Heat, Human Performance, and Occupational Health: A Key Issue for the Assessment of Global Climate Change Impacts

Tord Kjellstrom,[1,2] David Briggs,[3,4] Chris Freyberg,[3] Bruno Lemke,[5] Matthias Otto,[5] and Olivia Hyatt[3]

[1]Health and Environment International Trust, Mapua, Nelson, 7005, New Zealand

[2]University College London, London WC1E 6BT, United Kingdom; email: kjellstromt@yahoo.com

[3]Ruby Coast Research Centre, Mapua, 7005, New Zealand

[4]Geography Department, Imperial College, London, United Kingdom

[5]Nelson-Marlborough Institute of Technology, Nelson 7010, New Zealand

Annu. Rev. Public Health 2016. 37:97–112

First published online as a Review in Advance on January 21, 2016

The *Annual Review of Public Health* is online at publhealth.annualreviews.org

This article's doi:
10.1146/annurev-publhealth-032315-021740

Keywords

human heat exposure, climate change, health impacts, work capacity, productivity, socioeconomic effects

Abstract

Ambient heat exposure is a well-known health hazard, which reduces human performance and work capacity at heat levels already common in tropical and subtropical areas. Various health problems have been reported. Increasing heat exposure during the hottest seasons of each year is a key feature of global climate change. Heat exhaustion and reduced human performance are often overlooked in climate change health impact analysis. Later this century, many among the four billion people who live in hot areas worldwide will experience significantly reduced work capacity owing to climate change. In some areas, 30–40% of annual daylight hours will become too hot for work to be carried out. The social and economic impacts will be considerable, with global gross domestic product (GDP) losses greater than 20% by 2100. The analysis to date is piecemeal. More analysis of climate change–related occupational health impact assessments is greatly needed.

INTRODUCTION

Heat stress refers to heat received in excess of that which the body can tolerate, without physiological impairment. It is an important facet of the impact of climate change on human health (75). Heat stress stems from three factors: intra-body heat production from muscular physical activity, external (i.e., ambient) heat, and clothing that affects heat convection and sweat evaporation (64). Consequential adverse effects are generally known as heat strain and include clinical diseases, health impairments, and reduced human performance and work capacity (64, 66). Metabolism, which provides the energy source for muscular movements, is a major internal source of heat and increases with activity level. External heat influences the rate of transfer of intrabody heat away from the body. In hot ambient conditions, therefore, when heat transfer is limited, the core body temperature increases, resulting in serious health risks. Adverse health effects due to exposures to excessive ambient heat (termed here heat exposure) already occur in many parts of the world, not only during heat waves but also due to the need for intensive manual work in hot daily conditions (41). Climate change (10) will increase both the incidence and the severity of these effects. Heat exposure also affects workers' capability to undertake physical activities without harm; in hot conditions, work capacity falls, leading to a decrease of labor productivity. These effects highlight the need for better analysis of the heat/health interface.

This article draws on the large body of physiological evidence that provides indicative estimates of reduced human performance and work capacity because of increased environmental heat (4). The most vulnerable people are those in low-income tropical countries where heavy physical work is common and the hot season is long (62). Our analysis here shows that even in hot parts of some high-income countries, such as in the United States, there are likely to be increased occupational health problems as climate change progresses. In addition, excessive heat exposure affects exercise and sporting activities (6, 8), and it reduces individuals' ability to carry out daily household tasks.

HEAT STRESS AS A HEALTH AND SOCIAL HAZARD

The direct health impacts of heat exposure are usually assessed in terms of mortality (e.g., 24, 48) or hospital admissions (30, 46). Elderly people and individuals with impaired health are especially vulnerable, but heat stroke also occurs among workers who perform heavy labor in hot conditions with potentially wider social and economic implications (64). Reports on heat stroke deaths among agricultural workers in the United States [~30 deaths each year (9)] show that symptoms of serious heat strain are often ignored as individuals continue to work beyond a safe heat exposure limit. Hundreds of cardiovascular deaths each year among construction workers in Qatar may likewise be due to workplace heat (25). In addition, more than 1,000 additional deaths (as compared to the same weeks in preceding years) in the age range 20–70 years occurred during the two weeks of extreme heat in France in August 2003 (32). The fact that most of the deaths in this age range were among men suggests that the impacts may have been at least partly due to excess heat exposures during work (though no analysis has been done). In all of Europe, as many as 70,000 heat-related deaths may have occurred during this heat wave (69), but, again, no analysis of the occupational health component was carried out. In recent years, the epidemic of fatal chronic kidney disease in sugar cane harvesters in Central America (84) has been linked to daily dehydration due to excessive sweating in the hot work environment. However, the scarcity of quantitative field studies on these occupational health issues has created gaps in the evidence needed for climate change impact assessments.

Clinical effects are not the only consequences of excessive heat exposure (**Figure 1**). Physiological effects also act to reduce human performance and work capacity (4, 41). These outcomes have been overlooked in several international reviews of climate change effects (e.g., 12, 83, 86) but were highlighted in the Human Health chapter of the recent Intergovernmental Panel on

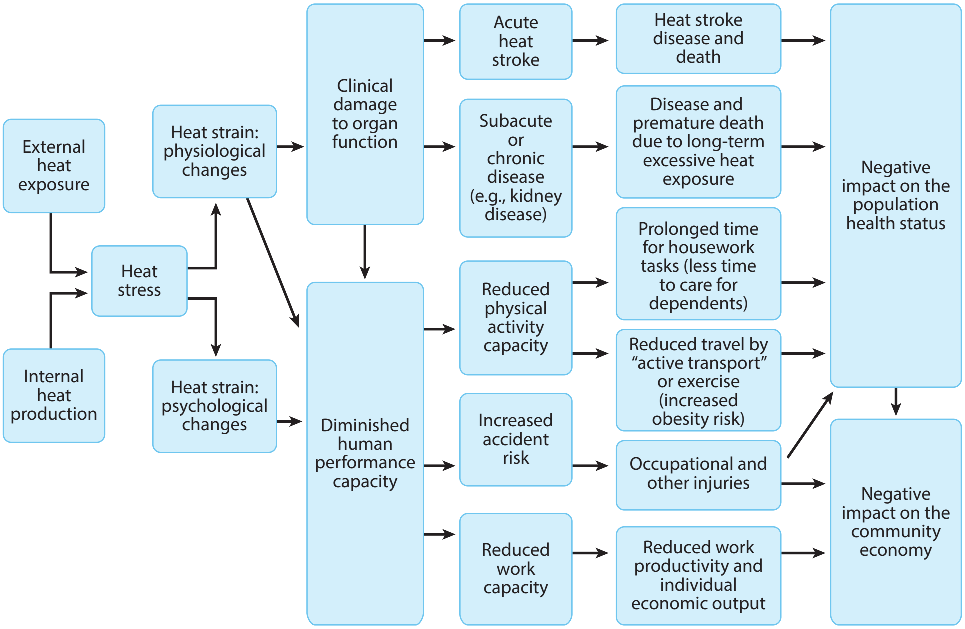

Figure 1

Framework of causal pathways for direct heat effects on working people (45).

