovernmental Panel on Climate Change Sixth Assessment Report for 2022, excess deaths are projected under moderate to high warming scenarios for largely populated North, West, and Central Africa (67), with West Africa anticipated to have the hottest areas globally (77). In addition to excess deaths, occupational heat stress is estimated to drive 6% GDP loss for West and Central Africa (34). In 2019, 226 million Africans were employed in agriculture (112), an industry that is highly susceptible to heat stress. Moreover, 57% of the largely low-income African population lives in rural areas (67). A large proportion of African workers are employed in informal jobs characterized by a lack of labor protections, with limited access to social benefits, including injury insurance; these factors increase the vulnerability of this worker population. Heat and drought will affect African agricultural industries; along with conflict, these climate changes are projected to drive large migratory shifts to urban areas by 2050 (67). Rapid urbanization may compound risks for workers due to the urban heat island, a phenomenon where urban areas experience higher temperatures than do rural areas (63). Rural-to-urban shifts may redistribute the workforce across industries; urban worker populations are increasingly vulnerable to HRI within manufacturing and services, particularly in settings that lack cooling resources and workplace protections. Thus, workers in African countries may be disproportionately affected by rising global temperatures.

## Middle East and Arid Asia

Middle Eastern and Arid Asian industries, including agriculture, construction, and services such as tourism, may be disproportionately stressed by heat waves or rising temperatures; these industries often rely on migrant or low-income labor in desert environments (38). Migrant workers comprise a large percentage of workers in this area and are employed predominantly in construction and domestic work (63); risk of HRI is exacerbated by language barriers in these populations.

## Australia and Pacific Islands

Several of Australia's major industries, including agriculture, mining, and construction, are particularly high risk. Moreover, as climate change drives increases in incidence and severity of wildfires, military personnel and firefighters are likely to face increased risks as they mobilize in emergency response (70). Heat extremes will also disrupt agriculture and forestry, construction, and service industries, which dominate select Pacific islands (Papua New Guinea and Samoa), placing workers at risk and forcing adaptation to new types of work or work processes (39, 63).

## Asia

A large portion of the world's working population is found in Asia; China and India comprised 22% and 14% of global employment in 2021, respectively (135). Together, China and India employ more than 400 million in agriculture (112). Indirect consequences of extreme heat have already impacted agricultural workers, e.g., suicides among Indian farmers because of drought (12). Garment manufacturing, in China and Cambodia (78), and auto manufacturing, in India, are crucial GDP contributors and predominantly indoors (25); many factories are poorly ventilated (73), increasing the risk of HRI. Informal workers, such as domestic workers, street vendors, laborers, and home-based workers, comprised 90% of employment within one Indian state (35), and these workers are vulnerable to extreme heat. As workers migrate to urban areas of South and Southeast Asia, both indoor and outdoor workers will be increasingly exposed to extreme heat for longer durations (63, 67) and may lack cooling resources. To address the growing threat of heat, the Chinese government instituted a regulation that requires employers to pay high-temperature subsidies to workers who are exposed to extreme heat (140); the costs of these subsidies are anticipated to soar after 2030 (140). Extreme heat will magnify existing disparities in Asia, placing workers increasingly at risk.

## Europe

Across Europe, heat waves have become longer and more frequent, while average temperatures are projected to gradually increase (see **Table 2**) (29). Workers in Southern European countries with larger agriculture and construction sectors, such as Cyprus, Italy, and Spain, were deeply impacted by past heat waves and remain at risk (101, 103).

## The Americas and the Caribbean

In North America, annual temperatures have trended upward since 1960 (67). WBGT-based models predict localized, hot areas within North America, including parts of Mexico and the United States, particularly in states with large migrant working populations, such as Texas and California (77). Inequities in heat-related outcomes are stark in the United States, where workers of color experience greater heat-related mortality compared with white workers (53) and are overrepresented in high-risk industries such as agriculture and construction (53). Central and South America have a high proportion of low-income populations (63) and are projected to have frequent, intense, and longer heat waves (67). Temperature increases and heat waves will affect agricultural communities in Central and South America (67), many of which are made up of indigenous populations (55). In addition, informal workers account for more than half of the workforce in Central and South America (55).

