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Occupational Heat Stress

Contribution to WHO project on "Global assessment of the health impacts of climate change", which started in 2009.

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Summary

Increasing heat exposure during the hottest seasons of each year is the most obvious outcome of global climate change, and the issue that greenhouse gas modeling can assess in the most predictable manner. Occupational heat stress is an important direct health hazard related to climate conditions and climate change. The physiological limits of a “livable thermal environment” are well defined, but naturally, the sensitivity to heat exposure has a substantial individual variation.

Modern methods of analysis make possible quantitative estimations of the impacts of current climate and future climate change: mortality, non-fatal heat stroke, heat syncope and heat exhaustion, the latter linked to work capacity loss, which is often overlooked in climate change health impact analysis. For these direct health impacts of climate change, it is the local climate where people live and work that matters.

Using a field change method for three climate model data provided by WHO, estimates of the heat stress index WBGT for 60,000 grid cells around the world were produced. These estimates included monthly values for the hottest four hours and other hours of each day. Using 30-year average estimates for baseline (1960-1989), 2030 and 2050 we calculated the occupational health impacts for fatal and non-fatal heat stroke, as well as work capacity loss. The results depend on whether a person works outdoors in the sun or indoors (or in full shade), the level of exertion required for the work (metabolic rate), and the clothing worn while working.

Occupational heat stress is already a significant problem in several of the 21 regions defined by WHO for this analysis, and more hot days will make the situation worse. The worst affected regions are East Asia; South Asia; South-East Asia; Oceania; Central America; Caribbean; Tropical Latin America; North Africa/Middle East; Central Africa; East Africa; and West Africa. Working populations in low and middle income countries are particularly vulnerable, but many people in high income countries in North America, Europe and Asia are also at risk. Taking estimates of potential changes in the future workforce distribution into account, in the most affected region, South Asia (major country is India), the annual number of fatal cases of occupational heat stress would increase from 14,000 in 1975 by 8,000 – 23,000 in 2030, and by 18,000 – 41,000 in 2050 (depending on the model used). The global number of additional occupational heat stress fatalities due to climate change may amount to 12,000 – 29,000 cases in 2030 and 26,000 – 54,000 in 2050. For non-fatal heat stroke cases we estimated 75,000 cases in 1975 and additional cases due to climate change may be 35,000 – 65,000 in 2030 and 40,000 – 73,000 in 2050 (taking changing workforce distribution into account).

The loss of work capacity globally will affect possibly 2 billion working age people in agriculture and industry resulting in a loss of 1.0 – 1.7% of global annual productive daylight work hours in 2030 (depending on climate model used) and 1.7 – 2.4% in 2050. This assumes no change in the application of workplace cooling methods, but with the assumption of a change in workforce distribution away from heavy labor in extreme heat.

If these work hour losses create equivalent reductions of global GDP, which has been estimated at 140 trillion US dollars in 2030, the global costs of increased occupational heat stress would be 1.4 – 2.4 trillion US dollars in 2030. In the worst affected regions (South Asia and West Africa) the estimated annual work capacity losses at population level are at least twice as high. The worst affected people are those working outdoors in the sun in heavy labor jobs. They already lose approximately 10% of annual daylight work hours due to extreme heat in the hottest regions and this may increase to beyond 20% in 2050. People working in light jobs indoors are not so much affected, and air conditioning can of course prevent the high workplace heat exposures at high cost in certain occupations and countries. Many outdoor jobs, and jobs in workshops and factories, in low and middle income countries are paid at low rates and not likely to receive the protective benefit of air conditioning.

The access to cooling systems for hundreds of millions of people is highly questionable as a recent estimate of the number of people lacking basic sanitation in 2050 was 1.4 billion people. Will they benefit from occupational heat stress prevention at work; - most likely not. Our analysis highlights the major negative impacts that climate change will have on millions of working people. More precise analysis is needed to quantify the costs and benefits of different adaptation and mitigation policies and programs in different countries.

A summary of quantitative estimates for 2030 implies:

- Grid cell based analysis of climate change shows increased heat and longer heat periods particularly in tropical and sub-tropical areas
- There may be 22,000 more occupational heat stroke fatalities in 2030 than in 1975; to this should be added many thousand cases of non-fatal heat strokes and other clinical effects
- Productive annual daylight work hours will be lost globally at 1.4% in 2030, and the global economic costs of the lost labor productivity may be 2 trillion USD per year. The losses at country level will be at multi-billion dollar level for many low and middle income countries.
- The "work life years" lost (similar notion as DALYs) due to occupational heat stroke fatalities in 2030 will be approximately 880,000, while the "work life years" lost due to labor productivity loss may be 70 million years, indicating that the labor productivity loss could be 70 times more damaging to healthy, productive and disability-free life years than the fatalities.
- For a country that will lose an estimated 100 billion USD per year in 2030 due to climate change related increasing heat exposures, it may be a good investment to spend 1 million USD on research and analysis to develop policies and programs to reduce the economic impacts of occupational heat stress. Even if the cost estimate (100 billion USD) is 10 times too high, and the research and analysis only reduces the actual cost by 10%, the savings could still be 1 billion USD per year.

Background

Occupational heat stress as a global health risk

The modelling of global climate change uses greenhouse gas emission estimates and resulting atmospheric heating as a key input into the global assessments (IPCC, 2013, WG1). Clearly, the atmospheric temperature is a primary modelling result and therefore any health and social effects of changing air temperatures are more directly assessed than most of the other projected changes of the climate (humidity, wind, rainfall, etc.). The details of these occupational health and social effects are described in a more detailed report (Kjellstrom et al., 2014a), while this paper summarizes the methods and selected results.

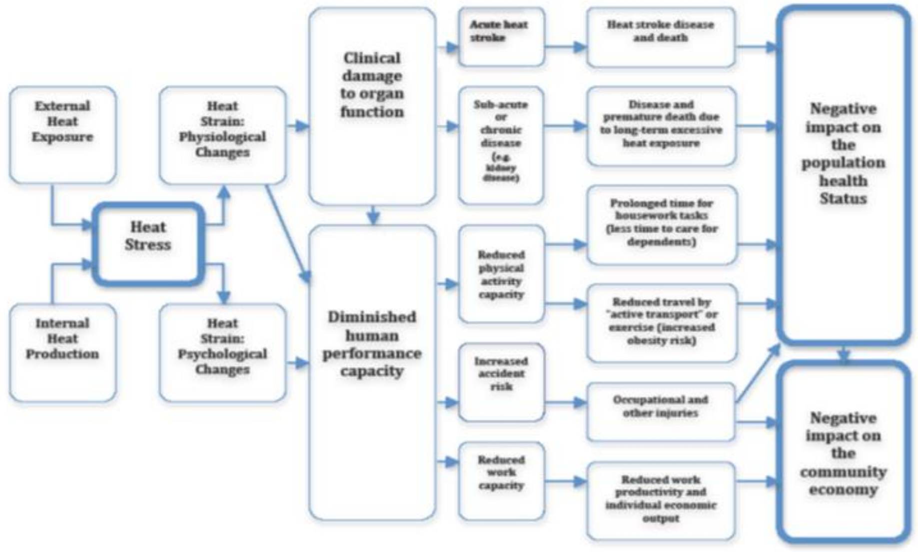
The direct health impacts of heat exposure are generally analysed principally in terms of mortality or hospital admissions (Kovats and Hajat, 2008). Elderly people are at the highest risk for these effects. However, the risk of heat stroke amongst younger working people is well known and explained by the limits of human physiological acclimatization (Parsons, 2003; a new edition of this textbook was published in 2014). Significant numbers of working people die due to heat stroke even in high income countries, as described in a recent study of agricultural workers in the USA (MMWR, 2008). It is also of interest that more than one thousand additional deaths occurred in the age range 15-64 years during the two weeks of extreme heat wave in France in August 2003 (Hemon and Jougla, 2003), but no analysis of the workplace heat exposure contribution to this increased mortality has been carried out.

Apart from clinical health effects, work capacity is affected by excessive heat exposure and hourly work output is reduced (Bridger, 2003; Kjellstrom, et al., 2009a). These impacts on working people have been generally ignored in international reviews of climate change effects (e.g. Costello et al., 2009), which is partly a symptom of the low priority given to occupational health, the focus on “diseases”, and the belief that adult humans can adapt to the emerging heat conditions.

Local people in any part of the world need to adapt as best they can to heat and cold exposure by cultural practices such as “siesta” during the hottest part of the day, reduced work intensity, and the use of hats outdoors and other appropriate clothing (Parsons, 2009). The performance of necessary work during the cooler night hours is an option in some situations, but many work tasks depend on daylight and with climate change even the coolest night hours may create heat stress because humidity can increase to near 100% at night. Traditional practices to reduce heat exposure (e.g. siesta) may be labelled “behavioural acclimatisation” as a part of “adaptation” (Ebi and Semenza, 2008; Fussel et al., 2006) as the preventive effects complement the benefits of “physiological acclimatisation”. The problem is that the hotter it gets, the longer siesta is needed.

As little as 20% of muscle energy contributes to external “work” (Parsons, 2014), and the rest becomes “waste heat” inside the body that needs to be released to the external environment. At high air temperatures (above 34-37 ^{o}C), the only method of heat loss to counteract bodily heat gain caused by work, is via evaporation of sweat. When there is high humidity, sweat evaporation is insufficient and other physiological changes cannot prevent the core body temperature from rising to dangerous levels (Bridger, 2003). Heavy labour in hot humid environments is therefore a particular health risk. Figure 1 shows causal pathways for direct heat effects on working people. While it is natural to “self-pace” and reduce work intensity when the heat stress rises, some people tend to keep working beyond the safe limit for heat exposure because of their need to complete work tasks during a particular period or their need to maintain work output to get paid. These practices are linked to the impacts on the community economy (Figure 1).

Figure 1. Framework of causal pathways for direct heat effects on working people
(source: Kjellstrom, et al., 2014b, in press)



In addition to the direct effects of heat exposure, there are also indirect effects from rising temperatures in certain occupational groups. Agricultural workers may get greater contact with disease vectors (e.g. malaria mosquitoes) that increase in density due to a hotter climate or because more of the work activities are shifted to dawn and dusk when the vectors are most active. Workplace exposures to chemicals that evaporate more rapidly in hot conditions can increase occupational health risks (Bennett and McMichael, 2010).

Studies of traditional agriculture in different countries (Leach, 1975; Rijal et al., 1991; Common and Stagl, 2005) have shown that very high proportions (up to 80%) of total farming energy input (MJ/ha/year) comes from the physical work carried out by farmers. Statistics from the Food and Agriculture Organization of the United Nations (FAO) support this and the importance of mechanization to reduce the problem has been stressed (Sims and Kienzle, 2006), but this approach requires financial resources and access to suitable energy supply.

Occupational heat stress has several potential negative health and well-being outcomes as listed in Table 1. Quantitative exposure-response relationships are available in the literature for some of these heat effects, but the evidence is limited and not always suitable for quantitative impact analysis. The concern for health impacts of occupational heat stress on working people in conjunction with climate change is starting to be documented (Kjellstrom, 2000, 2009a; Kjellstrom et al., 2009a; Maloney and Forbes, 2011; Dunne et al., 2013; and two series of Hothaps papers in 2009 and 2010 in the journal Global Health Action), but more quantitative research is needed. The Hothaps papers (Hothaps = High Occupational Temperature Health and Productivity Suppression; Kjellstrom et al., 2009b) describe situations in several tropical low and middle income countries and can be found in the Hothaps Program Update 2014 (see: www.ClimateCHIP.org).

Table 1. 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; USA agricultural workers; China, India and other countries	Wyndham, 1965, 1969; MMWR, 2008; media reports
Specific serious heat stroke symptoms; heat exhaustion	Many hot workplaces around the world; China, India, etc.	Parsons, 2003, 2014; Zhao et al., 2009; Nag et al., 2009 (and two series of papers in the journal *Global Health Action*, 2009 and 2010)
Clinical damage of organs; Heart overload and kidney damage	US military, Central American sugar workers; migrant construction workers in Qatar	Schrier et al., 1967; Garcia-Trabanino, et al., 2005; Kjellstrom et al., 2010; Tawatsupa et al., 2012; Wesseling et al., 2012; Gibson and Pattison, 2014
Injuries due to accidents in hot environments	Europe; Thailand	Ramsey et al., 1983; Tawatsupa et al., 2013
Mood/behaviour/mental health; Heat exhaustion and psychological performance effects	South African mine workers; Australian farmers; Thailand	Wyndham, 1969; Hancock et al., 2007; Kjellstrom, 2009c; Berry et al., 2010 ; Tawatsupa et al., 2010
Reduced work capacity, labor productivity and economic loss; heat impact on GDP	India; USA	Nag and Nag, 1992; Kjellstrom et al., 2009a, 2009c; Dell et al., 2009; Sahu et al., 2013; Kopp et al., 2014

Reduction of cold stress

In analysis of heat stress impacts on mortality and morbidity it is often pointed out that the rates of health impacts follow a U-shaped curve and that the health risks are high both at the cold and the hot end with elderly people being at highest risk (e.g. Kovats and Hajat, 2008). The question then arises to what extent a climate trend towards higher temperatures would reduce the health impacts at the cold end as well as increase it at the hot end. On this point it should be noted that hard work generates intrabody heat so it is of benefit in colder climates and a significant disadvantage in hotter climates. This must be considered when analyzing the impact of climate change on working people rather than on sedentary elderly people.

A factor of importance for heat and cold exposure is the distribution of the global population by latitude. In 2000 approximately 3,400 million people lived in the tropical and sub-tropical areas (30 degrees up and down from the equator), where additional heat is a hazard, while only 1.9 million people lived in the arctic area with extreme cold (beyond 66 degrees from equator) (based on UN population data). Few people live at high altitude where extreme cold can also be a hazard. In the highly populated warmer areas significant morbidity or work capacity loss due to cold is not to be expected (Parsons, 2014).

Relevant previous studies and estimates

A key issue in the analysis of climate impacts on occupational health and safety is the extent to which the daily “heat stress” or “heat load” will increase. Global gridded estimates of current and future “heat load” have been published by Jendritzky and Tinz (2009), including maps of a heat stress index used in Germany: the HeRATE index (Health Related Assessment of the Thermal Environment). This index takes into account “heat and cold comfort” based on common clothing use in different climates, and local acclimatization over preceding weeks. The published maps included background estimates for 1971 – 1980 and future estimates for 2041 – 2050, and show that increased heat stress is likely in most parts of the world. Another global gridded analysis, using Tw (here = Tpwb) (psychrometric wet bulb temperature) as an indicator of human heat stress (Sherwood and Huber, 2010), concluded that global climate change could substantially reduce habitability of some regions.

The impacts on health and work capacity (and productivity) at an individual level have been studied and published by physiologists and ergonomists for several decades (see reviews by Parsons, 2014 and Bridger, 2003), but analysis in relation to climate change is rare. An analysis for Perth, Australia (Maloney and Forbes, 2011) showed the likely physiological effect of heat exposure and physical activity intensity (including work) on human performance capacity in Perth in the current climate conditions and how it may change in the future based on projections of Australia’s climate until 2070. It was calculated (Maloney and Forbes, 2011) that an average person acclimatized to heat could safely carry out physical activity or manual labour outdoors in the daytime during all but one day per year in the 1990s. However, climate change would increase the number of days with dangerous daytime heat exposure to 15-26 days per year in the 2070s. It should be pointed out that Perth is not a place with the most extremely physiologically challenging heat as high temperatures often occur with concurrent low humidity.

The first quantitative estimates of the impacts of workplace heat on populations in relation to climate change were included as tentative analysis in a conference presentation by Kjellstrom (2000). Another analysis by Kjellstrom et al., (2009c) was the first attempt to assess regional and global impacts of climate change on workplace heat exposures and on productivity. The climate and heat stress data were estimated for a few "representative" locations within 21 large global regions (the same regions as the ones used in this report). The results (Kjellstrom et al., 2009c) showed that climate change until 2050 would reduce the available work hours in all regions (compared to 1961-1990 as a baseline; in this report labeled "1975"), assuming the mixture of jobs outdoors/indoors and at different work intensities stayed the same. The estimated reductions varied between 0.2 % for Australasia and 18.2 % for South East Asia and 18.6 % for Central America. Apart from these two regions, the other most affected regions were West Africa (15.8% reduction), Central Africa (15.4%), Oceania (15.2%), Caribbean (11.7%) and South Asia (11.5%).

When assumptions about changing workforce distributions due to increasing GDP (from baseline "1975" to 2050) were included (Kjellstrom et al., 2009c), the reductions of available work hours were more limited as it was assumed that fewer people will be working in highly heat exposed heavy physical labor jobs in the 2050s. Two regions had estimated population average work capacity increasing somewhat until 2050 due to such assumed workforce changes (tropical Latin America and Southern Africa) and two had no change (West Europe and Central Europe), but in all the other 17 regions the estimated reduction of work capacity by 2050 would be between 0.1 and 4.4%, except for the Caribbean region and Central America where particularly high reductions at 7.7 and 18.6%, respectively, were calculated (Kjellstrom et al., 2009c). These results will be compared with our new estimates in the Discussion section.

Additional analysis of the impacts of workplace heat on working people was published by Dunne et al (2013). They focused on the labor productivity loss during the hottest months in each part of the world and compared estimated WBGT levels with the US national (ACGIH, 2009) and international (ISO, 1989) standards. Very large reductions of "labor capacity" due to heat have already taken place (as high as 90%) and further major reductions are projected (Dunne et al., 2013). As we will show below, using the workplace standards create larger calculated reductions than the likely reductions for a typical workforce. Another analysis of labor productivity loss for the USA (Kopp et al., 2014) was based on a single study of time use patterns in the USA in relation to daily heat conditions. It showed reduced time use during the hottest months in most of the USA and the results were presented as economic losses. These issues will be analyzed in the Discussion.