Climate Change (IPCC) assessment of impacts of climate change (75). Excessive heat exposure affects not only individuals but also, through impacts on performance and productivity, the local community and economy (**Figure 1**).

Farming communities are particularly affected by increased heat exposures due to climate change. Studies of traditional agriculture in low- and middle-income countries (11, 49, 68) have shown that up to 80% of total farming energy input (megajoules/ha/year) comes from the physical work carried out by farmers. Mechanization clearly offers a substitute for human labor in many agricultural activities (74), but this solution requires economic resources and access to a suitable energy supply and is often beyond the financial capacity of agricultural communities in most developing countries.

Other outdoor occupations, such as construction work, open cast mining, transportation, and community services may also suffer from particular heat-related problems (72). Factory and workshop buildings in hot low-income countries often have no air-conditioning or other effective cooling systems (38). Millions of workers in these countries, who often produce low-price clothes, shoes, furniture, and other consumer products for sale in high-income countries, may experience extreme heat exposures on a regular basis.

Excessive workplace heat exposure is already a problem for many of the tropical and subtropical areas of the world. **Figure 2** shows 30-year monthly averages of the in shade afternoon WBGT (wet bulb globe temperature) heat index levels for the hottest month in each geographic grid cell (0.5 × 0.5° areas; approximately 50 × 50 km at the equator) for the period 1980–2009. WBGT (89) is a measure that combines, within a single index, temperature, humidity, wind speed, and heat radiation, all of which affect rates of heat transfer from the body. When hourly WBGT exceeds 26°C (79°F), hourly work capacity is reduced in heavy-labor jobs, and above 32°C (90°F), any work activity is made difficult (34).

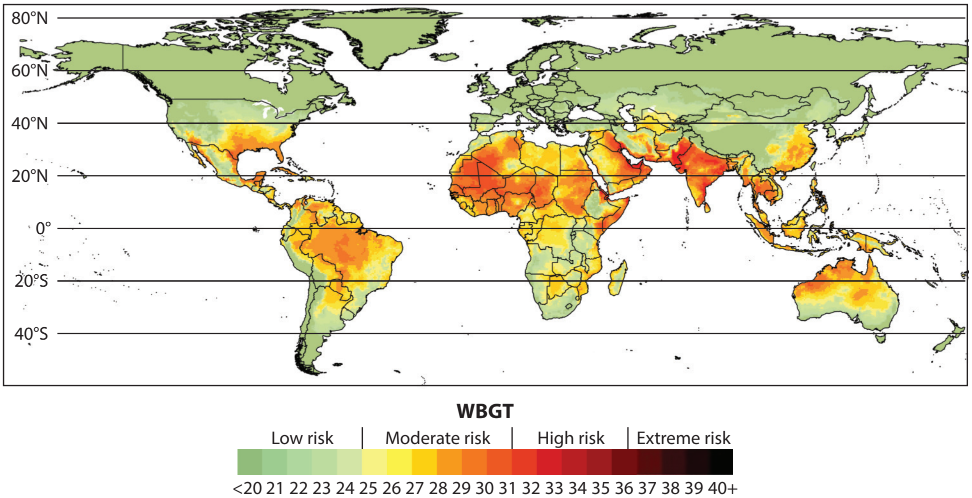

Figure 2

Grid cell–specific monthly average wet bulb global temperature (WBGT) max in-shade levels (afternoon) in the hottest month of each grid cell, based on CRU (Climate Research Unit, University of East Anglia, United Kingdom) data for 1980–2009 (75).

As **Figure 2** indicates, heat exposures over this recent period were sufficient to affect work activities in most of the tropical and subtropical zones. The hot areas in Africa, Asia, and Latin America are very highly populated, and more than four billion people may be affected. The southeast and southwest United States are also at risk on the basis of these values unless effects can be reduced by technologies such as air-conditioning. Historical data corroborate the importance of such cooling measures, at least in the context of factory and office work, as productivity improved when excessive heat exposure was reduced (17).

EFFECTS OF INTENSE HEAT ON HEALTH AND WELL-BEING

As little as 20% of metabolic energy used by muscles contributes to the muscular external work output (64); the remainder of energy used becomes waste heat and needs to be released from the body into the external environment if a rise in the core body temperature from the normal 37°C is to be avoided. Muscular movement is the major energy consumer in the body (4). At high air temperatures (above 34–37°C) (93–99°F), the only method of heat loss is via evaporation of sweat. In high humidity conditions, however, sweat evaporation is insufficient, and other physiological changes cannot prevent the core body temperature from rising to a dangerous level, beyond 39°C (102°F) (4). Heavy labor in hot humid environments is therefore a particularly serious health risk (41). Although it is natural to self-pace and reduce work intensity when the heat stress rises (56), some people keep working beyond the safe limit either because they need to complete work tasks or to maintain work output to get paid (9). Self-pacing will generally reduce individuals' labor productivity (e.g., 82).

Increased core body temperature and excessive sweating, leading to dehydration, can have several direct or indirect implications for health and well-being (**Table 1**). Exposure–response relationships are available for some of these effects, but the evidence is limited and not always suitable for quantitative analysis. This lack of information inevitably impedes attempts to estimate the global health impacts of climate change (55).

Table 1 Climate change–related health impacts of heat according to the Intergovernmental Panel on Climate Change (IPCC), the World Health Organization (WHO), and other sources [modified from De Blois et al. (15)]

Hazard exposure	Health impact	Confidence[a] of this impact	Specific effects at organ level	Source
Intense heat	Heat stroke death	Very high	Heart strain; CNS malfunction; dehydration	27[b], 75
	Heat stroke morbidity	Very high	Heart strain; CNS malfunction; dehydration	75
	Heat exhaustion,Work-capacity loss	High	Heart strain; mental fatigue	75
Forced migration	Undernutrition; infections; mental stress; injuries	High	Work-capacity loss, heart disease, fatigue	75
Health concerns not mentioned in detail in the IPCC or WHO reports				
Intense heat	Chronic kidney disease linked to dehydration		84	
	Increased incidence of violent crimes		22, 65	
	Increased incidence of suicides		3, 36	
	Teratogenic effects of high body temperature in pregnant women; damage to development of brain		19	
	Interactions with prescription drugs		80	
	Deteriorated clinical status in chronic noncommunicable diseases		40, 64	
	Increased damage due to head trauma		79	

[a]IPCC assessment judgment of the confidence for climate change impact.
[b]The WHO (27) report is on climate change–related mortality.

Table 1 indicates that the physiological strain of redistributed blood flow, increased heart rate, and prominent sweating due to excessive heat (possibly resulting in dehydration) affect primarily the cardiovascular system. When core body temperature increases beyond 39°C (102°F), effects on the function of the CNS, such as confusion or unconsciousness, mean that people may not take preventive actions in time. **Table 1** also includes indirect effects, such as forced migration, due to the environment becoming uninhabitable (57, 63, 73). This effect—and its associated health risks—may become a major international problem on a scale beyond the ongoing migrant crisis in Europe (54, 92). **Table 1** also lists concerns that were not analyzed in detail by either the IPCC or the World Health Organization (WHO), including fatal chronic kidney disease, increases in violent crimes and suicides, teratogenic effects of high core body temperature, interactions with prescription drugs, and poor clinical status [increased burden of disability (58)]. For all these reasons, actual health impacts of increased heat during climate change are likely to exceed those indicated by previous estimates (e.g., 55, 27).