## RESEARCH NEEDS AND GAPS

A key research need is an improved understanding of which, and how many, workers are at elevated risk for HRI; without these metrics, it is difficult to estimate the public health impact of HRI or to extrapolate the results of existing studies to the broader working population. Estimates of the magnitude and distribution of HRI are needed to ensure occupational safety and that health programs allot funding and target interventions accordingly. Low- and middle-income countries are anticipated to bear the brunt of climate change, including extreme heat, and have less capacity for occupational health research and legislation and fewer robust estimates of working populations (95, 97). Most research on HRI is performed using administrative data sources such as WC claims information or mandated reports to agencies such as the US OSHA and Bureau of Labor Statistics (111, 136). Even in high-income countries with established census programs and occupational health and safety infrastructure, administrative data sources provide poor estimates of the employment and demographics of at-risk industries. Many industries at highest risk for HRI, such as agriculture, are among the least consistent reporters to surveillance systems and have many immigrant, undocumented, and seasonal or temporary workers (52, 80, 111), which may not be captured in these data. These systems also typically exclude informally employed, self-employed, and contract workers (80, 111, 122). Evidence indicates that these sources miss a significant number of all occupational injury and illness cases and that this effect varies by industry and type of outcome (111). Syndromic and other public health surveillance systems should include occupation and industry data so that work-related end points can be identified.

Recognition of and diagnostic guidelines for work-related HRI and other outcomes of extreme heat exposure (e.g., acute kidney injury) are needed to accurately enumerate cases. While the risks faced by outdoor workers and industrial trades (e.g., mining, smelting) have been comparatively well characterized, rapid growth in warehouse and delivery occupations with a high risk of HRI will require further monitoring and research (52). Future research must include other population sensitivities acknowledged in evidence-based climate and health vulnerability tools (**https://skylab.cdph.ca.gov/CCHVIz/**) for subgroup analysis, including women participants (93, 136) and individual factors such as age and underlying health conditions as well as disabilities, income, race/ethnicity, immigration status, language, and health insurance status (52).

The hazards created by extreme heat in the workplace are affected by the contexts in which workers live. Urban heat islands and substandard worker housing can prevent overnight cooling periods, which are essential to reducing the risk of HRI (52, 83). In these cases, acclimatization may not be protective because longer periods exposed to workplace heat will correspond to elevated overnight heat (52). Research is needed to characterize these workers and design interventions that address workers' off-work hours as well. Climate change will also increase the frequency of heat wave events (41), preventing acclimatization. Interventions must be developed and assessed that are effective during short periods of intense heat.

Current methods of exposure assessment have limitations that could be addressed with further research and validation (49). While evidence indicates that WBGT provides the most accurate assessment of environmental HRI risk, it is not widely available at worksites, conditions may vary within a site depending on the location of work, and prevention measures based on WBGT do not account for a range of clothing worn and work activities (33). Heat index, which is sometimes used to guide workplace HRI prevention decisions, does not sufficiently protect workers (128). In an analysis of reported work-related HRI fatalities in the United States, researchers found that most deaths occurred when US National Weather Service heat warnings describing a risk of heat stroke were not in place (110). An evidence-based measure of environmental HRI risk that is easily interpreted and accessible to workers and supervisors would aid prevention efforts.

Specialized equipment and the practical burdens of implementation highlight the challenges of using individual measures. Physiological monitoring of Tc is the gold standard for field research and faces obstacles; rectal temperature is typically impractical or unacceptable to measure in occupational settings, and alternatives (tympanic thermometers, telemetric pills, wearable monitors) have limits in accuracy and acceptability (99). Workload or work rate is often poorly defined despite being a component of regulations. Estimates of workload are often unavailable for highly specific job tasks, and objective measurements can be burdensome to implement in research (time-motion analysis) or are in need of validation for specific work activities (accelerometers) (64, 90). When implemented correctly, individual monitoring can be useful for exposure assessment and early intervention; however, its limitations highlight the need for it to be used in conjunction with other prevention strategies.

Ongoing evaluation of prevention strategies and policies is needed to recognize successes and opportunities for improvement. While there is evidence in multiple countries and industries that programs including education, rest breaks, hydration, and cooling gear are acceptable to workers and increase knowledge of HRI prevention (43, 84–86, 93, 101), less evidence exists that these programs result in decreased rates of clinical or self-reported HRI symptoms or associated outcomes following implementation. Many studies of cooling interventions have a duration of two hours or less (26, 93) and do not provide evidence that these methods are successful in the longer term or even over a full work shift. Further assessment of existing occupational HRI regulations would also be beneficial; regulations have been established in several countries and localities, but all are subject to limitations (64). Within the United States, Tustin et al. (128) reported that the exposure limits recommended by the National Institute for Occupational Safety and Health (NIOSH) are sufficiently protective, but none of the state-based regulations include all recommendations made by NIOSH (36). WC claims for HRI in California continued to increase after implementation of an outdoor HRI prevention standard mandating access to water, shade, and rest periods (57), and workers at farms in regulatory compliance were still dehydrated at the end of their shift (79).