In conclusion, the few published studies with an analysis of heat exposure impacts on human capacity for physical activities at work (or during "active transport" or leisure or just carrying out routine daily tasks) indicate that substantial losses may occur in areas with hot seasons.

Description of models

Conceptual basis

There are four calculation models for this assessment. Three of the models are deterministic as they use physics principles and biological mechanisms for heat effects on working people, and descriptive studies of susceptibility as the foundation for impact calculations. These three models cover [Model 1] occupational heat stress exposure, [Model 2] exposure-response relationships for clinical health risks, and [Model 3] such relationships for suppression of labor productivity (or work capacity). The fourth model [Model 4] relates country level average GDP to the percentage of the country's workforce in agriculture, industry and services, and is based on statistical records. This model deals with "structural change" of economies. The associated longer report (Kjellstrom et al., 2014a) will provide additional detail about each model and the input data used.

Climate variables of importance to human heat exposure

Four climate variables influence the relevant human *heat exposure* quantification whether it is at "baseline", current situation, or at future time points: air temperature, humidity, air movement (wind speed) and heat radiation (outdoors mainly from the sun) (Parsons, 2014). Daily solar heat radiation is difficult to model because of variable cloud cover and the unavailability of future heat radiation values for each grid cell in our analysis. Estimates with no solar heat radiation would represent the exposure situation indoors (without a local heat source) or in full shade outdoors. Wind speed can vary significantly during the course of a day and an average daily wind speed is not useful to determine the WBGT during the hottest time of the day when wind speed may be low. Also, working persons usually move their arms and legs generating their own air movement over their skin (at approximately 1 m/s). Because of these uncertainties we have chosen to calculate heat exposure indoors (or in full shade) where there is no solar radiation and wind speed is likely to be more constant (it can be increased by fans, but when air temperature is above 37 ^{o}C and humidity is high, fans may actually increase the heat stress). The outdoor heat exposure is then estimated from the indoor values based on the expected additional exposure in full sun during the middle of the day. The wind impact on WBGT is limited when the wind speed exceeds 1 m/s, especially when the wind is warm (Lemke and Kjellstrom, 2012).

Heat stress depends on two additional factors (Parsons, 2014): the metabolic rate (a function of physical work intensity) and the type of clothing worn (which influences the evaporation of sweat and direct heat radiation on the body). Much detailed research has dealt with the design of clothing or the clothing materials that serve as a barrier against heat. The physiological basis for these relationships between the environment, behaviors and modifiers is well known (Bridger, 2003), and it has been taken into account when international standards were developed for heat stress (e.g. ISO, 1989; Parsons, 2014). We assume that people working in hot conditions are using light clothing. If they use chemical protection clothing the heat stress will increase. If the heat stress exceeds the individual limits of physiological defense mechanisms, symptoms and signs of *heat strain* will develop as steps towards the more serious clinical health effects listed in Table 1.

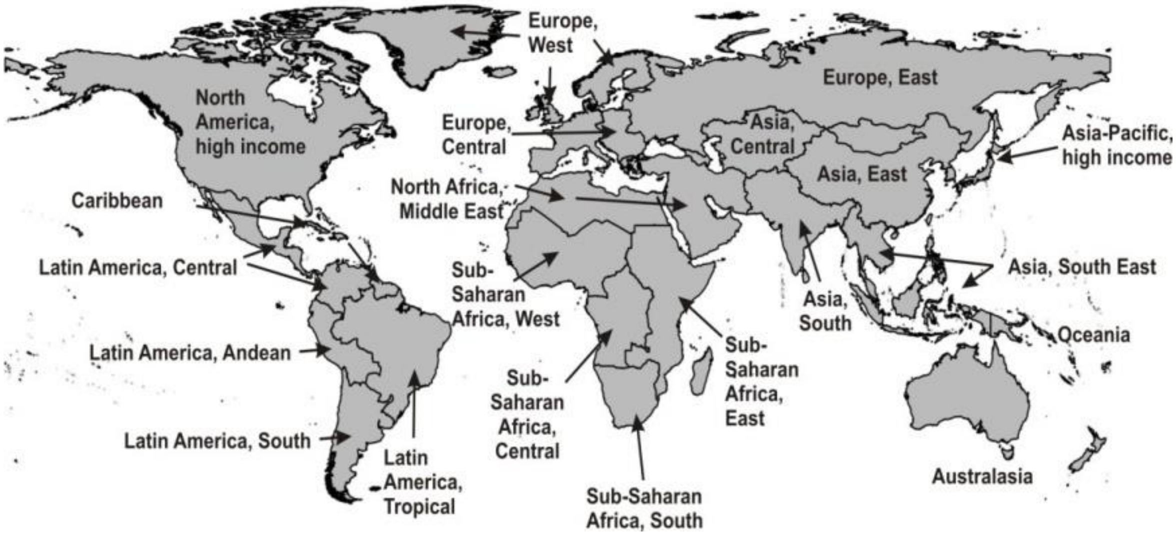
We use WBGT (Wet Bulb Globe Temperature) as the key indicator of occupational heat exposure as it is the most common human heat exposure index used in situations of occupational heat stress (Yaglou and Minard, 1957; Parsons, 2014). It is the parameter used in the international standard for occupational heat exposure (ISO, 1989), in the recommendations from the American Conference of Governmental Industrial Hygienists (ACGIH, 2009), and in guidelines or regulations from government departments in a number of countries (e.g. New Zealand: DoLNZ, 1997). The recently developed Universal Thermal Climate Index (UTCI; see website www.utci.org) is based on advanced physiological modeling (Fiala et al., 2011), but it is not designed for population health research or occupational heat stress estimations.

Model 1: Quantifying human occupational heat stress exposure

Calculation of WBGT from routine climate data

Having chosen WBGT as our occupational heat stress index, monthly values were calculated for each 0.5 x 0.5 degree grid cell in the global climate change models chosen by WHO and divided into 21 global regions (Figure 2). Our model for WBGT calculations used published equations for WBGT (indoors) as a function of humidity and temperature (Bernard and Pourmoghani 1999). A number of variables are included in the calculations of WBGT, and some of these can be estimated from a combination of climate data and other data. The detailed calculation formulas have been reviewed by Lemke and Kjellstrom (2012) and will not be repeated here.

Figure 2. Boundaries of the 21 regions used in this report.



Key variables in WBGT calculations are:

SH = specific humidity (kg water/kg air); Pv = vapor pressure, water in the air (hPa); Td = dew point (^{o}C);
RH = relative humidity (%);
Patm = total atmospheric pressure (hPa); V = wind speed (m/s);
Temperatures (^{o}C): Ta = ambient temperature; Tpwb = psychrometric wet bulb temperature, (a wet bulb exposed to fixed air movement at high speed);
Tnwb = natural wet bulb temperature (a wet bulb exposed to actual air movement);
Tg = black globe temperature (indicates radiated heat on a black globe; requires long adaptation time)

The calculations produce valid estimates of “in shade” (or indoor) WBGT using input formulas from Bernard and Pourmoghani (1999) and Brice and Hall (2009). Direct calculation of WBGT outdoors requires solar radiation data that is not normally available in climate modeling or from weather stations. WBGT outdoor calculation formulas have been published by Liljegren et al. (2008) and Gaspar and Quintela (2009), but they require daily heat radiation data. The method for “in sun” WBGT (outdoors) has been described in Lemke et al., (2011) and Lemke and Kjellstrom (2012).

Studies for selected locations using hourly climate data for 1999 (ISH GSOD data from: NOAA, 2009) showed the increase in WBGT when heat exposure from the solar radiation is included: the difference between “in sun” and “in shade” WBGT (solar radiation, SR > 600 W/m2) can be approximated to 3 ^{o}C (rounded value to single degree) during the hottest and sunniest part of the day (Kjellstrom et al., 2014a). A common heat radiation inflow in the full sun on afternoons in tropical and other hot locations is 600 W/m2. We chose the decile 7.5 value (2.91 → 3 ^{o}C rounded) because the maximum effect of the sun is expected during the hottest 2-4 hours each day (approximately 25% of daylight hours).

Hourly variations in WBGT levels

For the work capacity loss calculations we need to estimate the hourly WBGT levels, as the effects are acute and apply to each working hour (Parsons, 2014). In order to assess the relationship between routinely recorded climate variables, such as maximum and mean daily temperature and mean daily dew point, we used hourly data from NOAA/GSOD and compared calculations of indoor WBGT using daily and hourly data at a number of locations with very hot periods. We divided the daylight hours into three 4-hour time periods: The hottest part of the day between 12-15:59 where the WBGT = WBGTmax. The surrounding 2-hour periods (10.00 – 11.59 and 16.00 – 17.59 Hours) where the WBGT = WBGThalf = (WBGTmax + WBGTmean)/2 and the next surrounding 2 hour periods (08.00 – 09.59 and 18.00 – 19.59 hours) where WBGT = WBGTmean (for the 24 hour period). Thus, we decided to use these three WBGT levels during typical working days as our indicators of hourly heat stress levels. The estimates are not exact, but we consider them a reasonable approximation of the actual hourly WBGT levels indoors or in full shade outdoors.

Process used for quantifying heat exposure in global grid cells

General Circulation Models (GCM) used to calculate climate change often produce outputs on approximately 3 -degree grid cell size, though this varies from model to model. These large cells (300 km square at the equator) do not align well with the 21 regions defined by WHO for this project (Figure 2) and are much too large to attribute to specific locations. Half degree grid cell data (50 km square at the equator) was supplied by the WHO team. While 50 km grid cells derived from 300 km grid cells do not have more information than what is available from the 300 km grid cells, they do allow proportions of the larger grid cells to be assigned to the correct regions. This process of taking 300 km grid cells, downsizing to 50km grid cells (using bilinear interpolation) and then allocating the 50 km grid cells into regions leads to some inaccuracies, particularly in regions with variable topography (e.g. South Asia, Andean Latin America, West Europe) where substantial parts of the 300 km grid cell is at higher (colder) altitude than other parts. However, these errors are not likely to cause major errors in the heat stress calculations because the affected areas are colder than the thresholds for effects.

Suitable 0.5 x 0.5 degree gridded modeled data was supplied for 3 GCM models: BCM2, IPCM4, and EGMAM. The model results had been produced for WHO by CRU in the United Kingdom (Goodess and Harris, 2010) and will not be described in detail here. The results of the EGMAM model were supplied for three separate runs: EGMAM1, EGMAM2 and EGMAM3. We decided to use their average as one model, because the difference between the results of the three runs was minor.

BCM = Bergen Climate Model (from Bergen University, Norway)

EGMAM = ECHO-G^2 with Middle Atmosphere and Messy interface climate model (from Free University Berlin, Germany)

IPCM = Institute Pierre Simone Laplace – Climate Model (from Institute PSL, France)

We obtained the monthly actual climate data for every year in the period 1961 to 2002 for 0.5 x 0.5 degree (50km square at the equator) grid cells from the University of East Anglia Climate Research Unit (CRU, 2004; Mitchell & Jones 2005). We averaged the data (monthly water vapour pressure, maximum temperature, mean temperature) for the period 1961-1990 to get a single "1975" baseline value for each grid cell. The annual averages and standard deviations (and coefficients of variation, CVs) of the WBGTmax data for grid cells in each region were used to estimate the likely uncertainties in our results (Kjellstrom et al, 2014a). The CVs were generally in the range 2-5% of the average WBGTmax values**,** which indicates that the actual region-based values would not deviate more than 10% from our calculated estimates in the following analysis (see "Uncertainty" section in this report).

Computation method

The climate and population data for the grid cells (approximately 60,000 cells with land areas in the cell) were imported into Excel and then subjected to a number of quality control checks: a check for consistency of latitude/longitude, a check to ensure the year and the months matched and were consecutive, and a check to see if the various maps were keyed together.

The monthly grid cell data for the 30-year periods around 1975, 2030 and 2050 was processed to determine the following:

- Monthly averages of daily mean and maximum air temperatures. --- These temperatures (Ta) varied during the day and the calculation process described above captured this variation.
- Monthly averages of dew point (Td) from the water vapor pressure (or specific humidity) and the mean air temperature; the absolute humidity (indicated by Td), which is relatively stable during most days, was assumed to be constant throughout each 24-hour period.

- Psychrometric wet bulb temperature (Tpwb) calculated from the dew point and temperature with standard physics formulas.
- WBGT ("in shade" or indoor) calculated from the psychrometric wet bulb temperature and air temperature. --- The three levels were calculated: WBGTmax, WBGThalf, and WBGTmean. Air movement over the skin (wind speed) was set at 1 m/s and clothing was assumed to be light.
- The distributions for each region of the number of "grid-cell-months" per year at each WBGT ("in shade") one degree level for max, half and mean. These distributions show the changing heat exposure situation between the three time periods in each grid cell. The combined monthly data for the grid cells in each region provided a distribution of heat exposures in the full region.
- The WBGT ("in sun") levels during the four hottest hours were assessed by adding 3 ^{o}C to the WBGTmax levels (in shade) for each month. Clearly the percentage cloud cover and variation in cloud cover during each day will influence the resulting hourly WBGT outdoors levels. The WBGThalf and WBGTmean levels were kept at the "in shade" levels because the sun heat radiation is less intense at these hours and we did not want to over-estimate the daily averages.
- The population-based heat exposure was calculated as annual *person-months of exposure* for clinical health effects and annual *person-hours of exposure* for work capacity loss analysis at each 1 ^{o}C WBGT step for each of the 21 WHO regions. This uses the grid cell based WBGT values and population sizes in each of the three 30-year time periods.

Calculating person-time exposure variables

In order to calculate risks per million working people per year, we developed ***person-time exposure*** variables. The climate and WBGT estimates are for monthly time blocks, so we assume 20 working days per month (a conservative estimate, some people work every day) and that the monthly WBGT values apply to each working day of that month. Thus, the exposure variables are ***person-days of exposure*** based on person-months of exposure (and the 20 working days per month). When estimating work capacity loss we also use ***person-hours of exposure***, taking estimated daily variation in heat exposure into account. Our exposure estimates are "conservative" in the sense that half of the days each month would have exposure levels higher than the average, and the days with the highest heat levels create the greatest impacts (the exposure-response relationships are not linear).

For each time period (baseline "1975", "2030" and "2050") tables of the annual person-months of exposure in each of the 21 regions at each WBGT 1 ^{o}C level were calculated from the monthly grid cell estimates. The exposure-response relationships indicate that effects start occurring in working people carrying out intensive labor at WBGT = 26 ^{o}C. We start these person-month calculations at monthly average WBGTs at 23 ^{o}C as this gives us a chance to analyse the impact of region-wide changes in the WBGT values and we can also estimate afternoon outdoor heat exposures in the sun (+ 3 ^{o}C). Expressing the population average heat exposures in this manner makes it possible to calculate impacts per million people in specific geographic areas.

Model 2: Clinical health effects and exposure-response relationships

Health effects chosen

The clinical health effects included here are acute and related to the maximum heat exposure levels (WBGTmax) on a particular day, but the published exposure-response relationships for *fatal and non-fatal heat stroke* are annual incidence rates for people in mines with relatively continuous exposures (see the section on exposure-response relationships). The relationships for seasonally varying heat exposure levels are not known, so we calculated *person-months of exposure* at each WBGTmax level and applied 1/12 of the published annual risk to these monthly exposure estimates.

In calculations of *heat exhaustion* as a clinical effect, we can also assume that the risk relates to the highest exposure on each day. Thus the monthly average WBGTmax is used for each month and the exposure variable is the number of *person-days of exposure at WBGTmax* per year (assuming each working day in a particular month had the same level as the monthly average).

Published exposure-response relationships

The scientific evidence behind quantitative exposure-response relationships for clinical health effects and work capacity impacts of hot work environments is incomplete and varies between studies. One important problem is that published studies use different heat exposure variables. We assume that heat exposure indexes expressed as ^{o}C are correlated. As discussed earlier, we have based our estimates of heat exposures on WBGT, assuming that other heat stress indexes are approximately inter-changeable with WBGT (after correction for different scales and ranges of values).

We assumed, because of lack of gender-specific data sufficient to quantify gender differences, that the risks for women and men are the same (but this needs to be explored in future research). We also assume that the risks in different age ranges within the working age groups are the same (e.g. 20- and 50-year olds are at the same risk). However, in addition to potential age and gender differences, sensitivity to occupational heat exposure is likely to vary between societies. There are indications that people who live their whole lives in a hot environment develop behavioural adaptation to avoid heat impacts, and/or modify their physiological interaction with heat (Wakabayashi et al., 2010).

Wyndham (1965) and Wyndham (1969) report exposure-response relationships for serious health impacts in black (“Bantu”) mine workers in South Africa; non-fatal and fatal heat stroke (Table 2). The relationships are for acclimatized workers. For non-acclimatized workers the reported risks were higher, but our analysis assumes that most of the working people in hot places are already acclimatized to the local conditions. These South Africa data refer to underground mine workers, who worked in a hot environment with relative humidity (RH) close to 100% (because water spray was used inside the hot mine to reduce hazardous dust exposure). The calculated levels of effective temperature (ET) and WBGT are very similar (Walters, 1968) and Tpwb, as well as Ta, are equal to WBGT when the RH is near 100%. Thus, we consider the exposure-response relationships in Table 2 to be valid also for WBGT. These relationships indicate curvilinear continuously increasing risks as heat exposure increases. Wyndham

(1969) reports heat exposure data as Tpwb, ET and WBGT in different publications. These heat exposure variables are approximately equivalent at the very high humidity inside the mines (Wyndham reported cases for the whole 6-year period, which we show as annual and monthly rates in Table 2).