Table 2 focuses on the specific health effects related to work. Physical work capacity is taken into account in international and national standards for heat protection at work (64), but cognitive or psychological performance effects are considered primarily in terms of human comfort (29). Determining the effects of excessive heat on the learning ability of schoolchildren is also important, although to date this has been the subject of very little research (13). Given the extreme heat conditions that already occur in many hot, low-income countries, the resulting reduction in educational performance and social and economic development should be a greater concern for international and national agencies than it currently seems to be (no international assessment of the effects of climate change mentions it).

Table 2 Health effects and negative impacts of excessive heat exposure at work

Effect	Evidence; where described	References (examples)
Death from heat stroke at work	South African mine workers; US agricultural workers; China, India, Qatar, and other countries	25, 9, 87, 88, media reports
Specific serious heat stroke symptoms; heat exhaustion	Many hot workplaces around the world; China, India, etc.	60, 64, 91
Clinical damage of organs; heart overload and kidney damage	US military, Central American sugar workers; migrant construction workers in Qatar	23, 25, 40, 71, 77, 84
Injuries due to accidents in hot environments	Europe; Thailand	67, 78
Mood/behavior/mental health; heat exhaustion, cognitive and psychological performance effects	South African mine workers; Australian farmers; Thailand; Cameroon schoolchildren	3, 13, 28, 38, 76, 88
Reduced work capacity, labor productivity, and economic loss; forced migration due to loss of livelihood; heat impact on gross domestic product	India; United States; South Africa	7, 16, 39, 41, 42, 47, 57, 59, 70, 88

As indicated in **Table 2**, the direct effects on health are not the only consequences of concern from heat stress. Reduced work performance and resultant losses of income and nutrition are also important and may lead to further adverse health effects caused by the loss of income. Estimating the impacts on work performance and productivity are difficult because of the need to make assumptions about the capacity for adaptation (e.g., by shifting work to cooler times of the day, applying cooling systems, or supplying sufficient fresh water). There has also been relatively little research from which to derive the equivalent of exposure–response functions, relating performance loss to heat stress. Only three studies have explored these functions in studies of people carrying out their usual daily work, all showing increasing levels of productivity loss with increased heat stress (59, 70, 88). The studies are not directly comparable, however; whereas the last two were based on moderate metabolic rates (300W), the study by Nag & Nag (59) related to low rates (light labor, 200W), though even so, the increasing trend with increasing heat exposure was still apparent (44).

An important factor in the effects of heat stress during work is the frequency and duration of rest breaks. These breaks provide workers with the opportunity to cool down and recover optimum function (and thus work capacity), but these breaks do reduce work time and possibly daily labor productivity. Productivity also depends on the work environment (e.g., cool location with plenty of water for rest breaks), as well as the physiological condition of the workers. For all these reasons, the impacts of climate change on work capacity and on economic productivity are sensitive to adaptation measures and are thus difficult to estimate with confidence. In already hot locations in low-income communities, the opportunities for other adaptations than reduction in work intensity are very slim.

METHODS TO QUANTIFY HEALTH IMPACTS OF HEAT

Assessments of the health impacts of exposures to excessive heat are usually based on a heat index. To be effective, this method needs to be designed to account for all the key climate factors that affect both exposures to heat and human physiological mechanisms (**Table 3**), including air temperature, humidity, air movement (wind speed), and heat radiation (outdoors mainly from the sun) (64). The formula used to calculate the index should also reflect the physical transfer of heat into and

Table 3 Variables of importance to assessing workplace heat impacts on health and well-being

Factor	Variables	Description
Climate/meteorology	Temperature	Outdoors in full sun or in shade. Indoor conditions can be inferred from in-shade data in many tropical area factories and workshops.
	Humidity	
	Wind speed	Need for estimates of hourly heat exposure patterns, including exposure duration (modeled in future impact assessments).
	Solar radiation	
Population characteristics	Distribution	Numbers of residents (by age and sex group)
	Activity patterns	Time spent indoors/outdoors, working, etc.
	Socioeconomic characteristics	Factors such as education and wealth that affect long-term vulnerability to heat stress
	Employment	Numbers or percentages working in high-risk occupations (e.g., heat exposure risk in agriculture, construction)
	Work intensity	Metabolic rate during work for high-risk occupations
	Acclimatization to heat	Influenced by daily variations of heat exposure (e.g., air-conditioning indoors and also work outdoors)
Health outcome	See **Table 1**	Exposure–response functions for all outcomes of interest
Productivity	Work loss	Heat stress–productivity functions for all employment categories of interest

away from the human body and the physiological responses (e.g., sweating and vasodilation in the skin). The impact on the health and performance of an average worker performing an intense work activity can then be assessed from the index.

In any climatic context, the level of heat exposure depends on whether the individual is indoors, in shade, or in full sun. The duration of exposure is also critical in determining the effects of exposure, as are characteristics that influence workers' physiological tolerance to heat—e.g., the level and type of activity, acclimatization, and clothing. Preexisting health, obesity, age, and sex are also important for estimating impacts (**Table 3**).

More than 30 heat indexes have been developed (20), differing both in the input variables they use and in the way their effects are parameterized. Most indexes estimate comfort levels, and few have analyzed the situation in very hot tropical environments. Some indexes require specific measuring equipment, whereas others rely on graphic nomograms to estimate values from measured climate variables. For use in climate change impact assessment, an index should ideally be quantified with a mathematical formula based on climate variables for which reliable modeled estimates are available.

Some indexes do not include solar heat radiation or air movement [e.g., the Heat Stress Index, HSI (64)], and some calculations incorporate so-called standard conditions. For example, the UTCI (Universal Thermal Climate Index) assumes certain types of clothing at different heat levels and a physical activity of walking 4 km per hour (5). In analyses of impacts on occupational health and work capacity, however, the WBGT (89) has advantages. The WBGT was designed to represent heat effects on working people and has been used as a heat exposure index in the few occupational epidemiology studies available (59, 70, 88) and more generally in studies of occupational health. It has also been widely proposed in both national (e.g., 1) and international (34) guidelines and standards and has been extensively tested in laboratories and in the field by the US army (26). The in-shade or indoor values can also be calculated from routine weather station data using mathematical formulas (2, 50, 51).

Whichever index is used, the specific environment of exposure (outdoors in-sun or in shade, indoors with or without air-conditioning) also needs to be known (or inferred) to allow the risk of heat effects to be estimated (**Table 3**). These conditions vary both within and between countries.

In low-income tropical countries, for example, indoor heat exposures would be similar to those experienced outdoors in shade owing to the lack of air-conditioning. Agricultural workers in these countries may be assumed to be working in full sun during hotter periods of the day (e.g., afternoon), though they may seek shelter in the shade when possible. However, many agricultural and construction workers cannot protect themselves in this way except, in some situations, via large sun hats (84).