Current HRI prevention efforts are aimed largely at the employer or worker level; however, as extreme heat events become more common and affect more workers, structural interventions including climate change mitigation and adaptation will be necessary (67, 77, 123). These efforts should be based on research that ensures that measures will protect worker health, worker income, and the economic capacity of a locality. Broader interventions to cool cities including green infrastructure (green roofs on buildings, planting trees), pavement lightening to increase surface reflectivity, and increases in permeable surface areas can reduce surface temperatures; these efforts may provide cobenefits to persons living or working in urban areas (71, 125, 130, 131). Programs should be evaluated in a global context to prevent the adoption of strategies that are maladaptive in the long term (e.g., increased provision of AC generated using carbon-based fuel) (67, 93, 101).

Finally, all research must be based on the best available science and well-considered methodologies. Xiang et al. (136) identified a number of epidemiologic analyses of occupational HRI, which used estimation techniques inappropriate to the data or had incomplete adjustment for potential sources of confounding.

## SOLUTIONS AND CONCLUSIONS

HRI among workers has been well documented for several decades and should be an integral part of public health planning to mitigate and prevent the effects of extreme heat on the most vulnerable groups. Understanding the magnitude of HRI among occupational groups is critical to prioritizing resource allocation to address the health impacts of climate change. Extreme heat is likely to cause excess morbidity and mortality among outdoor workers as well as those who work indoors without adequate cooling. Employers should provide a safe environment for all workers, employing relatively simple measures to prevent HRI at work such as the provision of shade, adequate water, and frequent rest breaks. Employer-led occupational heat-stress interventions should be targeted based on workplace setting; interventions suitable for outdoor workplaces may be unsuitable for indoor workplaces and vice versa. For example, shade can be effective to reduce heat stress among outdoor workers, whereas strategies that target infrastructure including increased ventilation and AC are more appropriate for indoor workers. Transitioning away from piece-rate to fixed-pay arrangements may alleviate the risk of HRI by reducing the work pace and encouraging work rest periods. For outdoor workers, reorganizing work schedules to begin during cooler times of the day can reduce exposure to extreme heat (93). Worker education to recognize the signs and symptoms of heat illness as well as acclimatization programs that gradually expose workers to hotter conditions over time may protect workers from HRI.

Policy makers should prioritize promulgation and enforcement of workplace safety regulations that effectively protect workers from HRI; existing evidence-based guidelines and standards can be used as models for public health campaigns and regulatory enforcement (1, 20, 21, 69). Several other countries, including Thailand, China, Gabon, Mozambique, Cameroon, South Africa, Costa Rica, Brazil, Germany, Spain, Cyprus, Qatar, Kuwait, Bahrain, Oman, United Arab Emirates, and Saudi Arabia, have developed workplace protections related to heat (2). Detailed workplace standards with employer mandates, enhanced inspections, and adequate resources dedicated to enforcement can protect workers from the hazards of extreme heat.

Over the next few decades, large-scale global migration, the growing informal labor sector, and widening income inequality may increase the likelihood that low-income vulnerable workers will bear an unequal share of heat burden in the workplace; special attention should be paid to these most vulnerable workers in formulating local, regional, and global solutions. Public health workers, scientists, local community organizations, employers, workers, and their representatives should work together to identify resources and take measures to mitigate the effects of extreme heat in the workplace. Such actions should include

1. Tracking the prevalence of work-related heat illness using physician and hospital reports, administrative data (such as WC claims and disability benefits), and syndromic surveillance;
2. Investigating cases and outbreaks of HRI to identify risk factors and disseminate information about prevention and intervention steps to employers and workers;
3. Educating health care providers to recognize HRI and notify and collaborate with public health and regulatory authorities;
4. Developing and distributing community-level and industry/occupation-specific health information about heat illness, especially during heat waves when it is critical to implement mitigation and prevention measures;
5. Promulgating and enforcing workplace regulatory standards for HRI that include shade, water, rest breaks, and training of workers to recognize the early signs and symptoms of HRI; and
6. Supporting research to improve global data on the burden and magnitude of HRI, to strengthen knowledge about relative workload among occupational groups, and to evaluate effective interventions to mitigate HRI.

Occupational heat illness is a significant public health concern that will require a multifaceted, collaborative approach involving policy makers, regulatory agencies, public health agencies, employers, and workers. Prioritizing workplace safety regulations alongside worker and health care provider education will be critical first steps in preventing occupational HRI. These strategies should underscore workers' rights and environmental justice in their approach by engaging workers in the design and implementation of heat stress interventions and prioritizing solutions that do not exacerbate existing socioeconomic inequities. Last, addressing the underlying drivers of climate change through policies to reduce greenhouse gas emissions is necessary to prevent and mitigate the impacts of extreme heat on workers.

## DISCLOSURE STATEMENT

The authors are not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review. The findings and conclusions in this article are those of the authors and do not necessarily represent the views or opinions of the California Department of Public Health or the California Health and Human Services Agency.

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