Table 2. **Relationship between Effective Temperature (ET, similar to WBGT in this situation) and the annual and monthly heat stroke incidence (per million workers) in South African gold mines, 1956-1961** (Wyndham, 1965; 1969).

ET, ºF	**ET, ºC**	**Number of workers studied**	**Rate of non-fatal heat stroke/million workers**		**Rate of fatal heat stroke/million workers**		**Ratio of fatal to non-fatal**
			Annual	**Monthly**	**Annual**	**Monthly**	
< 80	< 26.7	371,318	1.6	0.13	0	0	0
80-83.9	26.7-28.7	177,960	6.7	0.55	0	0	0
84-87.9	28.8-31.0	178,536	49	4	17	1.4	0.3
88-90.9	31.1-32.6	89,113	139	11	36	3	0.3
91-92.9	32.7-33.7	15,507	320	27	114	9.5	0.3
93 +	33.8 +	1,800	889	75	666	56	0.7

Our modeling of the clinical heat stroke and heat exhaustion risks is based only on the Wyndham (1965, 1969) data, as no other quantitative studies could be found.

Calculation of health impacts at population level

The health impact calculations were expressed as annual rates per million working age people in each of the 21 regions in 2030 and 2050 using heat exposure model outputs for these years. We also calculated the rates per million persons if the heat exposure had stayed at the baseline level (1961-1990 = "1975"). The differences between the 2030 and 2050 model climate impacts and the calculated baseline impacts are presented as the impacts of climate change (due to the factors included in the climate models; e.g. increased greenhouse gases by region, deforestation, etc.). The actual number of affected cases can then be calculated by multiplying the rate/million with population forecasts for the regional numbers of people in the working age range 15-64 years. These first calculations assume everyone in that age group is working, and later we take workforce distribution into account in the regional assessments.

For clinical health risk calculations we used only the WBGTmax (the hottest hours) as the relevant heat exposure. The numbers of fatal and non-fatal heat strokes based on the estimates in Table 3, were calculated for each month and summed for the 12 months to create annual rates. For heat exhaustion the number of heat exposed days for each month at different WBGTmax levels over a year was multiplied by the risk functions in Table 3 (which assume 20 working days per month). In these health risk calculations we also took into account work location (indoors or outdoors) and work intensity (heavy, moderate or light).

Table 3.Monthly risks of clinical effects of heat exposure (WBGTmax) for physiologically acclimatized working people, based on the notion of full-time work and no behavioural acclimatization. (these risk estimates were approximately fitted to the data in Table 2 and the risk function curves in Wyndham, 1969)

WBGT (^oC)	**A. Rate of one-day heat exhaustion per working month, per million workers (estimated at 400 times column B values) (assuming 20 work days/month or 240 work days/year)**	**B. Monthly rate of non-fatal heat stroke/million workers (health damage lasts a week)**	**C. Monthly rate of fatal heat stroke/million workers**
26	40	0.1	0
27	120	0.3	0
28	800	2	0
29	1600	4	1.4
30	3200	8	2.5
31	4000	10	3
32	6000	15	4
33	8800	22	7
34	16000	40	17
35	23200	58	30
36	32000	80	55
37	40000	100	80
>=38	56000	140	130

Model 3: Work capacity loss and exposure-response relationships

Loss of work capacity is due to the physiological effects of heat that necessitate a person to reduce physical activity in order to avoid the core body temperature (Tcore) increasing beyond 38-39 ^oC (Parsons, 2014). If cooling of the work environment, sweat evaporation or other individual cooling approaches (e.g. cooling vests) are not sufficient to avoid Tcore increasing beyond this level, the only way to protect the body from over-heating and associated health impacts is to reduce physical activity. For working people this means taking more rest breaks or slowing down/reducing their work output per hour (= reduced labor productivity). In addition, substantial sweating can exceed one litre per hour. If the loss of body liquid is not replenished with sufficient drinking water, the body will become dehydrated, which also reduces work capacity and creates clinical health risks (Bridger, 2003). Dehydration also causes loss of performance in sports activities and as little as 2-3 % loss of body weight through dehydration can be a serious health threat (Parsons, 2014).

These health and productivity threats are well understood from a physiological point of view and have been integrated into the international standard for work in hot environments (ISO, 1989) that recommends limits of hourly work at different WBGT heat exposure levels and different work intensities. Adjustments for different types of clothing are also included in the standard as heavy or protective clothing increases the heat stress on the body. The standard aims to protect the majority of workers by keeping their Tcore below 38 °C. The "majority" protection implies that it recommends more rest time than is required by an average worker and for many individuals. National standards, such as ACGIH (2009) for the USA, are based on similar concepts.

The effects of heat on *work capacity* occur during each hour of work if there is excessive heat exposure. To calculate the equivalent *total number of work hours lost,* the number of hours at each level of WBGT exposure for each person is required. The three WBGT values were used to approximately calculate WBGT exposure: WBGTmax, WBGThalf and WBGTmean (four hours each) as indicated above. Thus, the variable *person-hours of exposure at a certain WBGT level* is the sum of the hours in a month at the three WBGT levels (four daylight hours of exposure at each WBGT level). Impacts on work during night time hours have not been assessed in this study.

Table 4 shows for each WBGT level the work capacity reductions suggested at three ISO standard work intensity levels (200W, 300W, 400W), as well as for three published studies of real life situations (Wyndham, 1969; Nag and Nag, 1992; and Sahu, et al., 2013). The Wyndham data (on gold mine workers) cover the greatest range of WBGTs and a curve was fitted by Wyndham's team to the production loss records (Wyndham, 1969). The mathematical basis of this Wyndham curve was not published, but its shape indicated that it was a logit curve for the cumulative Gaussian distribution of risk with a 50% loss at 33.5 °C and a standard deviation of 3.5 °C. Our fitted exposure-response function for moderate work intensity (300W) was based on this function while tapering off to a 90% work capacity loss as shown in Figure 3. The assumption was that even at very high WBGT levels a person could work for six minutes and avoid health effects. In order to leave some possibility for limited work (6 minutes per hot hour) at high heat exposure, we assume a maximum loss of 90% in Table 4 (both in the ISO standard columns and in the Hothaps "fitted" columns).

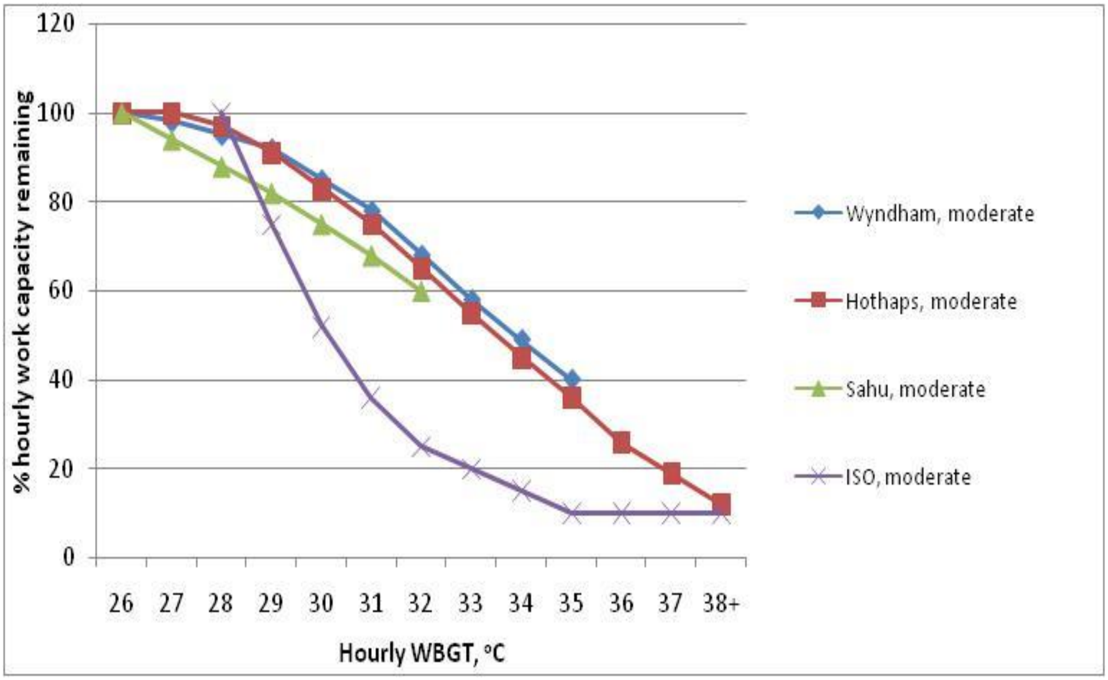
The Sahu data (on agricultural workers) fit reasonably close to the fitted Wyndham curve, but generally indicates additional work capacity loss, possibly due to more heavy labour in this type of work. We then estimated "our fitted exposure-response relationships" for light and heavy work using similar curve shapes and taking into account the limited epidemiological data and the relative difference between the fitted ISO standard curves at the three work intensity levels (Figure 4).

It is clear that the ISO standard recommendations for work/rest cycles include a "safety margin" compared with the heat sensitivity of the average worker. It is likely that in real life work situations workers will endeavour to take rest in a cooler place than where they have to work. Thus, we can expect exposure-response relationships in observational epidemiological studies to present lower average levels of work capacity loss than the levels coinciding with the ISO standard. Unfortunately, the ISO standard document (ISO, 1989) contains no scientific analysis that shows why the recommendations for hourly work/rest ratio are at these specific levels.

Table 4. Reduction of hourly work capacity at different levels of work intensity and heat exposure (% reduction from background in cooler environment; acclimatized workers).

Sources	ISO	ISO	ISO	Wyndham, 1969	Nag, 1992	Sahu, et al., 2013	Hothaps fitted	Hothaps fitted	Hothaps fitted
					Our fitted exposure-response relationships				
Labor intensity →	Light, 200W	Moderate, 300W	Heavy, 400W	Moderate	Light	Moderate-heavy	Light	Moderate	Heavy
WBGT, ET or Tw									
26	0	0	0	0	0	0	0	0	0
27	0	0	18	2		6	0	0	9
28	0	0	35	5	11	12	0	3	17
29	0	28	50	8		18	0	9	25
30	9	49	65	15		25	3	17	35
31	30	70	78	22		32	9	25	45
32	50	85	90	32	22	40	17	35	55
33	70	90	90	42			25	45	64
34	80	90	90				35	55	74
35	85	90	90	60			45	64	81
36	90	90	90		40		60	74	85
37	90	90	90				74	81	88
38 and above	90	90	90				86	88	90

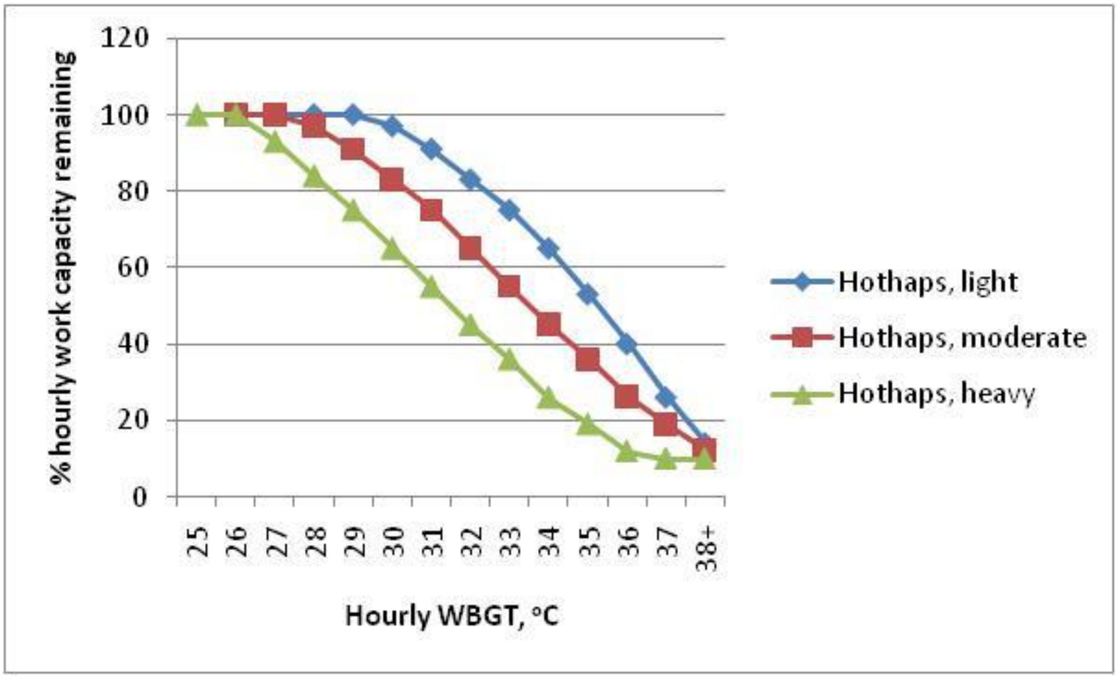
Figure 3. Graphic depiction of the relationships between hourly heat exposure and remaining work capacity for moderate work intensity (300W) . Hothaps = the fitted relationship established by our team for this project.



The ISO curve (Figure 3) has a different shape from the others because this is designed to protect most workers where the other results relate to the average worker. In a population of workers, some are very vulnerable to heat strain. At low heat stress all workers can cope with the conditions. As the heat stress increases the impact on the more vulnerable workers is more pronounced so standards that protect those workers must indicate lower work capacity. If the ISO (1989) standard (or the similar ACGIH, 2009, standard) is used to calculate work capacity loss (as was done by Kjellstrom et al, 2009c, and Dunne et al, 2013) the resulting values will be lower than if an average Hothaps relationship is used.

The calculation of work capacity loss each month for each grid cell follows similar calculation processes as for clinical health effects described above. For each cell there can be six impact models (Table 4). In this WHO report we only calculate the impacts on "average workers" using our fitted exposure-response relationships. We calculate for indoor and outdoor exposures the percentage of daylight work hours lost, assuming 12 potential daylight work hours per day and 20 work days per month (equivalent to 2880 hours per year). Taking holidays and other non-working days and hours into account, the usual annual work hours in other reports has been assumed to be 2000 hours in high income countries.

Figure 4. Graphic depiction of the relationships between hourly heat exposure and remaining work capacity based on our estimates for three levels of work intensity (light = 200W, moderate = 300W, heavy = 400W). Hothaps = the fitted relationship established by our team for this project.



To calculate lost work hours from the percentage of "safe work time", a 12 hour day is assumed, so for each 8% loss there is one hour per day lost per worker. While it is possible to avoid the hottest part of the day by starting earlier or finishing later, this is still likely to limit the number of productive work hours per 24-hour period. In outdoor jobs that require natural light the reduction of productive work hours is related to the daylight hours available (close to 12 hours per day in the tropics all year).

Model 4: Regional population estimates and workforce distributions

We estimated population - weighted average exposures (million person-months of specific level heat exposure) for each of the 21 regions, based on the exposure estimates as described above and the working age population (age range 15-64 years) in each grid cell for each estimation year (1975, 2030 and 2050; with 2000 for comparison purposes) (Table 5). Age-specific population estimates were acquired by the WHO team for the age groups 0-4, 5-14, 15-64, 65+ years. The population data at specific grid cell level was downscaled from larger geographic areas than our grid cells by IIASA (2010) (data supplied by WHO from IIASA website), which creates uncertainties in the local estimates.

Table 5 shows that the expected increase of working age population, with potential exposure to occupational heat stress, will be particularly great in parts of Africa, Latin America and Asia. These increases of the local populations at risk will contribute significantly to the estimated impacts of climate change.

Table 5. Population (millions; men and women combined) in the 15-64 year working age range in 1975, 2000, 2030 and 2050 by region (source IIASA = International Institute of Advanced Systems Analysis: http://www.iiasa.ac.at/Research/ECC/index.html)

		Population, millions, age 15-64				Ratio, 2050/1975
Region name		1975	2000	2030	2050	
1	Asia, High Income	77	110	98	79	1.0
2	Asia, Central	34	48	74	79	2.3
3	Asia, East	550	896	960	768	1.4
4	Asia, South	426	806	1297	1400	3.3
5	Asia, South East	166	336	491	484	2.9
6	Australasia	9	15	18	20	2.2
7	Caribbean	9	22	27	25	2.8
8	Europe, Central	77	82	77	64	0.83
9	Europe, East	140	150	128	104	0.74
10	Europe, West	217	260	242	218	1.0
11	Lat-America, Andean	13	28	46	49	3.8
12	Lat-America, Central	55	123	197	201	3.7
13	Lat-America, South	23	35	48	49	2.1
14	Lat-America, Tropical	56	117	158	151	2.7
15	North America	137	203	231	241	1.8
16	Africa – North	110	222	437	522	4.7
17	Oceania	2	3	7	8	4.0
18	Africa, Central	19	35	94	139	7.3
19	Africa, East	71	143	340	452	6.4
20	Africa, South	19	38	42	37	1.9
21	Africa, West	73	133	327	419	5.7
	World total	2283	3807	5338	5508	2.4

The changing distribution of workforce activities from labour intensive outdoor jobs to moderate intensive indoor jobs and air conditioned indoor jobs (including modern office jobs) is another essential aspect of future climate resilience trends and specific adaptation programs. Unfortunately, we did not have access to detailed workforce distribution estimates for the scenario A1B, but in order to test the impact of workforce changes we used a model that relates the percentage of the population in agriculture, industry or services to the country GDP PPP (Gross Domestic Product per person, based on Purchasing Power Parity; PPP). The estimates (Table 6) were calculated from World Bank data for 2000. This model was used for scenario A2 in Kjellstrom et al. (2009b) and we used the same 1975 and future (2050) estimates here. Estimates for 2030 assume linear trends between 1975 and 2050.