Weather stations routinely measure temperature and humidity in shade ["in a place sheltered from direct solar radiation" (85)]. The contribution of heat radiation from the sun is not always routinely measured. Full-sun values can be converted from estimates of heat in full shade using available hourly solar heat radiation values by latitude and longitude (see **http://power.larc.nasa.gov/cgi-bin/timeseries.cgi?&p=&email%20=dailylarc.nasa.gov**). WBGT levels in full sun during hot afternoons in tropical areas are ~2–3°C (36–37°F) hotter than the in-shade values (43).

Wind speed ideally also needs to be incorporated into the index. Wind speeds vary considerably over the short term (e.g., hourly) and also between indoors and outdoors. Indoors, air movement can be increased by fans; however, when air temperature is above 37°C (99°F) and relative humidity is above 60%, fans may actually increase the heat stress (35) because of the intensified flow of hot air over the skin. When relative humidity is very low (10%, very dry air), fans help reduce heat stress up to a temperature of 48°C (118°F) (35). Additionally, working people usually move their arms and legs, generating their own air movement over their skin (~1 meter per second). Allowing for these various effects is clearly difficult, though fortunately for calculations, the impact of air movements on heat stress varies little at speeds above ~1 m/s (50).

Given the complexity of the factors affecting heat exposure and stress, availability of relevant climatic and other data is clearly an important constraint in estimating impacts (**Table 3**). Depending on the type of assessment (e.g., retrospective or prospective) data on future as well as past conditions will be needed. The spatial representation of these data is also important because ultimately investigators usually need to apply the values to populations, which are unevenly distributed geographically. Point data (e.g., for weather stations) thus have to be extrapolated to provide estimates of population exposures. Many different methods may be used for this purpose; however, unless information on local conditions is incorporated, important variations in heat exposure—for example, the additional heating in urban areas due to urban heat island effects—tend to be ignored (61). Lack of information on intra-urban climate may mean that risks in urban areas, where the majority of people live, are underestimated.

The exposure periods and durations of relevance vary greatly depending on health outcomes and levels of stress (**Table 1**). Heat exhaustion, for example, may set in after less than an hour of exposure in extreme conditions (high temperature and humidity and intense work). Cardiac arrest may also occur in a short time in people with preexisting heart conditions. In contrast, effects of undernutrition and mental stresses (**Table 1**) may take years to manifest. Thus there is a need for different averaging times for the heat index for different circumstances. Information on the metabolic rate associated with work or other high-intensity activities (e.g., sports) is of great importance (**Table 3**). In addition, working people who have already suffered from health effects of heat are more vulnerable than the people without such experience (64).

Except for small—and not necessarily representative—groups of people (e.g., athletes), little of the information needed to estimate the social and behavioral aspects of heat stress is usually available at an individual level. For practical reasons, therefore, assessments of health effects generally rely on area or population averages, derived from census data, or demographic or health surveys. Nevertheless, the physiological relationships between the environment, behavior, and modifiers of heat stress are well known (4) and were taken into account when international standards were developed for heat stress (e.g., 34, 64). Likewise, much detailed research has been done on the design of clothing or clothing materials that serve as barriers against heat or that reduce heat stress (31, 33).

ASSESSMENTS OF CLIMATE CHANGE–RELATED HEAT STRESS IMPACTS IN WORKPLACES

As the preceding discussion has indicated, the potential climate change–related population-level health impacts of occupational heat stress on working people are now being recognized (18, 37, 38, 41, 53). The recent IPCC assessment of human health effects (75) highlighted this issue, but no quantitative analysis was included. To date, only two studies have attempted to assess the global health impact of heat due to climate change in any comprehensive way (55, 27). Both studies make assumptions about adaptations to climate change and the effects of susceptibility to heat stress, and both rely on epidemiological data from studies of prolonged heat waves, mainly in North America and Europe. Such heat wave effects are unlikely to represent the impacts felt in low-income, developing countries in tropical areas.

Studies on the impacts of heat stress on work capacity are also rare. An analysis from Perth, Australia (53), based on projections of Australia's climate through 2070, explored the likely physiological effects of heat exposure in association with intense physical activity (including work) on human performance. Results indicated that whereas an average person, acclimatized to heat, could safely carry out physical activity or manual labor outdoors during all but one day per year in the 1990s, climate change would increase the number of days with dangerous heat exposure to 15–26 days per year by the 2070s (53).

Using the WBGT index and the international standard (34) for safe work, Kjellstrom et al. (42) made quantitative, worldwide estimates of the impacts of increasing workplace heat on global and regional populations as a result of climate change. Analysis was based on the assumptions that the mixture of jobs outdoors/indoors and at different work intensities stayed the same and that gross domestic product (GDP) increased over the study period (1975–2050). Results showed that climate change between 1975 (as the median year of the period 1961–1990 for which climate data were used) and 2050 would reduce the available work hours in all regions. The estimated reductions at the population level varied between 0.2% for Australasia and 18.6% for Central America. Other highly affected regions were Southeast Asia (18.2%), West Africa (15.8%), Central Africa (15.4%), Oceania (15.2%), the Caribbean (11.7%), and South Asia (11.5%). A shift in the workforce distribution away from physically demanding jobs to less ardent service jobs will make these reductions smaller, and use of heat-protection methods (adaptation) will reduce them further; however, in some countries, significant reductions in labor productivity will likely remain.

A more recent study examined likely changes in work capacity for an average worker in Southeast Asia (43) using the Wyndham (88) productivity loss data. March is the hottest month in much of this region, and **Figure 3** shows the large potential decrease in work capacity from 1975 to 2050 and the differences between work in the sun and work in the shade. Heavy labor in the sun is most affected and, in 2050, would face a 29% loss of annual work hours. Moderate labor in the sun faces smaller losses (about 15%), and labor in the shade or indoors face even lower levels.

Another study of the worldwide impacts of workplace heat on working people was published by Dunne et al. (18). Their analysis focused on the loss of labor productivity during the hottest months in each part of the world over the period 1975–2200, using estimated WBGT levels together with the US national (1) and international (34) standards for safe work intensities at various WBGT levels. Reductions in work capacity, defined in this way, during the hottest months already occur at the global level [6–10% reduction (18)]. By 2100, the reductions in the hottest month may reach 37% based on RCP8.5 and 20% based on RCP4.5 (18). During the coolest months, the