Table 6 shows that in some high income regions with a small proportion of the population in agriculture (2.6% in North America and 5.6% in Australasia) no change is expected in the workforce distribution until 2050. Western Europe and High Income Asia (mainly Japan) are assumed to experience reductions of the agricultural and industrial workforce proportions down to the levels of North America. In most of the regions with low and middle income countries the reductions of the expected percentage of workforce in agriculture is dramatic (as in South-East Asia, Tropical Latin America, and South Africa), while the workforce proportion in industry changes less. Central Europe is also expected to experience these types of changes, while Central America shows no change at all (Table 6).

Table 6. Population proportions (%) working in agriculture, industry and services (workforce distribution) in 1961-1990 (1975) (baseline), 2030 and 2050.

		agriculture			industry			services		
Region name		1975	2030	2050	1975	2030	2050	1975	2030	2050
1	Asia, High Income	7.1	3.8	2.6	31.7	25.5	23.3	61.2	70.7	74.1
2	Asia, Central	42.5	29.6	24.9	16.9	20.8	22.2	40.6	49.6	52.9
3	Asia, East	60.5	33.8	24.1	23.8	37.2	42.1	15.6	29.0	33.8
4	Asia, South	65.1	50.5	45.2	13.5	17.2	18.5	21.5	32.3	36.4
5	Asia, South East	50.6	25.7	16.7	16.3	21.9	24.0	33.0	52.3	59.3
6	Australasia	5.6	5.6	5.6	22.5	22.5	22.5	71.9	71.9	71.9
7	Caribbean	22.8	14.6	11.6	21.9	24.4	25.3	55.3	61.0	63.1
8	Europe, Central	21.7	7.8	2.7	33.0	36.5	37.8	45.3	55.7	59.5
9	Europe, East	16.0	18.1	18.9	31.7	26.3	24.4	52.3	55.5	56.7
10	Europe, West	5.1	3.3	2.6	26.4	24.1	23.3	68.5	72.6	74.1
11	Lat-America, Andean	4.2	3.0	2.6	23.7	23.4	23.3	72.1	73.6	74.1
12	Lat-America, Central	18.9	18.9	18.9	24.4	24.4	24.4	56.7	56.7	56.7
13	Lat-America, South	5.0	3.2	2.6	25.5	23.9	23.3	69.5	72.9	74.1
14	Lat-America, Tropical	23.4	11.0	6.5	20.5	24.0	25.3	56.0	65.0	69.5
15	North America	2.6	2.6	2.6	23.3	23.3	23.3	74.1	74.1	74.1
16	Africa – North	29.2	29.2	29.2	24.0	24.0	24.0	46.7	46.8	46.7
17	Oceania	69.5	55.6	50.5	4.8	7.1	7.9	25.7	37.4	41.6
18	Africa, Central	60.2	45.1	39.6	11.5	14.0	14.9	28.3	40.9	45.5
19	Africa, East	68.0	53.1	47.7	8.0	10.3	11.1	24.0	36.6	41.2
20	Africa, South	24.0	11.1	6.4	22.5	24.3	24.9	53.5	64.6	68.6
21	Africa, West	59.5	44.4	38.9	11.7	14.2	15.1	28.7	41.4	45.9

In the calculations of regional heat impacts that include workforce distributions, we have assumed that agricultural workers are outside in the sun, and that they are required to carry out "heavy labour" (400W). The corresponding group working in industry are assumed to carry out "moderate labour" (300W) indoors or in full shade. People in service jobs are assumed to have air conditioning and very light labour, so their heat exposure is too low to create impacts due to climate change. In fact, many people in service jobs in low and middle income countries are not protected by air conditioning or other cooling systems, so our analysis is "conservative" (source: personal observations and information received by Kjellstrom from key informants in tropical countries). Intellectual tasks in office jobs, or other service jobs, are also slowed down or negatively affected in other ways (e.g. more errors) by high workplace heat exposure (Hancock et al., 2007).

The impact of climate change on health and productivity in the whole population is calculated by "weighted" analysis of impacts in the different workforce groups. If occupational heat stress in 2030 causes an annual mortality risk of 10/million in the "heavy labour" category and 2/million in the "moderate labour" category, and the respective proportions in the two workforce categories are 50% and 20%, then the impact in the whole population will be 0.5 x 10 + 0.2 x 2 = 5.4/million. We calculate these values for 2030 and 2050 for the 21 regions and our result sections show the separate and combined changes of health risks or work capacity loss due to climate change and workforce change.

Summary of the features of our four models

1. We use grid cell based observed climate data or climate model estimates of temperatures (monthly average of daily max, daily mean and the half-way point temperatures) and humidity (average of daily mean dew point) to calculate with **model 1** the corresponding monthly WBGT "in shade" or indoors assuming air movement over skin (wind speed) at 1 m/s and no additional heat radiation.
2. We use CRU grid cell data (0.5 x 0.5 degrees) for 1975 (based on observed data) to assess the actual levels of WBGT for each grid cell at that time (1975 is an average of 30 years of monthly data, 1961-1990).
3. We then use a "field change" method (average change for each region) to add the calculated change of regional average WBGT to the regional CRU 1975 data to calculate 2030 and 2050 grid cell WBGT levels in the 21 regions defined by WHO using the three supplied models (averaging the three runs of the EGMAM model into one estimate, and then using the other two climate models as independent input: BCM and IPCM).
4. Monthly data for WBGTmax, WBGTmean and WBGThalf (halfway between max and mean), is used to estimate the person-months and person-hours of heat exposure indoors at each WBGT one-degree level for a population of 1 million, assuming that each of the three WBGT levels represent four daylight hours per day during the month.
5. Additional heat exposure outdoors in sunny conditions during the four hottest hours is estimated by adding 3 ^{o}C to the indoor WBGTmax levels.

6. For clinical health risk calculations (acute effects) we use the monthly WBGTmax data as indicators of daily exposures during the afternoons. For the calculation of work capacity loss we use numbers of hours at different heat exposure levels based on the monthly averages of the WBGT levels estimates (max, half, mean).
7. For each WBGT level we use exposure-response relationships for fatal and non-fatal health risks (**model 2**), to calculate impacts per million working people at three different levels of work intensity (heavy, moderate and light) for the time points 2030 and 2050. The heat exposure levels are based on the three climate model outputs for these years (30-year periods around the years) and the "counter-factual" estimates use the baseline "1975" climate distributions in grid cells. The difference between calculated risks at 2030 and 2050 climate levels and 1975 climate levels in the same population is presented as the climate change impacts.
8. We also estimate potential impacts of heat exposure on work capacity and labor productivity during daylight hours applying different exposure-response relationships to the heat estimates by region (**model 3**).
9. Then we can calculate the number of people affected by applying working age population sizes (ages 15-64 years) and workforce distributions (**model 4**) for each region (based on grid cells in the region) at the two time periods (2030 and 2050).
10. The calculated impacts on clinical health and work capacity are discussed and analyzed in comparison with other analysis results of the consequences of current and future climate conditions for working people.

Assumptions

Assumptions in the model calculations

A number of specific assumptions were applied in the different model calculations and these will not be repeated here. The project was started in 2009 and most of the analysis of exposures and impacts were carried out in 2010 and 2011. Therefore the new RCP system of climate modeling was not used (analysis with these new models is in progress).

The general assumptions included:

- The future global economy, demography and society will evolve according to SRES scenario A1B
- The data from three climate models (five model runs) provided from WHO were valid examples of how global climate change will influence regional environmental heat exposures for the scenario A1B
- The heat exposure index used by us (WBGT) is a valid method to express exposures of relevance to occupational health based on a combination of climate variables

- The calculation of “in shade” (indoor) exposures in non-cooled work environments is a valid way to start estimating average exposure levels for populations of working people
- The addition of 3 ^{o}C to the in shade values produces reasonable estimates of outdoor exposures “in sun” for the hottest four hours of the day
- The exposure-response relationships established from the few available epidemiological studies are valid representations of how “average worker” groups would be affected by heat exposures.
- Adaptation will take place, but for certain job types protective measures, apart from taking rest breaks or avoiding work during the hottest periods, will be impossible or too expensive for the heat exposed working populations. Reduced vulnerability via changes in the workforce distribution was taken into account with the methods we use.
- Because of uncertainties in the input climate data, the exposure-response relationships, and the actual exposed population sizes, our analysis uses rather basic statistical and mathematical methods to produce the results. More advanced analysis would not make the results more accurate.

Adaptation options

Ideally if we were to describe and quantify the current and future adaptation to occupational heat stress, we should have access to regional data or estimates for the time points i.e. 1975, 2030 and 2050 for the following variables. However, valid data of this type is not available at either global or regional level.

- Distribution of workforce into outdoor and indoor workers, as well as into groups working at different work intensity

- Availability of air conditioning or other cooling technologies in workplaces

- Local work restrictions related to heat exposure and their enforcement

- Hydration program implementation at each workplace

- Routine use of reliable and non-invasive methods of monitoring heat stress in working people

- Access to medical treatment in case of serious clinical effects of heat

- Other occupational health and safety program activities

Our starting point in this study was to calculate occupational heat stress impacts for three different work intensity levels (heavy, moderate, light) in “in shade” and “in sun” heat exposure conditions. The results indicate the impact of climate conditions separate from other workplace changes. As in other health impact assessments of climate change, we do not have detailed predictions of how other relevant variables will change (including local adaptation actions or population health status). However, we use estimates of changes in workforce distributions to assess one important aspect of changing climate resilience that also indicates a potential for adaptation. More use of technology that reduces the need for heavy labor activities is another important aspect.

For the WHO project we were asked to develop scenarios for heat adaptation that ranged from “optimistic” (= major adaptation implemented) to “pessimistic” (= no adaptation implemented). In the case of occupational heat stress impacts, one can assume that adaptation to the increasing heat exposures will involve increase of rest periods and reduction of average work intensity, which will potentially prevent most of the clinical heat effects. However, the work capacity loss will then increase as estimated by our analysis. The exact degree of future application of technology for cooling workplaces and for reducing work intensity is not known, but it is very unlikely that all occupational heat stress impacts can be prevented. In addition, it should be pointed out that heat impacts on daily life activities (collecting water or firewood, gardening, subsistence farming, home industry, etc.) will be of great importance for billions of people, and air conditioning is not likely to be used in all aspects of daily life.

It is important to consider the likely adaptation trends in light of other global projections of future health related infrastructure. The OECD Environmental Outlook report (OECD, 2012) assembled data and analysis from different UN agencies and other sources and concluded that in 2050 it is likely that 1,400 million people among the 9,000 million inhabitants of the planet at that time will still be without access to basic sanitation. More than 240 million people will not have access to safe and sufficient household water (OECD, 2012). These numbers indicate that access to workplace air conditioning or other cooling systems will also be lacking for hundreds of millions of people. The occupational heat stress problems due to climate change identified in our analysis will most likely become an additional burden in the daily life of a vast number of people, and these problems are already affecting life and well-being of many million people.

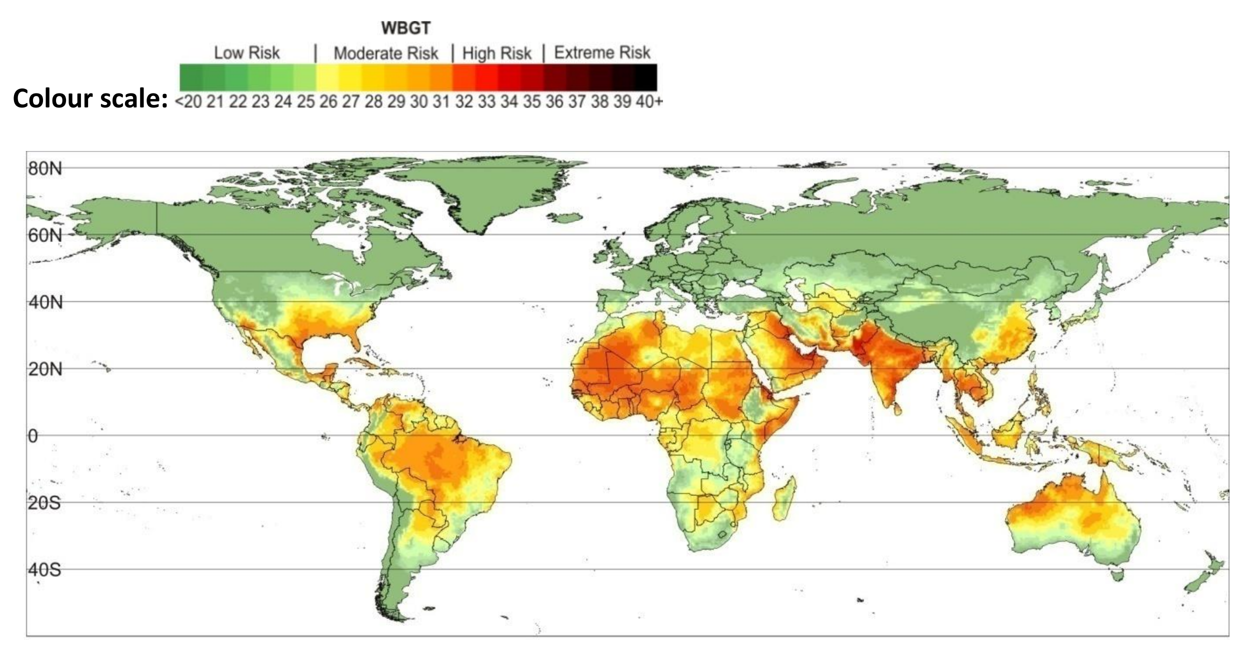
Results and comments

Future heat exposure due to climate change

Geographic distribution of occupational heat exposures

Our estimates of occupational heat exposure use grid cell calculations, but the results are generally presented by region. The great variation in intra-region occupational heat exposures during the hottest month of 1995 can be seen in Figure 5 (based on CRU real data), where North America, for instance, has very large differences between the southern states of the USA and the northern states and Canada. Southern Africa, Australasia and East Asia (mainly China) also have great internal variations in maximum heat exposure.

Figure 5. Grid cell specific monthly average WBGTmax "in shade" levels (afternoon) in the hottest month of each grid cell, based on CRU data for 1980-2009 (this figure was produced by us and included in the report IPCC, 2014)



Field change adjustments and distributions of grid-cell-months of heat exposure

The distributions of the number of months that each grid cell had estimated indoor WBGT levels at 23, 24,25, 26 °C, etc is the foundation for our occupational heat stress exposure estimates. The 23 °C threshold represents the 26 °C level for direct sunlight exposure during the hottest hours of each day, and as described earlier this addition of 3 °C for outdoor exposures in the sun is based on middle of the day data for a number of tropical cities (Kjellstrom et al., 2014a).

The analysis started with baseline (1961-1990, or "1975") grid cell temperature and humidity data and then added field change values for the three climate models to estimate these variables for 2030 and 2050 (see methodology section). Applying our model 1, we then calculated the WBGT relating to monthly average of daily Tmax and Tmean for each month and produced WBGTmax, WBTmean, and WBGThalf (halfway between WBGTmax and WBGTmean).

Differences between patterns of heat distribution and human exposure distribution

The proportion of the populations living in the hotter parts of each region is indicated by the differences in percentages of the total person-months of exposure and the percentages of grid-cell-months. Figure 5 displays this for individual one-degree levels of WBGTmax (world total data) at the high end (> 23 ºC).

Some of the hotter regions with high percentage (above 40%) of grid-cell-months above 26 ºC had much lower person-months at such high exposures. Areas with large deserts with low populations are in this category (e.g. North Africa, South Africa and Australasia), as well as areas with high average altitude (e.g. in Latin America and East Asia) or regions dominated by oceans (e.g the Caribbean and Oceania; island regions where many grid cells are not fully occupied by land). The highly populated regions of East Asia, South Asia, South-East Asia and West Africa are those where the person-month percentages are higher than the grid-cell-month percentages. Because of their large populations, the world total percentages at high heat exposure end are much higher for person-months than for grid-cell-months. For example, in the range of monthly WBGTmax between 27 ºC and 28 ºC we find 5.7% of the grid cell months, but as much as 9% of the person-months (Kjellstrom et al., 2014a). Above 27 ºC we find 10% of grid cell months and 20% of person-months.

Climate related clinical health risks

In this report we present the most detailed results for occupational fatal heat stroke, as this is of particular interest to this WHO project.

Fatal heat stroke

For each region we calculated the health and productivity impacts per million people and used those to calculate estimated number of cases using assumptions about changes in population size and workforce distribution. We started with fatalities due to heat stroke at workplaces. The underlying exposure-response relationships present relatively low risks per degree of WBGT (see Table 3). Table 7 presents the risks in 2030 and 2050 for selected regions according to the three climate models and two different exposure situations. BCM generally produces the lowest estimates, but the estimates are reasonably close. In the regions with the highest occupational heat stroke risks the deviations between the three climate models and the average of the three models are generally within +- 20-30% of the average. More detailed regional tables are included in the longer report (Kjellstrom et al., 2014a).