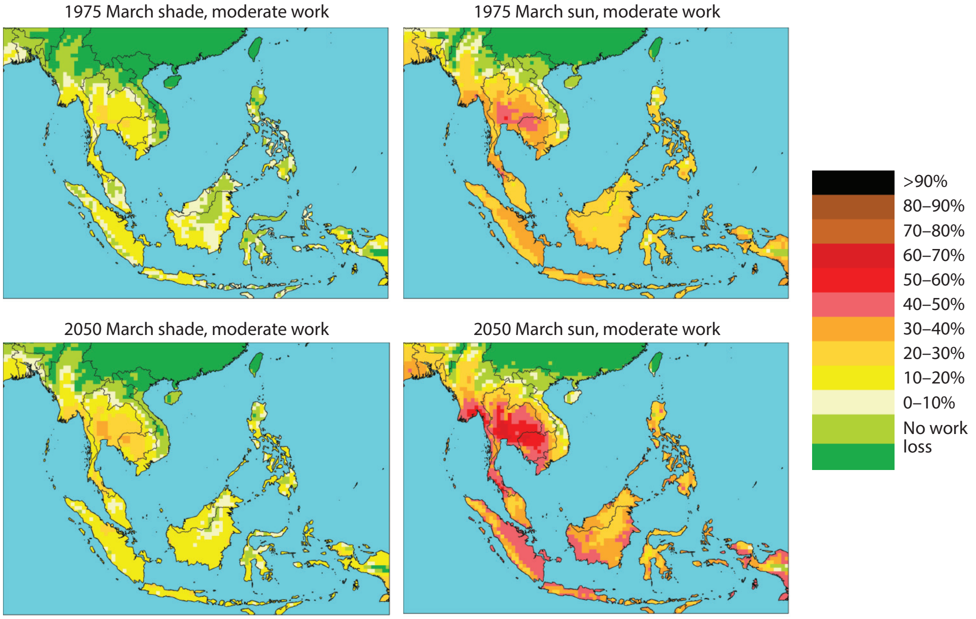

Figure 3

Modeled work capacity loss, in percent of available afternoon working hours in March, in Southeast Asia for moderate (300W) intensity work; comparison of 1975 and 2050 for in-shade and in-sun conditions (43).

reductions may be ~5% and 1% for these RCPs, respectively. By 2200, very significant further changes in work capacity are projected for the hottest month based on RCP8.5 (as high as 61% reduction during the hottest month), and the annual work capacity loss is 12% using the industrial threshold limit (safety standard) for light labor [further details are shown in graphics by Dunne et al. (18)].

Another analysis of labor productivity loss for the United States (47) was based on a single study of US time-use patterns in relation to daily heat conditions. The analysis reported a reduction in the proportion of time applied to work during the hottest months in most of the United States and presented the results in terms of economic losses. Together, these studies show that reductions in human capacity for physical activity (including work, active transport, leisure, sport and performance of routine daily tasks) are likely to induce substantial work time losses, with potentially serious economic consequences in geographic regions that will experience increased duration and intensity of the hot seasons.

The first global and national estimates of the economic consequences of reduced labor productivity resulting from increasing heat exposure due to climate change were made by DARA (14), on the basis of physiological impacts and labor productivity loss data from Kjellstrom et al. (42). These results projected a total global GDP loss of US$2.1 trillion (PPP $) for 2030. As a percentage of the national GDP, losses varied markedly and were greatest in tropical low- or middle-income countries (e.g., 0.0% in the United Kingdom and Japan, 0.2% in the United States, 0.8% in China, 3.2% in India, 6.0% in Indonesia and Thailand, and 6.4% in Nigeria and Ghana) (14, 39). A second, more recent global analysis using annual average temperatures and national GDP for different countries (7) concluded that as much as 23% of global GDP in 2100 will be lost owing to climate change. Reduced labor productivity due to increasing heat was just one of a number of causes considered.

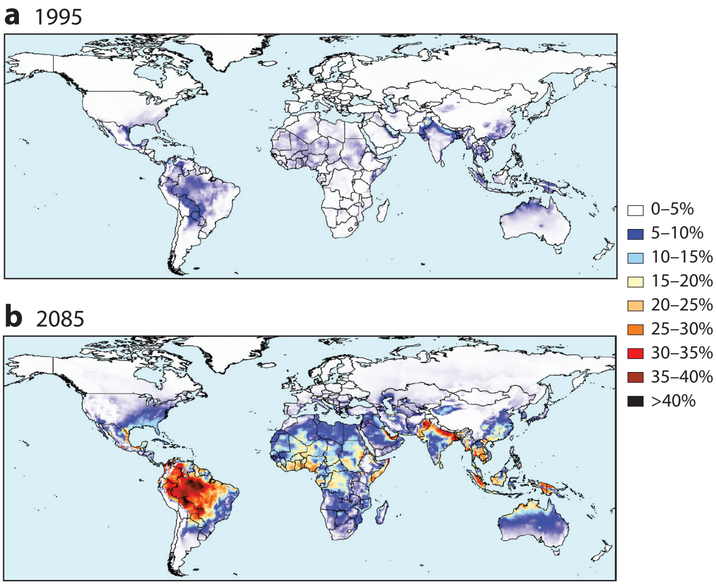

Figure 4

The percentage of annual daylight in-shade work hours lost (at a metabolic rate of 300W) in each grid cell in (*a*) 1995 and (*b*) 2085 as a result of climate change (based on HadGEM2, RCP8.5) (B. Lemke, T. Kjellstrom, and C. Freyberg, unpublished observations).

A third methodological approach was used in the study by Zander et al. (90). Self-reported estimates of absenteeism and reductions in work performance (presenteeism) caused by heat in Australia were based on information from 1,726 employed people. The individual economic losses due to heat were US\$655 per person, which translates to an economic burden totaling US\$6.2 billion in Australia. Future projections were not presented, but these results indicate the importance of heat exposure for economic output. Further studies would clearly improve our understanding of potentially significant social and economic effects and perhaps inspire further political motivation to mitigate the consequences of climate change.

Figure 4 shows results from a new analysis, conducted by the authors of this article (B. Lemke, unpublished observations), using climate data derived from the HadGEM2-ES model and the RCP (Representative Concentration Pathways) 2.6 and 8.5. These represent the most extreme of the potential future climate scenarios used by the IPCC in 2013 (10). Analysis was done using climate data presented on a $0.5 \times 0.5°$ grid (81) for 1995 and 2085 (surrounding 30-year periods, 1980–2009 and 2070–2099). WBGT was calculated using modeled daily measurements of temperature and humidity (ISI-MIP data) for the 67,000 grid cells over land, assuming an average air movement at 1 m/s and no solar heat radiation, as would be experienced for a physical laborer working indoors (without cooling) or outdoors in the shade (50). Population and employment data for the two target years were converted to the same grids. An exposure–response function for work capacity loss was derived on the basis of two available epidemiological studies (70, 88) to estimate the percentage of daylight hours that would be so hot in 2085 that work capacity would necessarily be reduced.

The substantial reduction in work capacity (and related labor productivity) between 1995 and 2085 is clearly seen in the maps (**Figure 4**). The areas with the greatest risk in 2085 remain the same (Amazon region, West Africa, Arab Gulf area, Pakistan, North India, Indonesia, and parts of China), but substantial reductions in work capacity are apparent in the southeast United States, parts of Europe, Africa, and the rest of India and China. Although some of these areas have low populations (e.g., parts of the Amazon and Australia), the majority have a high population density, implying that large numbers of people will be affected. The southern coast of the Arab Gulf area has a number of large cities and few people in between. The urban heat island effect may have special importance in this region. A recent paper (63) highlights the extreme daily heat levels of the local atmosphere that will occur later this century.

Expressed as the number of person-hours lost due to heat in whole regions (i.e., the work capacity loss multiplied by the working population in each grid cell and then summed up for all grid cells in a region), the impact in the hottest regions varies between 1% and 10%, assuming that no change in heat adaptation takes place (B. Lemke, unpublished observations). These numbers are averages at the regional level for a mixed workforce (average metabolic rate = 300W; in shade or indoor noncooled work). The amount of work capacity loss varies both by job intensity (activity level) and by environment (shade or sun). Locally, and nationally, therefore, impacts may be more severe, depending on the working conditions and type of employment (as illustrated in **Figure 3**).

The calculations we present are based on the human performance and work capacity loss for people acclimatized to the local heat situation. Physiological acclimatization takes less than two weeks (64); even once individuals are fully adjusted, they will have to utilize behavior change (work during cooler hours, take more rest periods, improve hydration, etc.) and/or technical solutions to further reduce their heat vulnerability. Air-conditioning or other cooling systems can reduce the heat effects of indoor work, but the cost and sustainability of any cooling system will influence the extent of its application (52). Many millions of people will likely be unable to protect their daily activities and work from the increasing heat due to climate change. It should also be noted that the daily use of air-conditioning makes the person more sensitive to heat exposure, as the acclimatization may be incomplete.

CONCLUSIONS

Climate change during the twenty-first century will result in increased exposures to intense heat in many parts of the world. Without effective adaptation measures, workers engaged in heavy labor or working in humid and poorly ventilated conditions face increased risks of heat stress and are likely to suffer reduced performance and work capacity as consequences. In situations where full adaptation to the increased heat levels cannot be implemented, labor productivity will diminish, with potentially large economic consequences. The physiological basis for the reduction in human performance and work capacity is well known, but the application in assessments of climate change impacts has, so far, been piecemeal.

The local loss of work capacity (or labor productivity) during daylight working hours is currently up to 10% in particularly hot areas of the world and could be as high as 30–40% by 2085. Estimates of the related global reductions in GDP project a loss of US$2 trillion per year by 2030 and another loss of 23% of global GDP in 2100. These costs will be distributed unevenly across the world, with tropical regions experiencing the greatest impacts and poor communities bearing the brunt of the effects. To reduce these impacts, a range of adaptation measures will be needed, geared toward local conditions and communities. These include changes in working practices, mechanization of heavy labor, and the installation and use of air cooling technologies. Because these adaptations are often costly and themselves take time to implement, the initial steps to introduce them are already urgently needed. On the other hand, the economic losses without climate change mitigation and heat adaptation are likely to be substantial in many affected countries and, at the global level, may be counted in trillions of USDs.

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.

ACKNOWLEDGMENTS

This project was carried out via the Health and Environment International Trust and the Ruby Coast Research Center. We acknowledge the provision of detailed global grid cell data on climate conditions and modeling from ISI-MIP at Potsdam Institute (Berlin) and CRU, the Climate Research Unit at the University of East Anglia (Norwich). Funding for some of our costs was provided by the Pufendorf Institute, Lund University, Sweden.

LITERATURE CITED

1. ACGIH (Am. Conf. Gov. Ind. Hyg.). 2009. *TLVs for Chemical Substances and Physical Agents and Biological Exposure Indicators*. Cincinnati, OH: ACGIH
2. Bernard TE, Pourmoghani M. 1999. Prediction of workplace wet bulb global temperature. *Appl. Occup. Environ. Hyg.* 14:126–34
3. Berry HL, Bowen K, Kjellstrom T. 2010. Climate change and mental health: a causal pathways framework. *Int. J. Public Health* 55:123–32
4. Bridger RS. 2003. *Introduction to Ergonomics*. London: Taylor & Francis. 2nd ed.
5. Bröde P, Balzejczyk K, Fiala D, Havenith G, Holmér I, et al. 2013. The Universal Thermal Climate Index UTCI compared to ergonomics standards for assessing the thermal environment. *Ind. Health* 51:16–24
6. Brotherhood JR. 2008. Heat stress and strain in exercise and sport. *J. Sci. Med. Sport* 11:6–19
7. Burke M, Hsiang SM, Miguel E. 2015. Global non-linear effect of temperature on economic production. *Nature* 527:235–39
8. Casa DJ, Clarkson PM, Roberts WO. 2005. American College of Sports Medicine Roundtable on hydration and physical activity: consensus statements. *Curr. Sports Med. Rep.* 4:115–27
9. CDC (Cent. Dis. Control Prev.). 2008. Heat-related deaths among crop workers—United States, 1992–2006. *MMWR Weekly* 57(24):649–53
10. Collins M, Knutti R, Arblaster J, Dufresne J-L, Fichefet T, et al. 2013. Long-term climate change: projections, commitments and irreversibility. In *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, ed. TF Stocker, D Qin, G-K Plattner, M Tignor, SK Allen, et al., pp. 1029–36. Cambridge, UK/New York: Cambridge Univ. Press
11. Common MS, Stagl S. 2005. *Ecological Economics: An Introduction*. Cambridge, UK: Cambridge Univ. Press
12. Costello A, Abbas M, Allen A, Ball S, Bell S, Bellamy R, et al. 2009. Managing the health effects of climate change. Lancet-Univ. Coll. London Inst. Glob. Health Comm. *Lancet* 373:1693–733
13. Dapi LN, Rocklov J, Nguefack-Tsague G, Tetanye E, Kjellstrom T. 2010. Heat impact on schoolchildren in Cameroon, Africa: potential health threat from climate change. *Glob. Health Action* 3: doi: 10.3402/gha.v3i0.5610
14. DARA. 2012. *Climate Vulnerability Monitor 2012: A Guide to the Cold Calculus of a Hot Planet*. Madrid: Fund. DARA Int. 2nd ed. **http://www.daraint.org/wp-content/uploads/2012/10/CVM2-Low.pdf**
15. De Blois J, Kjellstrom T, Agewall S, Ezekowitz JA, Armstrong PW, Atar D. 2015. The effects of climate change on cardiac health. *Cardiology* 131:209–17
16. Dell M, Jones BF, Olken BA. 2009. Temperature and income: reconciling new cross-sectional and panel estimates. *Am. Econ. Rev.* 99:198–204
17. Dorgan CB, Dorgan CE, Kanarek MS, Willman AJ. 1998. Health and productivity benefits of improved indoor air quality. *ASHRAE Trans.* 104:658–68