In order to understand the scale of these fatality impacts we have summarized estimates for the number of fatalities that would occur globally *if all working age people were involved in moderate labor* and exposed to the in shade WBGTmax levels (afternoon heat) or the in sun WBGTmax levels (Table 7). Some regions have both high heat exposure levels and large populations and such regions play a greater role than most of the other regions in a global impact analysis. We selected the nine hottest regions for presentation of tabular data. If all working age people are working at moderate intensity and in sun, the baseline (1975) afternoon heat levels were such that approximately 50,000 people (globally) (50,072 in Table 7) would die from heat stroke in 2030, assuming that the climate level is the same as at the baseline (1961-1990). If the full working population is working in the shade, at this work intensity level 5,000 fatal cases (4,950 in Table 7) would occur (Table 7).

Table 7. Number of cases of fatal heat stroke in selected regions among working age people (assuming they all work "in sun" or "in shade" exposures) at baseline and after climate change in 2030 and 2050 (differences between climate model estimates and baseline), based on person-months of exposure to in sun and in shade WBGTmax; Pop = working age population in millions in 2030; Rates = assuming **moderate physical intensity** work as in Wyndham (1969). BL = baseline (1975) climate values.

		Additional cases of fatal heat stroke per year due to occupational heat exposure increase during climate change					
	Baseline (BL) climate	**Climate 2030; Three model results minus BL, 2030**			**Climate 2050; Three model results minus BL, 2050**		
Region Year →		**BCM-BL**	**EGMAM-BL**	**IPCM-BL**	**BCM-BL**	**EGMAM-BL**	**IPCM-BL**
Cases in sun (outdoor) exposure							
3 Asia, East, China	3223	1417	2404	2771	2225	3370	5174
4 Asia, South, India	26528	15286	42404	32410	36412	79111	80585
5 Asia, South East	9039	3561	4416	5840	6235	7533	9743
12 Lat-America, Central	875	469	613	827	953	1094	1521
14 Lat-America, tropical	448	365	343	521	588	512	942
15 North America	419	266	369	339	538	668	841
16 North Africa, M. East	1859	1206	2782	2377	3052	5985	7206
19 Africa, East	1498	802	1158	1266	2149	2820	3433
21 Africa, West	5453	2726	3559	4403	6856	8877	10627
World total, in sun	**50072**	**27004**	**59273**	**52153**	**61081**	**112408**	**122984**
Cases in shade and indoor exposure							
3 Asia, East, China	29	292	821	885	622	1226	1699
4 Asia, South, India	4205	3579	7893	7122	7624	15822	14634
5 Asia, South East	193	495	749	1194	1413	2017	2946
12 Lat-America, Central	10	71	98	161	181	224	353
14 Lat-America, tropical	0	15	15	37	46	42	121
15 North America	10	80	99	98	154	177	234
16 North Africa, M. East	264	170	447	330	463	932	1082
19 Africa, East	63	153	250	247	498	695	823
21 Africa, West	174	710	1008	1220	2014	2611	3288
World total, in shade	**4950**	**5576**	**11397**	**11321**	**13048**	**23786**	**25281**

The additional number of heat fatalities, *if all working age people work in sun* with the modeled climate change heat exposure levels (based on the three climate models), would be between 27,000 and 59,000 in 2030, and between 61,000 and 123,000 in 2050 (Table 7). The equivalent numbers for the whole *working age population working in shade* would be between 5,600 and 11,400 in 2030 and between 13,000 and 25,000 in 2050 (Table 7). These estimates are included here in order to highlight the potential impact of a hotter climate on specific groups of working people. The estimates of actual regional occupational heat fatality impacts need to take other factors into account.

There are two factors unrelated to climate itself that influence the likely future impacts by region, whether these are clinical effects or work capacity loss. These factors are the size of the working age populations in each region (Table 5) and the workforce distribution (Table 6) in terms of work intensity and location of work (in sun or in shade, and with or without workplace cooling system). The detailed report (Kjellstrom et al., 2014a) shows that in the most affected regions the working age population in 2050 may be several times larger than in 1975 (baseline). On the other hand, associated with increased GDP in the most affected regions, it was assumed that less people will work in labor intensive agricultural work outdoors or in factory work indoors (Kjellstrom et al., 2014a).

Table 8. Fatal occupational heat stroke case numbers in 2030 and 1975 depending on climate estimates for 2030 (3 models and average), based on person-months of heat exposure; Cases = numbers of workplace heat stroke deaths; moderate work intensity; agricultural workers exposed outdoors; industrial workers exposed indoors; service workers not exposed to excessive workplace heat .

Climate	**A, 1975**	**2030**	**2030**	**2030**	**B, 2030**	
Model		**BCM**	**EGMAM**	**IPCM**	**Average**	**Difference**
Population	**2030**	**2030**	**2030**	**2030**	**2030**	**B - A**
Workforce distribution	**2030**	**2030**	**2030**	**2030**	**2030**	
Region	**cases**	**cases**	**cases**	**cases**	**cases**	**cases**
1 Asia, High Income	2	5	7	6	6	4
2 Asia, Central	7	16	31	22	23	16
3 Asia, East	1100	1688	2218	2367	2091	991
4 Asia, South	14120	22455	36892	31712	30353	16233
5 Asia, South East	2369	3394	3670	4134	3733	1364
6 Australasia	0	0	0	0	0	0
7 Caribbean	29	49	55	60	55	26
8 Europe, Central	0	0	0	0	0	0
9 Europe, East	0	0	0	0	0	0
10 Europe, West	0	1	1	1	1	1
11 Lat-America, Andean	2	4	5	5	5	2
12 Lat-America, Central	168	274	308	363	315	147
13 Lat-America, South	1	1	1	3	2	1
14 Lat-America, Tropical	49	93	91	116	100	50
15 North America	13	39	46	45	43	30
16 Africa – North	606	999	1526	1380	1302	695
17 Oceania	35	53	54	61	56	21
18 Africa, Central	135	379	434	495	436	301
19 Africa, East	802	1244	1443	1500	1395	593
20 Africa, South	1	2	3	4	3	2
21 Africa, West	2445	3756	4169	4573	4166	1721
World total	21885	34453	50953	46848	44084	22199
World, difference by model, as compared with 1975 (A)	0	12568	29068	24963	22199	

The impact on calculated fatal cases due to occupational heat stress may be reduced in some regions in 2050 to 1/3 of the case numbers in 1975 because less people are working in the highly exposed occupations. These changes for each region are taken into account in the final calculations of the clinical and work capacity impacts (Tables 8 and 9 uses populations in 2030 and 2050 as a base).

When we adjust the calculation for the impact of increasing population and changing workforce distribution and only look at differences in model outputs caused by the calculated climate change, we find increasing fatalities in most regions (Tables 8 and 9). The worst affected are South Asia, West Africa and South-East Asia. Few or no fatalities at all are estimated for Australasia, Europe and the southern parts of Latin America and Africa. For the three climate models the additional fatal occupational heat stroke cases in 2030 would be in the range 12,000 – 29,000 (average 22,000; Table 8). In 2050 the equivalent additional cases are in the range 26,000 – 54,000 cases (average 43,000; Table 9).

Table 9. Fatal occupational heat stroke case numbers in 2050 depending on climate estimates for 1975 and 2050 (3 models and average), based on person-months of heat exposure; Cases = numbers of workplace heat stroke deaths; moderate work intensity; agricultural workers exposed outdoors; industrial workers exposed indoors; service workers not exposed to excessive workplace heat

.

Climate	**A, 1975**	**2050**	**2050**	**2050**	**B, 2050**	
Model		**BCM**	**EGMAM**	**IPCM**	**Average**	**Difference**
Population	**2050**	**2050**	**2050**	**2050**	**2050**	**B - A**
Workforce distribution	**2050**	**2050**	**2050**	**2050**	**2050**	
Region	**cases**	**cases**	**cases**	**cases**	**cases**	**cases**
1 Asia, High Income	1	5	6	8	6	5
2 Asia, Central	6	31	49	49	43	37
3 Asia, East	639	1437	1967	2601	2002	1363
4 Asia, South	14006	31874	52691	53137	45901	31895
5 Asia, South East	1531	2911	3273	3865	3350	1819
6 Australasia	0	0	0	0	0	0
7 Caribbean	20	45	52	61	52	33
8 Europe, Central	0	0	0	0	0	0
9 Europe, East	0	0	0	0	0	0
10 Europe, West	0	1	2	2	2	1
11 Lat-America, Andean	2	6	6	10	7	5
12 Lat-America, Central	173	397	434	546	459	286
13 Lat-America, South	0	2	2	6	3	3
14 Lat-America, Tropical	26	76	70	118	88	62
15 North America	14	64	72	90	75	62
16 Africa – North	821	1824	2793	3185	2601	1779
17 Oceania	39	73	75	87	78	39
18 Africa, Central	166	722	771	871	788	622
19 Africa, East	983	2063	2405	2711	2393	1410
20 Africa, South	0	2	2	4	2	2
21 Africa, West	2800	5771	6648	7431	6617	3816
World total	**21228**	**47303**	**71319**	**74783**	**64468**	**43240**
World, differences by model, as compared with 1975 (A)	0	26075	50091	53555	43240	

In the published estimate of the annual number of deaths due to climate change during the decade 1990 - 2000 (McMichael, et al., 2004) the global number of heat stress deaths, principally among elderly people, was given as 3,000 per year in 2000. Our calculations of global occupational heat stress deaths due to climate change in 2030 and 2050 indicate 22,000 and 43,000 additional cases per year. This increase represents an addition of approximately 10,000 annual deaths each decade due to workplace exposures alone, higher than the previous estimate by McMichael et al. (2004) focusing on the elderly population. It is also interesting to note that in North America, high income region, the expected fatal cases due to occupational heat exposure with the baseline (1975) climate was 14, not far from the annual reported numbers in MMWR (2008) (423/15 per year = 28 fatalities per year). Climate change in 2030 and 2050 may increase these numbers by a factor of 3 to 5. However, these estimated numbers of occupational heat deaths are low compared to South Asia where approximately 16,000 (Table 8) and 32,000 (Table 9) additional occupational heat stroke fatalities are estimated for 2030 and 2050.

Table 10. Non-fatal occupational heat stroke case numbers in 2030 and 1975 depending on climate estimates for 2030 (3 models and average); workforce distribution = agriculture workers assumed to be outdoors and carry out heavy work, and industry workers working indoors at moderate work intensity. Service workers assumed not to be affected by climate change related heat exposure.

Climate	**A, 1975**	**2030**	**2030**	**2030**	**B, 2030**	
Model	**Baseline**	**BCM**	**EGMAM**	**IPCM**	**Average**	**Difference**
Population	**2030**	**2030**	**2030**	**2030**	**2030**	**B - A**
Workforce distribution	**2030**	**2030**	**2030**	**2030**	**2030**	
Region	**cases**	**cases**	**cases**	**cases**	**cases**	**cases**
1 Asia, High Income	10	24	33	30	29	19
2 Asia, Central	39	74	128	98	100	61
3 Asia, East	4219	6437	8148	8655	7747	3527
4 Asia, South	46250	67156	90263	86903	81441	35190
5 Asia, South East	8347	12085	13051	14582	13239	4892
6 Australasia	0	1	1	1	1	1
7 Caribbean	122	194	214	230	213	91
8 Europe, Central	0	1	1	1	1	1
9 Europe, East	0	0	1	1	1	1
10 Europe, West	2	4	7	7	6	4
11 Lat-America, Andean	11	21	24	31	25	14
12 Lat-America, Central	678	1052	1170	1351	1191	513
13 Lat-America, South	3	8	9	15	11	8
14 Lat-America, Tropical	209	393	386	489	423	214
15 North America	77	160	185	180	175	97
16 Africa – North	2063	3173	4197	4009	3793	1729
17 Oceania	124	181	185	211	192	68
18 Africa, Central	722	1341	1504	1690	1512	790
19 Africa, East	2883	4451	5078	5312	4947	2064
20 Africa, South	5	11	15	21	15	11
21 Africa, West	8730	12889	14194	15510	14198	5468
World total	74494	109655	138790	139326	129257	54763

The three climate models produce data that deviate from the average by up to 1/3. The exposure-response relationships also have uncertainties that cannot be exactly quantified. Thus, we find that the global number of additional occupational heat stress fatalities due to climate change may amount to 12,000 – 29,000 cases in 2030 and 26,000 – 54,000 cases in 2050 (Tables 8 and 9).

Non-fatal heat stroke and heat exhaustion

Just like for the fatal occupational heat stress impacts South Asia has the greatest risks and number of cases followed by West Africa, South-East Asia and East Asia (Tables 10 and 11). More details can be found in the full report (Kjellstrom et al., 2014a). At a global level climate change in 2030 (difference in Table 10) may cause an additional 55,000 cases of non-fatal occupational heat stroke, and in 2050 (difference in Table 11) the average estimate is at 61,000.

Table 11. Non-fatal occupational heat stroke case numbers in 2050 and 1975 depending on climate estimates for 2050 (3 models and average); workforce distribution = agriculture workers assumed to be outdoors and carry out heavy work, and industry workers working indoors at moderate work intensity. Service workers assumed not to be affected by climate change related heat exposure.

Climate	**A, 1975**	**2050**	**2050**	**2050**	**B, 2050**	
Model		**BCM**	**EGMAM**	**IPCM**	**Average**	**Difference**
Population	**2050**	**2050**	**2050**	**2050**	**2050**	**B - A**
Workforce distribution	**2050**	**2050**	**2050**	**2050**	**2050**	
Region	**cases**	**cases**	**cases**	**cases**	**cases**	**cases**
1 Asia, High Income	10	26	38	42	36	26
2 Asia, Central	39	76	136	105	106	67
3 Asia, East	4147	6656	8487	9455	8199	4052
4 Asia, South	46555	69636	93952	91147	84912	38357
5 Asia, South East	8339	12802	13914	15629	14115	5776
6 Australasia	0	1	1	1	1	1
7 Caribbean	120	201	224	249	225	105
8 Europe, Central	0	1	1	2	1	1
9 Europe, East	0	0	1	1	1	1
10 Europe, West	2	5	10	9	8	6
11 Lat-America, Andean	11	30	31	44	35	24
12 Lat-America, Central	678	1143	1268	1505	1305	628
13 Lat-America, South	3	10	11	21	14	11
14 Lat-America, Tropical	207	431	415	561	469	262
15 North America	79	219	249	286	252	172
16 Africa – North	2158	3525	4686	4690	4300	2142
17 Oceania	124	184	187	214	195	71
18 Africa, Central	723	1381	1546	1750	1559	836
19 Africa, East	2903	4591	5249	5520	5120	2216
20 Africa, South	5	11	15	23	16	12
21 Africa, West	8829	13585	15004	16545	15045	6216
World total	74931	114512	145424	147798	135911	60980

We also calculated the number of cases of one-day occupational heat exhaustion, as described in the methods section. The additional annual number of such heat exhaustion cases lasting one day would be between 14 and 27 million in South Asia in 2030 and 2050, and in the whole world we estimate 22 and 43 million additional cases (Tables 12 and 13).

Table 12. Occupational heat exhaustion case numbers (millions) in 2030 and 1975 depending on climate estimates for 2030 (3 models and average); workforce distribution = agriculture workers assumed to be outdoors and carry out heavy work, and industry workers working indoors at moderate work intensity. Service workers assumed not to be affected by climate change related heat exposure.

Climate	**A, 1975**	**2030**	**2030**	**2030**	**B, 2030**	
Model		**BCM**	**EGMAM**	**IPCM**	**Average**	**Difference**
Population	**2030**	**2030**	**2030**	**2030**	**2030**	**B - A**
Workforce distribution	**2030**	**2030**	**2030**	**2030**	**2030**	
Region	**cases**	**cases**	**cases**	**cases**	**cases**	**cases**
1 Asia, High Income	0.004	0.010	0.013	0.012	0.012	0.008
2 Asia, Central	0.016	0.030	0.051	0.039	0.040	0.024
3 Asia, East	1.688	2.575	3.259	3.462	3.099	1.411
4 Asia, South	18.500	26.862	36.105	34.761	32.576	14.076
5 Asia, South East	3.339	4.834	5.220	5.833	5.296	1.957
6 Australasia	0.000	0.000	0.000	0.000	0.000	0.000
7 Caribbean	0.049	0.077	0.086	0.092	0.085	0.036
8 Europe, Central	0.000	0.000	0.000	0.001	0.000	0.000
9 Europe, East	0.000	0.000	0.000	0.000	0.000	0.000
10 Europe, West	0.001	0.002	0.003	0.003	0.002	0.002
11 Lat-America, Andean	0.004	0.009	0.010	0.012	0.010	0.006
12 Lat-America, Central	0.271	0.421	0.468	0.540	0.476	0.205
13 Lat-America, South	0.001	0.003	0.004	0.006	0.004	0.003
14 Lat-America, Tropical	0.084	0.157	0.154	0.196	0.169	0.086
15 North America	0.031	0.064	0.074	0.072	0.070	0.039
16 Africa – North	0.825	1.269	1.679	1.603	1.517	0.692
17 Oceania	0.050	0.073	0.074	0.084	0.077	0.027
18 Africa, Central	0.289	0.537	0.602	0.676	0.605	0.316
19 Africa, East	1.153	1.781	2.031	2.125	1.979	0.826
20 Africa, South	0.002	0.004	0.006	0.008	0.006	0.004
21 Africa, West	3.492	5.156	5.677	6.204	5.679	2.187
World total	29.798	43.862	55.516	55.730	51.703	21.905

Table 13. Occupational heat exhaustion case numbers (millions) in 2050 and 1975 depending on climate estimates for 2050 (3 models and average); workforce distribution = agriculture workers assumed to be outdoors and carry out heavy work, and industry workers working indoors at moderate work intensity. Service workers assumed not to be affected by climate change related heat exposure.