18. Dunne JP, Stoufer RJ, John JG. 2013. Reductions in labour capacity from heat stress under climate warming. *Nat. Clim. Change* 3: doi: 10.1038/NCLIMATE1827
19. Edwards MJ, Shiota K, Smith MSR, Walsh DA. 1995. Hyperthermia and birth defects. *Reprod. Toxicology* 9:411–25
20. Epstein Y, Moran D. 2006. Thermal comfort and the heat stress indices. *Ind. Health* 44:388–98
21. Field CB, Barros VR, Dokken DJ, Mach KJ, Mastrandrea MD, et al. 2014. *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*. New York /Cambridge, UK: Cambridge Univ. Press
22. Gamble JL, Hess JJ. 2012. Temperature and violent crime in Dallas, Texas: relationships and implications of climate change. *West. J. Emerg. Med.* 13(3):239–46
23. García-Trabanino R, Dominguez J, Jansa J, Oliver A. 2005. Proteinuria and chronic kidney disease on the coast of El Salvador. *Nefrología* 25:31–38. (in Spanish)
24. Gasparrini A, Guo Y, Hashizume M, Lavigne E, Zanobetti A, et al. 2015. Mortality risk attributable to high and low ambient temperature: a multi-country observational study. *Lancet* 386:369–75
25. Gibson O, Pattisson P. 2014. Qatar World Cup: 185 Nepalese died in 2013 - official records. *Guardian*. Jan. 24. **http://www.theguardian.com/world/2014/jan/24/qatar-2022-world-cup-185-nepalese-workers-died-2013**
26. Goldman RF. 2001. Introduction to heat-related problems in military operations. In *Textbook of Military Medicine*, Vol. 1, pp. 3–49. Washington, DC: Dep. US Army
27. Hales S, Kovats S, Lloyd S, Campbell-Lendrum D, eds. 2014. *Quantitative Risk Assessment of the Effects of Climate Change on Selected Causes of Death, 2030s and 2050s.* Geneva: WHO
28. Hancock PA, Ross JM, Szalma JL. 2007. A meta-analysis of performance response under thermal stressors. *Hum. Factors* 49:851–77
29. Hancock PA, Vasmatzidis I. 2003. Effects of heat stress on cognitive performance: the current state of knowledge. *Int. J. Hyperth.* 19:355–72
30. Hansen AL, Bi P, Ryan P, Nitschke M, Pisaniello D, Tucker G. 2008. The effect of heat waves on hospital admissions for renal disease in a temperate city of Australia. *Int. J. Epidemiol.* 37:1359–65
31. Havenith G. 1999. Heat balance when wearing protective clothing. *Ann. Occup. Hyg.* 43:289–96
32. Hemon D, Jougla E. 2003. *Excess mortality associated with heat wave in August 2003* (*Surmortalité liée à la canicule d'août 2003 - Rapport d'étape*). Tech. Rep. to the Minist. of Health, Family and Disabled Pers. (Rapp. remis au Minist. de la Santé, de la Famille et des Pers. Handicap.), Sept. 25. INSERM, Paris. (in French)
33. Holmer I, Nilsson H, Havenith G, Parsons K. 1999. Clothing convective heat exchange—proposal for improved prediction in standards and models. *Ann. Occup. Hyg.* 43:329–37
34. ISO (Int. Stand. Org.). 1989. *Hot environments - estimation of the heat stress on working man, based on the WBGT-index* (wet bulb globe temperature). ISO Stand. 7243. ISO, Geneva
35. Jay O, Cramer MN, Ravanelli NM, Hodder SG. 2015. Should electric fans be used in a heat wave? *Appl. Ergon.* 46:137–43
36. Kim Y, Kim H, Honda Y, Guo YL, Chen BY, et al. 2015. Suicide and ambient temperature in East Asian countries: a time-stratified case-crossover analysis. *Environ. Health Perspect.* doi: 10.1289/ehp.1409392
37. Kjellstrom T. 2000. Climate change, heat exposure and labour productivity. *Epidemiology* 11:S144
38. Kjellstrom T. 2009. Editorial: Climate change, direct heat exposure, health and well-being in low and middle-income countries. *Glob. Health Action* 2: doi: 10.3402/gha.v2i0.1958
39. Kjellstrom T. 2015. Impact of climate conditions on occupational health and related economic losses: a new feature of global and urban health in the context of climate change. *Asia-Pac. J. Public Health*. doi: 10.1177/1010539514568711
40. Kjellstrom T, Butler A-J, Lucas R, Bonita R. 2010. Public health impact of global heating due to climate change—potential effects on chronic non-communicable diseases. *Int. J. Public Health* 55:97–103
41. Kjellstrom T, Holmer I, Lemke B. 2009. Workplace heat stress, health and productivity - an increasing challenge for low and middle-income countries during climate change. *Glob. Health Action* 2(Spec. Vol.):46–51

42. Kjellstrom T, Kovats S, Lloyd SJ, Holt T, Tol RSJ. 2009. The direct impact of climate change on regional labour productivity. *Int. Arch. Environ. Occup. Health* 64:217–27
43. Kjellstrom T, Lemke B, Otto M. 2013. Mapping occupational heat exposure and effects in South-East Asia: ongoing time trends 1980–2009 and future estimates to 2050. *Ind. Health* 51:56–67
44. Kjellstrom T, Lemke B, Otto M, Hyatt O, Dear K. 2014. *Occupational heat stress.* Tech. Rep. 2014: 4. Health Environ. Int. Trust, Mapua, New Zealand. **http://www.climatechip.org/sites/default/files/publications/TP2014_4_Occupational_Heat_Stress_WHO.pdf**
45. Kjellstrom T, Lemke B, Otto PM, Hyatt OM, Briggs DJ, Freyberg CA. 2015. Heat impacts on work, human performance and daily life. In *Climate Change and Public Health*, ed. BS Levy, JA Patz, pp. 73–86. New York: Oxford Univ. Press
46. Knowlton K, Rotkin-Ellman M, King G, Margolis HG, Smith D, et al. 2008. The 2006 California heat wave: impacts of hospitalizations and emergency department visits. *Environ. Health Perspect.* 117:61–67
47. Kopp R, Hsiang S, Muir-Wood R, Jina A, Rising J, Delgado M, et al. 2014. *American Climate Prospectus: Economic Risks in the United States*. New York: Rhodium Group. **https://gspp.berkeley.edu/assets/uploads/research/pdf/American_Climate_Prospectus.pdf**
48. Kovats RS, Hajat S. 2007. Heat stress and public health: a critical review. *Annu. Rev. Public Health* 29:41–55
49. Leach G. 1975. Energy and food production. *Food Policy* 1:62–73
50. Lemke B, Kjellstrom T. 2012. Calculating workplace WBGT from meteorological data. *Ind. Health* 50:267–78
51. Liljegren J, Carhart R, Lawday P, Tschopp S, Sharp R. 2008. Modeling wet bulb globe temperature using standard meteorological measurements. *J. Occup. Environ. Hyg.* 5:645–55
52. Lundgren K, Kjellstrom T. 2013. Sustainability challenges from climate change and air conditioning use in urban areas. *Sustainability* 5:3116–28
53. Maloney SK, Forbes CF. 2011. What effect will a few degrees of climate change have on human heat balance? Implications for human activity. *Int. J. Biometeorol.* 55:147–60
54. McLeman R, Smit B. 2006. Migration as an adaptation to climate change. *Clim. Change* 76:31–53
55. McMichael AJ, Campbell-Lendrum D, Kovats S, Edwards S, Wilkinson P, et al. 2004. Global climate change. In *Comparative Quantification of Health Risks, Global and Regional Burden of Disease Attributable to Selected Major Risk Factors*, Vol. 2, ed. M Ezzati, A Lopes, A Roders, pp. 1543–650. Geneva: World Health Organ.
56. Miller VS, Bates GP. 2007. The Thermal Work Limit is a simple reliable heat index for the protection of workers in thermally stressful environments. *Ann. Occup. Hyg.* 51:553–61
57. Mueller V, Gray C, Kosec K. 2014. Heat stress increases long-term human migration in rural Pakistan. *Nat. Clim. Change* 4:182–85
58. Murray C, Lopez A. 1996. *Global Burden of Disease*. Boston, MA: Harvard Sch. Public Health
59. Nag A, Nag P. 1992. Heat stress of women doing manipulative work. *Am. Ind. Hyg. Assoc. J.* 53:751–56
60. Nag PK, Nag A, Sekhar P, Pandit S. 2009. *Vulnerability to heat stress: scenario in Western India*. World Health Organ. (WHO) Rep. APW No. SO 08 AMS 6157206, Natl. Inst. Occup. Health, Ahmedabad, India. **http://searo.who.int/india/topics/occupational_health/Occupational_Health_Vulnerability_to_heat_stress_scenario_of_western_India.pdf**
61. Oke TR. 1973. City size and the urban heat island. *Atmos. Environ.* 7:769–79
62. Olsson L, Opondo M, Tschakert P, Agrawal A, Eriksen SH, et al. 2014. Livelihoods and poverty. See Ref. 21, pp. 793–832
63. Pal JS, Eltahir EAB. 2015. Future temperature in southwest Asia projected to exceed threshold for human adaptability. *Nat. Clim. Change.* doi: 10.1038/NCLIMATE2833
64. Parsons K. 2014. Human thermal environments. In *The Effects of Hot, Moderate and Cold Temperatures on Human Health, Comfort and Performance*, pp. 1–32. London: Taylor & Francis. 3rd ed.
65. Raleigh C, Linke A, O'Loughlin J. 2014. Extreme temperatures and violence. *Nat. Clim. Change* 4(2):76–77
66. Ramsey JD, Bernard TE. 2000. Heat stress. In *Patty's Industrial Hygiene*, ed. RL Harris, Ch. 22. New York: Wiley. 5th ed.
67. Ramsey JD, Burford CL, Beshir MY, Jensen RL. 1983. Effects of workplace thermal conditions on safe working behavior. *J. Saf. Res.* 14:105–14

68. Rijal K, Bansal NK, Grover PD. 1991. Energy in subsistence agriculture: a case study of Nepal. *Int. J. Energy Res.* 15:109–22
69. Robine JM, Cheung SL, Le Roy S, Van Oyen H, Griffiths C, et al. 2008. Death toll exceeded 70,000 in Europe during the summer of 2003. *C. R. Biol.* 331(2):171–78
70. Sahu S, Sett M, Kjellstrom T. 2013. Heat exposure, cardiovascular stress and work productivity in rice harvesters in India: implications for a climate change future. *Ind. Health* 51:424–31
71. Schrier RW, Henderson HS, Tisher CC, Tannen RL. 1967. Nephropathy associated with heat stress and exercise. *Ann. Intern. Med.* 67:356–76
72. Schulte PA, Chun HK. 2009. Climate change and occupational safety and health: establishing a preliminary framework. *J. Occup. Environ. Hyg.* 6:542–54
73. Sherwood SC, Huber M. 2010. An adaptability limit to climate change due to heat stress. *PNAS* 107:9552–55
74. Sims BG, Kienzle J. 2006. *Farm Power and Mechanization for Small Farms in Sub-Saharan Africa*. Agric. Food Eng. Tech. Rep. No. 3. Rome: Food and Agric. Organ. (FAO) of the U.N.
75. Smith KR, Woodward A, Campbell-Lendrum D, Chadee DD, Honda Y, et al. 2014. Human health: impacts, adaptation, and co-benefits. See Ref. 21, pp. 709–54
76. Tawatsupa B, Lim LL-Y, Kjellstrom T, Seubsman S, Sleigh A, Thai Cohort Study Team. 2010. The association between overall health, psychological stress and occupational heat stress among a large national cohort of 40,913 Thai workers. *Glob. Health Action* 3:5034
77. Tawatsupa B, Lim LL-Y, Kjellstrom T, Seubsman S, Sleigh A, Thai Cohort Study Team. 2012. Association between occupational heat stress and kidney disease among 37,816 workers in the Thai Cohort Study (TCS). *J. Epidemiol.* 22:251–60
78. Tawatsupa B, Yiengprugsawan V, Kjellstrom T, Berecki-Gisolf J, Seubsman SA, Sleigh A. 2013. Association between heat stress and occupational injury among Thai workers: findings of the Thai Cohort Study. *Ind. Health* 51:34–46
79. Titus DJ, Furones C, Atkins CM, Dietrich WD. 2015. Emergence of cognitive deficits after mild traumatic brain injury due to hyperthermia. *Exp. Neurol.* 263:254–62
80. Vanakoski J, Seppälä T. 1998. Heat exposure and drugs: a review of the effects of hyperthermia on pharmacokinetics. *Clin. Pharmacokinet.* 34:311–22
81. Warszawski L, Frieler K, Huber V, Piontek F, Serdeczny O, Scewe J. 2014. The Inter-Sectoral Impact Model Intercomparison Project (ISI-MIP): project framework. *PNAS* 111:3228–32
82. Wasterlund DS. 1998. A review of heat stress research with application to forestry. *Appl. Ergon.* 29:179–83
83. Watts N, Adger WN, Agnolucci P, Blackstock J, Byass P, et al. 2015. Health and climate change: policy responses to protect public health. *Lancet* 386:1861–914
84. Wesseling C, Crowe J, Hogstedt C, Jakobsson K, Lucas R, Wegman D. 2013. *Mesoamerican Nephropathy. Report from the First International Research Workshop on MeN*. Heredia, Costa Rica: IRET, Univ. Nac.
85. WMO (World Meteorol. Organ.). 2008. *Guide to Meteorological Instruments and Methods of Observations*. WMO No 8. Geneva: WMO. 7th ed.
86. World Bank. 2014. *Turn Down the Heat: Confronting the New Climate Normal*. Washington, DC: World Bank
87. Wyndham CH. 1965. A survey of the causal factors in heat stroke and of their prevention in the gold mining industry. *J. S. Afr. Inst. Min. Metall.* 65:125–55
88. Wyndham CH. 1969. Adaptation to heat and cold. *Environ. Res.* 2:442–69
89. Yaglou CP, Minard D. 1957. Control of heat casualties at military centers. *AMA Arch. Ind. Health* 16:302–16
90. Zander KK, Botzen WJW, Oppermann E, Kjellstrom T, Garnett ST. 2015. Heat stress causes substantial labour productivity loss in Australia. *Nat. Clim. Change* 5:647–51
91. Zhao J, Zhu N, Lu S. 2009. Productivity model in hot and humid environment based on heat tolerance time analysis. *Build. Environ.* 44(11):2202–7
92. Zhou J. 2011. Climate change, health and migration in urban China. *Front. Econ. China* 6:592–615

Annual Review of Public Health

Volume 37, 2016

Contents

Epidemiology and Biostatistics

Environmental and Occupational Health

Public Health Practice

Social Environment and Behavior

Health Services

Indexes

Errata

An online log of corrections to *Annual Review of Public Health* articles may be found at http://www.annualreviews.org/errata/publhealth