Climate	**A, 1975**	**2050**	**2050**	**2050**	**B, 2050**	
Model		**BCM**	**EGMAM**	**IPCM**	**Average**	**Difference**
Population	**2050**	**2050**	**2050**	**2050**	**2050**	**B - A**
Workforce distribution	**2050**	**2050**	**2050**	**2050**	**2050**	
Region	**cases**	**cases**	**cases**	**cases**	**cases**	**Cases**
1 Asia, High Income	0.003	0.012	0.017	0.021	0.016	0.013
2 Asia, Central	0.018	0.058	0.088	0.085	0.077	0.059
3 Asia, East	1.366	2.759	3.527	4.400	3.562	2.196
4 Asia, South	20.114	37.723	49.766	54.379	47.289	27.175
5 Asia, South East	3.287	5.998	6.576	7.502	6.692	3.406
6 Australasia	0.000	0.000	0.000	0.001	0.001	0.000
7 Caribbean	0.042	0.087	0.099	0.113	0.100	0.058
8 Europe, Central	0.000	0.001	0.000	0.002	0.001	0.001
9 Europe, East	0.000	0.000	0.001	0.002	0.001	0.001
10 Europe, West	0.001	0.003	0.005	0.005	0.004	0.004
11 Lat-America, Andean	0.004	0.014	0.014	0.020	0.016	0.012
12 Lat-America, Central	0.280	0.590	0.638	0.784	0.670	0.391
13 Lat-America, South	0.001	0.005	0.006	0.010	0.007	0.006
14 Lat-America, Tropical	0.075	0.203	0.187	0.287	0.226	0.150
15 North America	0.032	0.098	0.110	0.131	0.113	0.081
16 Africa – North	1.114	2.167	2.946	3.254	2.789	1.674
17 Oceania	0.063	0.112	0.115	0.136	0.121	0.058
18 Africa, Central	0.411	1.127	1.202	1.372	1.233	0.822
19 Africa, East	1.569	3.215	3.614	4.053	3.627	2.059
20 Africa, South	0.002	0.006	0.008	0.013	0.009	0.007
21 Africa, West	4.549	8.699	9.651	10.815	9.722	5.173
World total	32.932	62.878	78.568	87.384	76.277	43.345

Climate related work capacity loss

All the details of the analysis can be seen in the longer report (Kjellstrom et al., 2014a), but Table 14 and 15 show the work capacity losses in 2030 and 2050 for the population sizes listed in Table 5 and the workforce distributions listed in Table 6. Heavy labor in the sun is most affected with 6.2 % of annual hours lost for these work conditions in 2050, while work in the shade and moderate labor in sun and in shade have lower loss percentages. As an example, Figure 6 shows the situation for South-East Asia in 2030 and 2050. Light labor is even less affected, but in the hottest regions there will, be some work capacity loss also in this group.

Figure 6. Percentage work capacity loss due to workplace heat exposure in jobs with different exposure characteristics, South-East Asia.

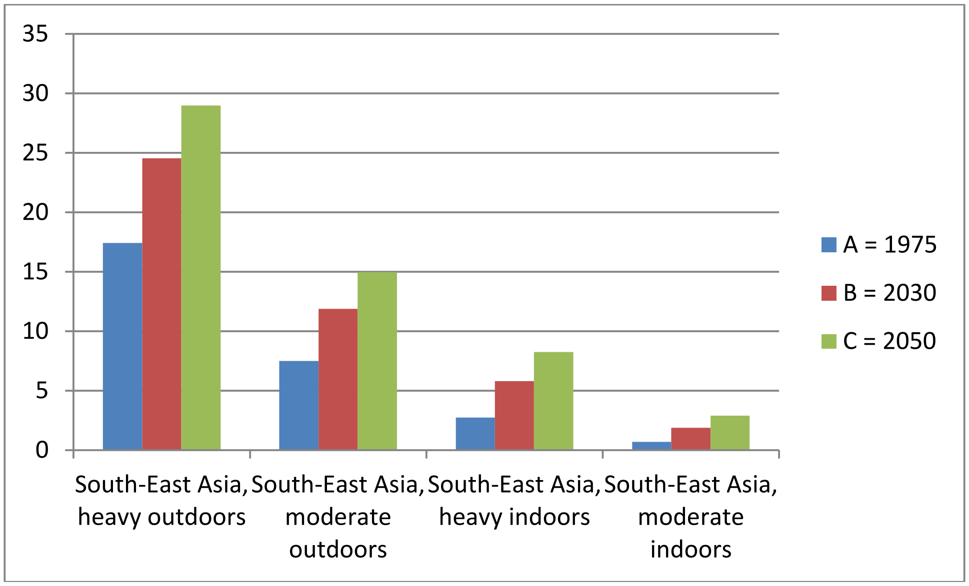


Figure 6 highlights the equality impact of climate change. People in heavy labor outdoors will be much more affected than people in moderate or light labor indoors. The first category includes mainly low income or poor working people, while those with less heat stress exposure are likely to have a higher income. The changes during climate change will thus affect low income people more than higher income people. Air conditioning or other cooling systems can eliminate the increasing indoor or in shade heat impacts shown here, but air conditioning cannot always be applied and it contributes to greenhouse gas emissions (Lundgren and Kjellstrom, 2013).

The percentage work capacity loss estimates in Tables 14 and 15 may look limited, but the resulting economic impact may be considerable if the annual loss of economic output is similar to the losses of daylight work hours. The two tables use different estimates of working age population and workforce distributions (2030 and 2050), which creates different loss estimates for 1975. The most affected regions are South Asia (losses at 8.1% in 2030 and 7.3% in 2050) and West Africa (losses at 7.0% in 2030 and 6.2% in 2050). The total losses of productive daylight work hours in 2050 are in the range 10 – 13% in these regions (Table 15).

The only estimate to date of the economic consequences of labor productivity loss in different regions around the world due to increasing heat exposure during global climate change until 2030 has been presented in the Climate Vulnerability Monitor 2012 (DARA, 2012). Using a similar analysis approach based on global GDP (estimated at 140 trillion USD PPP), for example, the 1.36% loss of daylight working hours shown in Table 14 could amount to 1.9 trillion USD PPP losses due to climate change in 2030. The published estimate was a loss of 2.1 trillion (DARA, 2012). The economic aspects of the occupational heat stress effects during climate change will be analyzed further in the Discussion.

The percentage losses in 2050 (Table 15) are higher than in 2030 (Table 14) for most regions, in spite of the expected reduced vulnerability to heat due to workforce changes (shown in Table 6). In 2030 the highest loss regions were in order South Asia, West Africa, Oceania and South-East Asia (Table 14), while in 2050 it was West Africa, South Asia, Oceania and Central Africa (Table 15).

Table 14. Work capacity loss as percent of annual available daylight working hours. Differences between losses in 2030 and 1975 depending on climate estimates for 2030 (3 models and average); workforce distribution = agriculture workers assumed to be outdoors and carry out heavy work, and industry workers working indoors at moderate work intensity. Service workers assumed not to be affected by climate change related heat exposure.

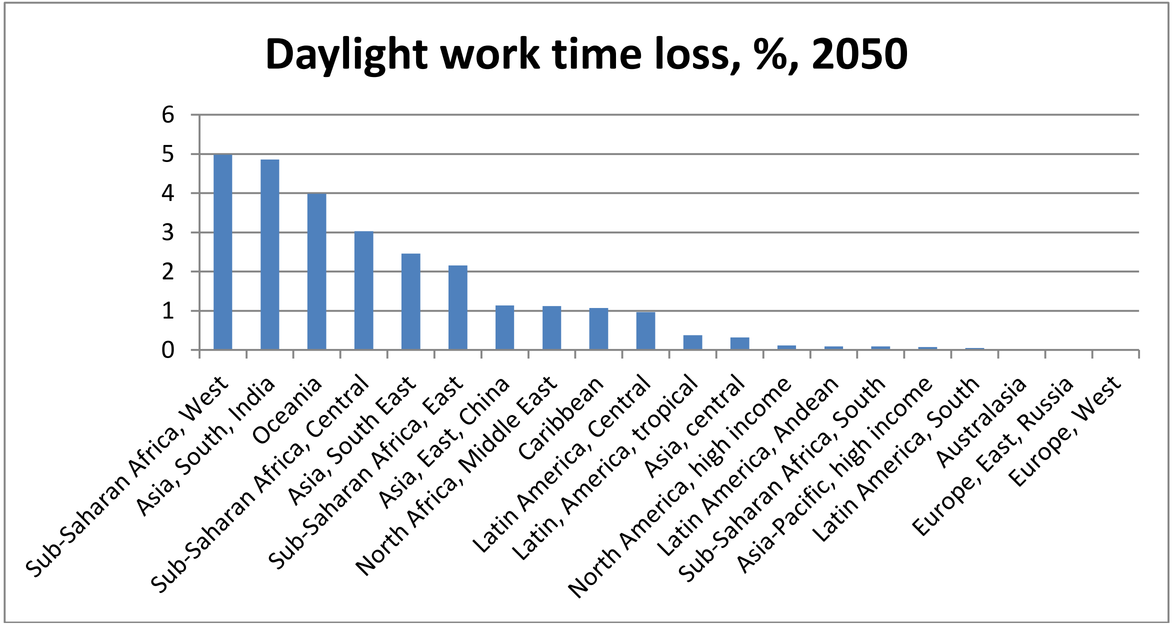
Climate	**A, 1975**	**2030**	**2030**	**2030**	**B, 2030**	
Model		**BCM**	**EGMAM**	**IPCM**	**Average**	**Difference**
Population	**2030**	**2030**	**2030**	**2030**	**2030**	**B - A**
Workforce distribution	**2030**	**2030**	**2030**	**2030**	**2030**	
Region						
1 Asia, High Income	0.04	0.08	0.10	0.10	0.09	0.05
2 Asia, Central	0.17	0.27	0.41	0.35	0.34	0.17
3 Asia, East	1.28	1.83	2.16	2.32	2.10	0.83
4 Asia, South	8.09	10.45	11.86	12.13	11.48	3.39
5 Asia, South East	4.63	6.29	6.67	7.22	6.73	2.09
6 Australasia	0.01	0.01	0.02	0.02	0.02	0.01
7 Caribbean	1.40	1.99	2.18	2.31	2.16	0.76
8 Europe, Central	0.00	0.00	0.01	0.01	0.01	0.01
9 Europe, East	0.00	0.00	0.01	0.01	0.00	0.00
10 Europe, West	0.00	0.01	0.01	0.01	0.01	0.00
11 Lat-America, Andean	0.06	0.10	0.11	0.13	0.11	0.05
12 Lat-America, Central	0.94	1.35	1.47	1.64	1.49	0.55
13 Lat-America, South	0.02	0.04	0.05	0.07	0.05	0.03
14 Lat-America, Tropical	0.41	0.69	0.68	0.84	0.74	0.33
15 North America	0.07	0.11	0.14	0.13	0.13	0.06
16 Africa – North	0.96	1.38	1.64	1.65	1.56	0.60
17 Oceania	5.41	7.62	7.76	8.77	8.05	2.64
18 Africa, Central	2.62	4.21	4.57	5.06	4.62	1.99
19 Africa, East	2.23	3.28	3.63	3.87	3.60	1.36
20 Africa, South	0.05	0.10	0.12	0.16	0.13	0.08
21 Africa, West	7.00	9.64	10.34	11.17	10.39	3.38
World total	2.76	3.75	4.20	4.41	4.12	1.36

The additional work capacity loss due to climate change in 2050 for the hottest regions varies between 1 and 5% (Table 15), assuming no change in heat adaptation takes place (apart from workforce distribution change). It should be emphasized that these numbers are averages at regional level for a mixed workforce and the work capacity losses for groups of workers carrying out heavy labor are much greater. Figure 6 showed an example of this type of assessment for one region (South-East Asia). (additional figures showing the equity impact are included in the longer report (Kjellstrom et al., 2014a).

Table 15. Work capacity loss as percent of annual available daylight working hours. Differences between percentages in 2050 and 1975 depending on climate estimates for 2050 (3 models and average); workforce distribution etc, as in Table 14.

Climate	**A, 1975**	**2050**	**2050**	**2050**	**B, 2050**	
Model		**BCM**	**EGMAM**	**IPCM**	**Average**	**Difference**
Population	**2050**	**2050**	**2050**	**2050**	**2050**	**B - A**
Workforce distribution	**2050**	**2050**	**2050**	**2050**	**2050**	
1 Asia, High Income	0.03	0.08	0.11	0.13	0.10	0.08
2 Asia, Central	0.15	0.36	0.51	0.52	0.47	0.32
3 Asia, East	0.95	1.73	2.06	2.48	2.09	1.14
4 Asia, South	7.25	10.86	12.15	13.32	12.11	4.86
5 Asia, South East	3.07	5.12	5.44	6.04	5.53	2.46
6 Australasia	0.01	0.02	0.02	0.04	0.03	0.02
7 Caribbean	1.06	1.91	2.13	2.34	2.13	1.07
8 Europe, Central	0.00	0.00	0.00	0.01	0.01	0.00
9 Europe, East	0.00	0.01	0.01	0.02	0.01	0.01
10 Europe, West	0.00	0.01	0.01	0.01	0.01	0.01
11 Lat-America, Andean	0.05	0.12	0.12	0.16	0.14	0.09
12 Lat-America, Central	0.96	1.75	1.87	2.18	1.93	0.97
13 Lat-America, South	0.02	0.05	0.06	0.09	0.07	0.05
14 Lat-America, Tropical	0.24	0.57	0.52	0.76	0.62	0.38
15 North America	0.07	0.16	0.18	0.20	0.18	0.12
16 Africa – North	1.09	1.86	2.26	2.51	2.21	1.12
17 Oceania	4.91	8.35	8.53	9.81	8.90	3.99
18 Africa, Central	2.24	4.88	5.12	5.83	5.27	3.03
19 Africa, East	2.05	3.85	4.11	4.67	4.21	2.16
20 Africa, South	0.03	0.08	0.10	0.16	0.11	0.09
21 Africa, West	6.21	10.47	11.04	12.08	11.19	4.98
World total	2.58	4.25	4.69	5.23	4.72	2.14

Figure 7. Additional losses of annual productive daylight work hours in 2050 compared with 1975 in the 21 regions ranked from highest to lowest losses.



The data in Table 15 can also be presented graphically with a ranking from highest to lowest losses in order to highlight the worst areas (Figure 7). Tropical low and middle income countries are most affected. The highest additional losses occur in 2050 in West Africa, South Asia (India), Oceania, Central Africa, South-East Asia, East Africa and East Asia (China). In terms of regional equity it is also important to note the number of workers likely to be affected in the different regions (Table 16). South Asia and East Asia are particularly populous regions, which implies that they will contribute much to the global impact. Oceania, Caribbean, Andean Latin America and Australasia have very few workers likely to be affected.

Table 16. Millions of working people affected by work capacity loss by region in 2050, and the % additional work capacity loss due to climate change.

Region	**Agriculture**	**Industry**	**Agriculture +Industry**	**Loss, %**
Sub-Saharan Africa, West	69	17	86	4.98
Asia, South, India	466	124	590	4.86
Oceania	2	0	2	3.99
Sub-Saharan Africa, Central	18	4	23	3.03
Asia, South East	128	64	192	2.46
Sub-Saharan Africa, East	87	13	100	2.16
Asia, East, China	422	273	696	1.14
North Africa, Middle East	65	53	118	1.12
Caribbean	4	5	9	1.07
Latin America, Central	23	30	53	0.97
Latin, America, tropical	20	26	46	0.38
Asia, central	17	9	26	0.32
North America, high income	5	47	53	0.12
Latin America, Andean	1	7	8	0.09
Sub-Saharan Africa, South	7	9	16	0.09
Asia-Pacific, high income	6	31	37	0.08
Latin America, South	1	9	10	0.05
Australasia	1	3	4	0.02
Europe, East, Russia	26	44	69	0.01
Europe, West	11	66	77	0.01
Europe, central	12	28	41	0
World, total			2255	

Uncertainty

In the WHO guidance for this project four key components of the uncertainty of the results were listed:

- Climate model uncertainty
- Emission uncertainty
- Measurement uncertainty
- Process uncertainty

To this we add a fifth which we call **Policy uncertainty**. It captures the unknown future development of the world's population and economy, which will largely determine future workforce composition, average income (GDP), use of cooling or labor intensity reduction technology, and relevant heat protection legislation and enforcement (Table 17).

Climate model uncertainly appears to be a relatively minor factor. We have found, as described earlier that the three climate models we were offered from the WHO team actually showed rather small differences of proportions at high heat exposure level. In weighted average population based heat exposure expressed as million person-degrees, the three individual models only differed by approximately 10% from the 3-model average (Kjellstrom et al., 2014a). The results of impact calculations with the three models differ more from the average because the impact is not proportional to exposure. However, the lowest and highest results from the three climate models are always within ±25% of the average.

E**missions uncertainty** is a fundamental issue that affects all the health impact assessments. Using just the A1B scenario in this project may limit the general applicability of our results. Emissions uncertainty arises from policy uncertainty coupled with future developments in technology, particularly for energy supply and transport services.

Measurement uncertainty is more related to the specific variables that we have referred to and calculated. The underlying data for our heat exposure assessments were the annual averages of monthly climate variables, and as we point out in our analysis the coefficient of variation (SD/mean) for the key variable, WBGT, was relatively small, a few percent based on a 30-year data set. We conclude that the underlying measurements were reasonably accurate with a confidence interval 10% around the means.

The **process uncertainty** emerges from a lack of mechanistic understanding of the cause-effect relationships that we are quantifying. In the case of heat effects on working people, the physiological and ergonomic understanding of the mechanisms are well established, but the actual exposure-response relationships for heat vs. effects are not so well established. The actual uncertainties are unknown, but one can assume that the uncertainties are no greater than in some of the other calculations of climate induced health effects (such as malnutrition or vector-borne diseases), which depend strongly on several assumptions and models.

Table 17. Sources of uncertainty

Sub-model	Class of uncertainty	Source of uncertainty
Economic scenarios	Policy	Economic development
GHG emissions	Emissions	Technology development
Climate Model	Climate model	Scientific progress in understanding
Future conditions	Emissions	Random (simulation)
Data	Measurement	Random (sampling)
Assumed mechanisms	Process	Scientific progress in understanding
Exposure-response relationships	Measurement	Random (sampling)
Future GDP	Policy	Political stability vs conflict
Workforce profile	Policy	Cultural change; Economic Development

An important aspect of the uncertainty is the variability of the climate modeling estimates, which determine our heat exposure distributions, but we have limited ability to assess the accuracy of this modeling. Another uncertainty is the variability of the exposure-response relationships, for which additional field studies would be of great value. Another major uncertainty is the extent to which the workforce distribution in the future will change so that the average heat impact in the population is slowed or even reduced from the 2000 levels.

It is very difficult to make meaningful quantitative estimates of the uncertainties based on so many analytical steps, many of which have more than one potential source of errors (Table 16). Further quantitative research on the different variables in the table is urgently needed.

Discussion

Impacts of current and future climate on occupational heat stress and its effects

Workplace heat links to health and productivity suppression

This analysis of effects of occupational heat exposure at regional level with an integration of climate change impacts is the first of its kind and includes methods and assumptions not tested in earlier studies. Our analysis shows that climate change can be expected to have substantial impacts on the incidence of clinical health effects of excessive heat exposure among working people in certain regions (e.g. 32,000 additional fatal heat stroke cases in South Asia in 2050 taking the workforce distribution into account, Table 9), while the occupational heat stress fatality rate in the global population is still relatively low (43,000 deaths out of a total global deaths at > 50 million). This is in line with previous analysis of the problems and health policy implications of climate change (Campbell-Lendrum et al., 2007).

However, the effects on work capacity, which have been considered in only one previous health impact assessments of climate change or current climate (DARA, 2012), can be significant (5% additional loss in

South Asia and West Africa in 2050, Table 15). Naturally these effects are greatest in people with jobs that involve heavy labor, while in light labor jobs the changing climate has an impact but with more limited losses in work capacity. Our analysis of work capacity loss involves effects related to the physiological function of people carrying out physical activity. It does not yet consider the psychological exhaustion effects of heat exposure at work, which can be considerable even in light office type work (see discussions by Wyndham, 1969 and Hancock et al., 2007). The differences in the impacts between different job types create important challenges to both health and socio-economic equity, exacerbating the existing health gap between low income outdoor or indoor workers doing hard labor and high income indoor workers in less physically strenuous jobs.

It is important to consider the potential additional exposures in urban and peri-urban areas where the urban heat island effect (Oke, 1973) creates higher heat exposure levels than those estimated via the grid cell modeling used by WHO in this project. The WBGT levels in urban areas may be 3 ^{o}C higher than the grid cell estimates, but extensive heat exposure monitoring programs are needed to get more accurate exposure estimates. In addition to extra heat exposure the urban and peri-urban workers may also face urban air pollution (especially photochemical oxidants), which creates clinical health risks and possibly work capacity loss. There is evidence that the two exposures create additive effects (e.g. Dear et al., 2005). There is also research in progress analyzing the increasing air pollution levels in urban areas as a result of increasing heat levels.

The mean estimates of the global number of additional occupational heat stroke fatalities is 22,000 in 2030 (Table 8, range 12,000 – 29,000) and 43,000 in 2050 (Table 9, range 26,000 – 54,000). These numbers show a doubling of the annual occupational heat stroke fatalities in 2030 and a further doubling in 2050. Compared with the calculations of the potential mortality impact of climate change from 1990 to 2000 (3,000 deaths in mainly elderly age groups; McMichael et al., 2004) these numbers are large, but no previous estimates of the occupational mortality are available. Emerging data from the USA (MMWR, 2008), India (Nag et al., 2009) and Qatar (Gibson and Pattison, 2014) indicate that further mortality analysis is of importance for making more accurate estimates. Appropriate preventive policies and actions can reduce the occupational heat stroke problems already now, but the prevention of clinical health effects may reduce labor productivity unless efficient methods to reduce work intensity or to cool workplaces are applied.

An important health impact for the affected communities will be the likely work capacity and labor productivity loss. The current loss of 6 – 7 % of workable daylight hours each year (or an additional loss due to climate change of 5 %) (Table 15) in regions like South Asia and West Africa will cause major problems for the local community to keep economic activities going all year around. For individual low income families any income loss caused by climate conditions will reduce the resources available for safe drinking water, sanitation, nutrition, and other health protecting daily needs and the family health will suffer.

Comparing clinical health effects and work capacity loss

It is of interest to attempt to quantify how the occupational heat stress clinical health impacts compare with the work capacity loss. We use 2030 as an example. It was estimated that 22,000 additional heat fatalities at work would occur in 2030 due to climate change since 1975 (Table 8). If each such death creates 40 years of lost productive work, the fatalities globally would have created 880,000 work life years lost in a year due to heat fatalities. These “work life years” lost are similar in character to the “disability-adjusted life years” (DALYs), which are used in much public health impact assessment these days. There will also be work years lost due to non-fatal occupational heat strokes as well as clinical heat exhaustion, but these are likely to have less impact on work years lost than the fatalities. For example, the 55,000 non-fatal cases in 2030 (Table 10) may each just create a work time loss of one week, so they represent only approximately 1,000 work years lost per year. In 2030 the global working age population (ages 15 – 64 years) was estimated at 5.3 billion (Table 5). The average work capacity loss as percent of daylight working hours lost due to climate change by 2030 was 1.4% (Table 14). As this percentage loss is an average for the whole global population, it implies that approximately 70 million work years will be lost due to labor productivity loss. This is more than 70 times the work years lost due to fatalities.

Table 18. Additional work capacity loss due to occupational heat as percent of annual available daylight working hours. Differences between losses in 2050 and 1975 depending on climate estimates, population size and workforce distribution in 2050

Region	Results, this report	Published results (Kjellstrom et al., 2009c)	Published with large deviations
1 Asia, High Income	0.08	0.2	
2 Asia, Central	0.32	0.4	
3 Asia, East	1.14	0.4	
4 Asia, South	4.86	4.4	
5 Asia, South East	2.46	2	
6 Australasia	0.02	0.2	
7 Caribbean	1.07		7.7
8 Europe, Central	0	0	
9 Europe, East	0.01	0.4	
10 Europe, West	0.01	0	
11 Lat-America, Andean	0.09		3.2
12 Lat-America, Central	0.97		18.6
13 Lat-America, South	0.05	0.1	
14 Lat-America, Tropical	0.38		-6
15 North America	0.12		3.4
16 Africa – North	1.12	0.6	
17 Oceania	3.99	3.1	
18 Africa, Central	3.03	0.8	
19 Africa, East	2.16	4.9	
20 Africa, South	0.09	-0.4	
21 Africa, West	4.98	3.4	
World total	2.14		

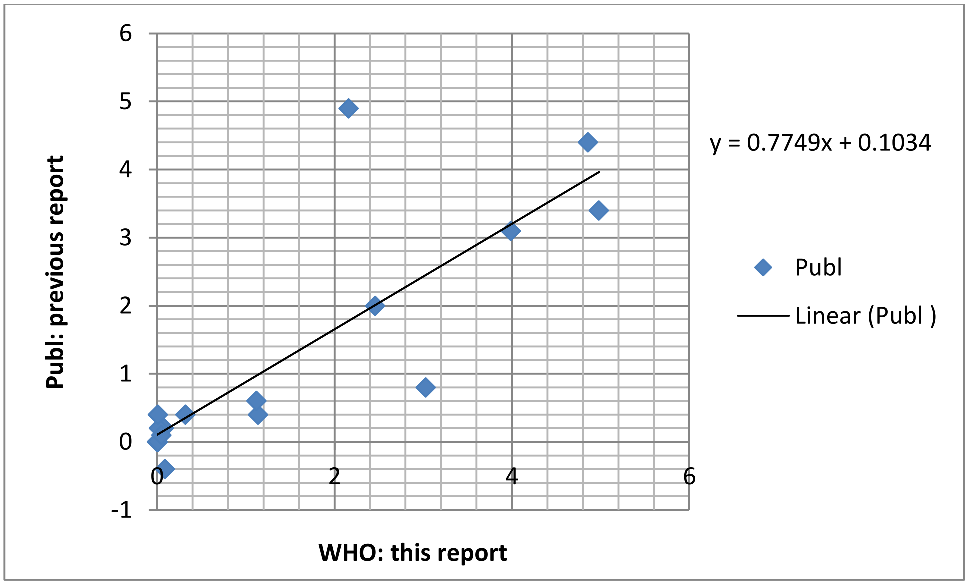
Comparing the results in this analysis with the published results

The previously published report on labor productivity loss due to climate change in the same 21 global regions (Kjellstrom et al., 2009c) included a table of “change in available work days” for the 2050s compared to “baseline” (1975). The climate condition data for each region were based on a few “selected grid cells, representative of the main climate types within each region”. This may give rather crude estimates compared to the actual grid cell based climate estimates in the current report.

In addition, the calculation of WBGT values used the Australian Bureau of Meteorology website formula, which has now been established to have errors (Lemke and Kjellstrom, 2012), and it was taken off the website in 2013. The interpretation of the work capacity loss due to heat used the ISO (1989) standard, which as we mentioned earlier may give too high loss estimates in certain heat situations.

In any case, the work capacity loss estimates for 2050 are reasonably similar for most of the regions (Table 18), and some of the highly affected and highly populated regions (Table 16) have good agreements. Five regions with large deviations between the two estimates have been identified in Table 18, and they all have relatively small working age populations (Table 16). The comparison of the results in this report and the publication show the two outliers (Central Africa and East Africa), but overall the published results are 0.8 times the new results (Figure 8). In three of the highly populated regions (South Asia, South-East Asia and West Africa) the results were close to the fitted regression line (Table 18 and Figure 8).

Figure 8. Comparison of annual work time loss due to heat according to this report (x) and the previously published report (y), excluding large deviation results shown in Table 18 (Kjellstrom et al., 2009c).



Economic aspects of the work capacity loss

As mentioned, the published work time loss estimates were used to calculate the losses at country level in the Climate Vulnerability Monitor 2012 (DARA, 2012). The estimated numbers for annual losses in 2030 are very large for many countries (Table 19), as even a limited percentage of labor productivity loss can create a big economic loss when the GDP of countries is at billions of US dollars each year.

Table 19. Heat exposure and economic data for 19 member countries of Climate Vulnerable Forum (data from DARA, 2012, assembled by Kjellstrom et al, 2015, in press)

Variable code	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**
Country	GNP/cap 2011	Heat loss 2010	Heat loss 2030	Heat loss 2030 in GDP	Total CC loss 2030	WBGTmax trend	Serious heat days, trend	Serious heat days
Unit	USD	% of GDP	% of GDP	millions USD/PPP	% of GDP	°C/ decade	days/ decade	days/year
Selected members of Climate Vulnerable Forum, CVF (20 member countries)								
Bangladesh	1529	1.5	3.0	30000	6.8	0.09	NA	NA
Costa Rica	10497	2.3	4.5	9000	6.3	0.1	NA	3
Ethiopia	971	1.3	2.4	6000	3.7	0.24		0
Ghana	1584	3.2	6.5	15000	8.9	0.16	12	280
Kenya	1492	1.2	2.3	4750	3.7	0.17	0	0
Maldives	5276	3.0	5.6	550	15.9	0.09	NA	360
Nepal	1160	1.5	2.8	3750	4.1	0.44	NA	0
Philippines	3478	2.9	5.9	85000	7.1	-0.12	19	320
Tanzania	1328	1.3	2.2	4000	4.8	0.16	26	260
Vietnam	2805	2.9	5.7	85000	10.7	0.02	0	170
Selected observer countries in CVF								
China	7476	0.4	0.8	450000	1.30	0.24	3	75
India	3468	1.5	3.2	450000	4.30	0.45	10	195
Indonesia	3716	2.9	6.0	250000	7.00	0.06	NA	NA
Mexico	13245	2.3	4.4	250000	6.10	0.28	0	0
Nigeria	2069	3.3	6.4	75000	7.60	0.21	NA	NA
Pakistan	2550	1.5	2.8	50000	4.40	0.2	8.5	140
South Africa	9469	0.2	0.5	7250	1.90	0.24	0	0
Thailand	7694	2.9	6.0	150000	7.20	0.39	7.8	335
Australia	34431	0.0	0.0	100	0.80	0.66	2.3	6
France	30462	0.0	0.0	0	0.90	0.35	0.5	2
Sweden	35837	-0.1	-0.2	-950	-1.40	0.49	0	0
UK	33296	0.0	0.0	0	-0.30	0.23	0	0
USA	43017	0.1	0.2	50000	0.50	0.14	0.4	44
Selected other countries								
Cambodia	1848	3.0	5.7	9250	10.30	0.09	6	320
Malaysia	13685	2.8	5.9	95000	7.30	0.35	4	362
Sri Lanka	4943	3.0	5.9	25000	7.40	0.15	NA	320
Brunei	45753	0.0	0.0	15	0.70	0.17	5	362

Table 19 shows examples of countries in different climate zones and at different income level. The highest costs for losses of work time in 2030 due to occupational heat exposure are in China and India

(450 billion USD PPP per year), but several other countries have estimated multi-billion USD losses (e.g. Bangladesh, the Philippines, Vietnam, Indonesia, Mexico, Nigeria, Pakistan, Thailand, USA, Malaysia and Sri Lanka).

These data are tentative, because of the way they were created from the published work time loss estimates by Kjellstrom et al (2009c), but it is the only available detailed analysis of national economic impact of climate change effects on working people. Decision-making and policy development for this aspect of climate change will be significantly assisted by an updated more precise analysis for each country. Funding for such analysis has been applied for without any meaningful response so far.

In terms of the cost benefit of financial support for improved analysis, one can consider the example of Malaysia, where the estimated cost of labor productivity loss due to increased workplace heat with climate change is 95 billion USD in 2030. Let's assume that this number is in fact 10 times higher than the real cost, because 90% of the impact is eliminated with climate adaptation. There is still 9.5 billion in cost for lost productivity. If new analysis and research on this topic can reduce the cost by 10%, then the value of such work would be 950 million USD per year in 2030. The cost of such work now could be less than 1 million USD for one country analysis, or even multi-country analysis.

So, is this an attractive cost-benefit relationship to consider in Malaysia (or any other country):

1 million USD analysis work now → savings of 950 million USD per year in 2030, or even bigger savings

For the USA, the savings from 1 million dollars in analysis and research investment could be 500 million USD per year, using this calculation basis, and in China and India the savings could be several billion USD.

The economic aspects of the occupational heat stress impacts of climate change are still poorly developed, even though recently for the first time an analysis was published for the USA (Kopp et al., 2014). Adaptation to climate change and mitigation efforts will, of course, require considerable economic investments, but the reduction of the costs of losses of labor productivity may balance off all or a large part of such costs.

Policies and practices to reduce climate change impacts

Our results section showed that heat stress will increase due to global heating with substantial increases of clinical health risks and with major reductions of worker productivity during hot seasons. Adaptation to these negative impacts will vary from region to region. It is expected that there will be almost complete adaptation to occupational heat stress in high income countries in temperate climate regions, while there will be minimal adaptation possible in many jobs in tropical regions.

Temperate zone adaptation

Physical acclimatization to increasing heat should be possible in temperate regions, possibly to the extent currently existing in hot tropical countries, but the physiological limits will remain in the future.

Adaptation to hot summer hours may include starting work earlier, taking breaks during the hot part of the day and resuming work in the late afternoon or early evening. This is already common practice in "siesta" countries, but hourly productivity during work hours in the middle of the day will be reduced.

Full air conditioning indoors will relieve heat stress but adds to the outside heat in urban areas as heat is pumped from buildings into streets (Grimmond, 2007). Air conditioning adds to the energy use (and contributes to global warming) except where new renewable energy methods are employed: for example, "free cooling" using phase change (Raj and Velraj, 2010), the use of reflective coatings especially on roofs (Shen et al., 2011), and systems using solar radiation as energy source (Chan et al., 2010). A reduction of the urban heat island effect could counteract global warming on a local scale. Increased tree planting and other vegetation cover is very effective (Grimm et al., 2008) and very noticeable in some cities (such as Buenos Aries) where there are some tree lined streets and others with no trees. Water features also contribute to local cooling via water evaporation, but this may increase local humidity levels that increase WBGT and other heat stress indexes.

Adaptation will be most effective at the local level (CCD, 2009). Effective heat exposure warnings need to be developed that work for a local community. A new heat stress index like UTCI (Universal Thermal Climate Index; see: www.utci.org) is likely to require time before it becomes widely used, and familiar local heat indexes like WBGT, Humidex and the Heat Index will still be used. While heat stress indexes in different regions do not need to be the same, some quality control is needed so that the heat stress index is applicable anywhere in the world and valid at local level. In addition, recalculation formulas that can convert one index number to another need to be freely available. Some published calculation formulas for WBGT have been incorrect, and different formulas need to be compared and assessed (Lemke and Kjellstrom, 2012).

Education is needed because many people still believe that sweating cools you down rather than understanding that evaporation of the sweat is necessary for cooling. Humans are not able to sense high humidity as accurately as we sense high temperature (Parsons, 2014) and if a large amount of un-evaporated sweat is mistaken as effective cooling, exposed individuals will fail to take necessary precautions against heat.

Social adaptation is also important to protect the vulnerable from heat stress (Yardley et al., 2011). Studies of heat impacts on elderly people in temperate climates identify two risk groups: those who live isolated lives and those who have low socioeconomic status. We have identified another risk group: people working in heavy physical intensity jobs without cooling systems, a group that often has low socio-economic status.

In the USA it is suggested that public interventions generally have less effect on low socio-economic groups (Ebi and Semenza, 2008). While some adaptations (e.g. heat stress regulations) need a top-down approach, such as government regulations with proper enforcement, many adaptations "will be more effective if designed, implemented and monitored with strong community engagement." (Ebi and Semenza, 2008). Occupational heat stress protection guidelines are available in a number of countries (e.g. for USA it is ACGIH, 2009), but their implementation needs to involve the exposed worker groups. Local monitoring of heat stress indexes is becoming increasingly feasible with access to low cost temperature and humidity dataloggers (see: www.ClimateCIP.org).

Adaptation in the tropics

As the duration of daylight in tropical areas does not vary much from 12 hours there is less opportunity to compensate for heat impacts during the middle of the day by starting work early or finishing late, unless major lighting equipment is easily available. A siesta/rest break during the hottest part of the day truly results in lost opportunities for work that requires daylight. Evaporative cooling is less effective with the high humidity common in tropical areas (and cooling systems do not reduce the humidity). However, buildings can be designed differently with roof ventilation (Susanti et al., 2011) and by the construction of traditional style buildings rather than modern buildings. As the life-time of a new building is about 50 years, changes to the architecture of buildings need to be implemented now to cope with the expected temperature rise by 2050.

Nag et al (2009) did extensive research on the vulnerability of Western India to heat stress from climate change and the potential for adaptation. Their report showed that fatalities due to heat stroke among farmers were about 11% of the total rural casualties at the workplace. Most heat related mortality occurred outdoors mainly among those who live in rural areas at the poverty threshold. This is in contrast to the heat waves in Europe where most fatalities were in urban areas. Nag et al (2009) state that "there is a lack of health surveillance" in most states of India, and that "the public recognition of the magnitude of the hazards of [heat strain] remains at a minimum level." Furthermore, "most people come to believe that the natural phenomena are unavoidable, and therefore, the heat related mortality that might be grave during a particular year in a region does not leave a lasting reminder …". The most vulnerable people are "urban and rural poor who cannot afford shelters … and those living alone who cannot access cooling systems" (Nag et al., 2009). Data from several worker groups (Iron workers, Ceramic workers and Stone Quarry workers) showed that "different forms of artificial hot atmospheres often exceeded the climatic stresses found even in these extreme natural climates."

Workplace climate conditions in places without effective air-conditioning, are a combination of the local heat source contributions and the outdoor "natural" climates. If outdoor heat exposure increases by 1 ºC, the combined heat exposure indoors will also increase by 1 ºC causing additional heat stress. It is difficult to quantify the degree of adaptation possible where work processes produce substantial heat exposure. Clearly adaptation via education and properly enforced regulations on occupational heat stress can make a significant difference in reducing death and injury from heat stress, such adaptations are likely to reduce worker productivity and add to the burden of poverty.

In this initial analysis we have assumed that the changes in the workforce distribution will correspond to the "adaptation" that involves reducing the heavy labour input into the economic activities and protecting those in service jobs by cooling systems. It is not possible at this time to foresee if any other adaptation to climate change, that would reduce occupational heat stress and its effects, will take place in the vulnerable regions.

Recent projections of the likely future continued lack of access to safe drinking water and basic sanitation (OECD, 2012) indicates that many hundreds of millions of people are likely to also suffer from lack of protection against occupational heat stress. Unless the vulnerability to health impacts from climate conditions is substantially reduced via significant investments in community infrastructure for low income people anywhere in the world, the climate change impacts will remain a major challenge for these people. There will always be a limit to the extent that adaptation can reduce health and productivity risks, and climate change mitigation is therefore an urgent issue to address.

Conclusions

Occupational heat stress is an important component of impacts of climate conditions on human health. Working people create internal surplus heat in the body, which adds to the heat stress caused by the ambient climate. Therefore, working people are a vulnerable group as climate change brings an increase of very hot days. The physiological and ergonomical evidence about heat effects on human bodies is very substantial, and the direct effects of heat in a defined working population can be estimated with more confidence than some of the indirect effects on health from climate change.

Four different types of health effects from climate conditions and climate change are estimated in this report: heat stroke fatalities, non-fatal serious heat effects, short-term heat exhaustion, and work capacity loss due to excessive heat exposure, which leads to income loss and greater vulnerability to adverse health conditions. Using grid cell based climate and population data for 30-year periods around 1975, 2030 and 2050, the quantitative effects on the working age population in 21 geographical regions and the global total were calculated.

The estimated numbers of additional occupational heat stress fatalities due to climate change are 22,000 in 2030 and 43,000 in 2050 (averages), implying a doubling and quadrupling of cases compared to 1975. There may be three times as many non-fatal heat stress cases, as well as more than 40 million daily heat exhaustion cases. If each fatality implies a loss of 40 work life years for the person who died from occupational heat stroke, the global loss of work years due to climate change in 2030 would be 880,000 work life years. Non-fatal clinical heat effects add just a small number of lost work life years.

The global loss of work capacity (or labor productivity) during daylight working hours could be 1.4 % in 2030 and 2.1 % in 2050. This may look small, but, if GDP is reduced at a similar rate and with an estimated global GDP in 2030 of 140 trillion USD, 1.4 % loss means a loss of 2 trillion USD of economic output. The global loss of work life years in 2030 among the 5 billion working age people would be 70 million years (1.4% x 5 billion). This is more than 70 times greater than the work life years lost due to clinical heat effects.

For most of the 21 global regions the new estimates of labor productivity loss (as % of daylight work hours) are similar to an earlier published report. Economic cost estimates for different countries based on the previously published report need to be updated. The global economic cost estimates are similar, which gives some confidence in the overall analysis method. The losses of health and economic resources can be reduced by climate change adaptation and mitigation. Further analysis work and adaptation and mitigation advice is urgently needed.

References

ACGIH (2009). TLVs for chemical substances and physical agents & Biological exposure indicators. Cincinatti, American Conference of Government Industrial Hygienists.

Bennet C, McMichael T (2010). Non-heat related impacts of climate change on working populations. *Global Health Action*, Dec 17;3. doi: 10.3402/gha.v3i0.5640.

Bernard TE, Pourmoghani M (1999) Prediction of Workplace Wet Bulb Global Temperature. Applied Occupational and Environmental Hygiene 14: 126-134

Berry HL, Bowen K, Kjellstrom T (2010). Climate change and mental health: a causal pathways framework. Int J Public Health, 55: 123-132, (DOI: 10.1007/s00038-009-0112-0)

Brice T, Hall T (2009) Wet-bulb calculator. http://www.srh.noaa.gov/epz/?n=wxcalc

Bridger RS (2003). Introduction to ergonomics, 2nd edition. London: Taylor & Francis; 2003.

Campbell-Lendrum D, Corvalan C, Neira M (2007) Global climate change: implications for international public health policy. Bull World Health Org, 85, 235-237.

Chan HY, Riffat SB, Zhu J (2010). Review of passive solar heating and cooling technologies. Renewable and Sustainable Energy Reviews 14: 781-789

Costello A, Abbas M, Allen A, Ball S, Bell S, Bellamy R, et al. (2009) (Lancet-University College London Institute for Global Health Commission). Managing the health effects of climate change. The Lancet 373: 1693-1733.

Dear K, Ranmuthugala G, Kjellstrom T, Skinner C and Hanigan I. (2005) Effects of temperature and ozone on daily mortality during the August 2003 heat wave in France. Arch. Environ Occup Health, 60: 205-212.

Dell M, Jones BF, Olken BA (2009). Temperature and income: reconciling new cross-sectional and panel estimates. Amer. Econ Rev 99: 198-204.

DoLNZ (1997) Guidelines for the management of work in extremes of temperature. 1997. Occupational Safety and health, Department of Labour, Wellington, New Zealand. P.91.ISBN 0-477-03605-8

Dunne JP, Stoufer RJ, John JG. (2013) Reductions in labour capacity from heat stress under climate warming. Nature Climate Change 2013, DOI 10.1038/NCLIMATE1827.

Ebi KI, Semenza JC (2008). Community-based adaptation to the health impacts of climate change. Am J Preventative Medicine 35: 501 – 507

Fiala D, Havenith G, Broede P, Kampmann B, Jendritzky G (2011). UTCI-Fiala mulit-node model of human heat transfer and temerpature regulation. Int J Biometeorology. (on website).

Fussel H-M, Klein RJT, Ebi KL (2006) Adaptation assessment for public health. In: Menne B. and Ebi KL, Eds. Climate change and adaptation strategies for human health. Darmstadt, Steinkopff Verlag, pp. 41-62.

García-Trabanino R, Dominguez J, Jansa J, Oliver A (2005). Proteinuria and chronic kidney disease on the coast of El Salvador (in Spanish). Nefrología 25: 31–8. (http://www.revistanefrologia.com/mostrarfile.asp?ID=2144)

Gaspar A, Quintela D (2009). Physical modelling of globe and natural wet bulb temperatures to predict WBGT heat stress index in outdoor environments. International Journal Biometeorology 53: 221-230

Gibson O, Pattisson P. Qatar World Cup: 185 Nepalese died in 2013 – official records. The Guardian, 2014, 24 January, 2014.

Grimm NB, Faeth SH, Golubiewski NE, Redman CL, Wu J, Bai X, Briggs JM (2008). Global change and the ecology of cities. Science 319: 756-760

Grimmond S (2007) Urbanization and global environmental change: local effects of urban warming. The Geographical Journal 173, 83-88.

Hancock PA, Ross JM, Szalma JL (2007) A meta-analysis of performance response under thermal stressors. Human Factors, 49, 851-877.

IIASA (2010). Population data from website. Laxenburg (Vienna), International Inst. of Advanced Systems Analysis.

IPCC (2013) Climate Change: Working Group 1 report. Geneva: The Intergovernmental Panel on Climate Change. (http://www.ipcc.ch)

IPCC (2014) Impacts of Climate Change: Working Group 2 report. Geneva: The Intergovernmental Panel on Climate Change. (http://www.ipcc.ch)

ISO (1989) Hot environments - Estimation of the heat stress on working man, based on the WBGT-index (wet bulb globe temperature). ISO Standard 7243. Geneva: International Standards Organization.

Jendritzky G, Tinz B (2009). The thermal environment of the human being on the global scale. Global Health Action. Special Vol, pp. 10-21. DOI: 10.3402/gha.v2i0.2005.

Kjellstrom T (2000). Climate change, heat exposure and labour productivity. Epidemiology 11: S144.

Kjellstrom T (2009a). Editorial: Climate change, direct heat exposure, heath and well-being in low and middle-income countries. Global Health Action 2: on web (DOI: 10.3402/gha.v2i0.1958)

Kjellstrom, T (2009b). Climate change exposures, chronic diseases and mental health in urban populations -- a threat to health security, particularly for the poor and disadvantaged. Technical report, WHO Kobe Centre. Kobe, Japan: World Health Organization; (http://www.who.or.jp/2009/reports/Technical_report_work_ability_09.pdf)

Kjellstrom T, Holmer I, Lemke B (2009a). Workplace heat stress, health and productivity - an increasing challenge for low and middle-income countries during climate change. Global Health Action 2: Special Volume, pp. 46-51.

Kjellstrom T, Gabrysch S, Lemke B, Dear K. (2009b) The "Hothaps" program for assessment of climate change impacts on occupational health and productivity: An invitation to carry out field studies. *Global Health Action* 2009; 2: DOI 10.3402/gha.v2i0.2082.

Kjellstrom T, Kovats S, Lloyd SJ, Holt T, Tol RSJ (2009c). The direct impact of climate change on regional labour productivity. Int Arch Environ Occup Health, 64: 217-227

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.

Kjellstrom T, Lemke B, Otto M, Dear K (2014a) Occupational heat stress: exposures and effects in relation to climate change. Technical report 2014:2. On website: www.ClimateCHIP.org (in press).

Kjellstrom T, Lemke B, Otto M, Hyatt O, Briggs D, Freyberg C. (2014b) Heat impacts on human performance and daily life. In: Levy B, Patz J. Eds. Climate change and Public Health. New York, Oxford Univ Press, 2014 (in press).

Kopp R, Hsiang S, Muir-Wood R, et al. (2014) American Climate Prospectus. Economic risks in the United States. New York: Rhodium Group, 2014 (accessed on July 18, 2014 at http://rhg.com/wp-content/uploads/2014/06/RHG_AmericanClimateProspectus_June2014_LowRes1.pdf)

Kovats RS, Hajat S (2007). Heat stress and public health: a critical review. Ann Rev Publ Health. 29: 41-55.

Leach G (1975). Energy and food production. Food policy 1: 62-73.

Lemke B, Kjellstrom T. Calculating workplace WBGT from meteorological data. Industrial Health, 2012, 50, 267-278.

Lemke B, Hyatt O, Kjellstrom T (2011). Estimating workplace heat exposure using weather station and climate modeling data: new tools to estimate climate change impacts on occupational health in Asia and the Pacific region. Asia-Pacific Newsletter on Occupational Health and Safety. 18: 20-23.

Liljegren J, Carhart R, Lawday P, Tschopp S, Sharp R (2008). Modeling Wet Bulb Globe Temperature using Standard Meteorological Measurements. J Occup Environ Hygiene 2008; 5: 645-655.

Lundgren K, Kjellstrom T. (2013) Sustainability challenges from climate change and air conditioning use in urban areas. *Sustainability* 2013;5:3116-3128; doi:10.3390/su5073116

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. 2011; 55: 147-160.

McMichael AJ, Campbell-Lendrum D, Kovats S, et al (2004). Global climate change. In: Ezzati M, Lopes A, Roders A, et al, editors. Comparative quantification of health risks, global and regional burden of disease attributable to selected major risk factors. Vol. 2. Geneva, World Health Organization, pp. 1543-1650.

MMWR (2008). Center for Disease Control and Prevention (CDC). Heat-related deaths among crop workers- United States, 1992-2006. MMWR Weekly. June 20, 57(24); 649-653.

Nag A, Nag P (1992). Heat stress of women doing manipulative work. Am Ind Hyg Assoc J, 53: 751-756.

Nag PK, Nag A, Sekhar P, Pandit S (2009). Vulnerability to heat stress: Scenario in Western India. WHO report APW No. SO 08 AMS 6157206). Delhi, World Health Organization Regional Office.

NOAA (2009) National Oceanic and Atmospheric Administration. Global Summary of the day. http://www.ncdc.noaa.gov/cgi-bin/res40.pl?page=gsod.html.

OECD (2012) OECD Environmental Outlook to 2050: The consequences of inaction. Paris, Organisation for Economic Co-operation and Development. http://www.oecd.org/env/indicators-modelling-outlooks/49846090.pdf

Oke, TR. City size and the urban heat island. Atmosph Environ 1973; 7: 769-79.

Parsons K (2003). Human thermal environments. The effects of hot, moderate and cold temperatures on human health, comfort and performance. 2nd edition. London: Taylor & Francis. ISBN 0-415-23793-9

Parsons K (2009). Maintaining health, comfort and productivity in heat waves. Global Health Action, 2. (on web*)*

Parsons K (2014). Human thermal environments. The effects of hot, moderate and cold temperatures on human health, comfort and performance. 3rd edition. London: Taylor & Francis.

Raj VAA, Velraj R, (2010). Review on free cooling of buildings using phase change materials. Renewable and Sustainable Energy Reviews 14: 2819-2829

Ramsey JD, Burford CL, Beshir MY, Jensen RL (1983). Effects of workplace thermal conditions on safe working behavior. J Safety Res 14: 105-114.

Rijal K, Bansal NK, Grover PD (1991). Energy in subsistence agriculture: a case study of Nepal. Internat. J Energy Research 15: 109-122.

Sahu S, Sett M, Kjellstrom T. Heat Exposure, Cardiovascular Stress and Work Productivity in Rice Harvesters in India: Implications for a Climate Change Future. Ind Health, 2013, 51, 424-431.

Schrier RW, Henderson HS, Tisher CC, Tannen RL (1967). Nephropathy associated with heat stress and exercise. Annals of Internal Medicine 67: 356-376.

Shen H, Tan H, Tzempelikos A, (2011). The effect of reflective coatings on building surface temperature, indoor environment and energy consumption. Energy and Buildings 43: 573-580

Sherwood SC, Huber M, (2010). An adaptability limit to climate change due to heat stress. PNAS 107: 9552-9555.

Sims BG, Kienzle J (2006). Farm power and mechanization for small farms in sub-Saharan Africa. Agricultural and food engineering technical report Nr 3. Rome, FAO, Food and Agriculture Organization of the United Nations.

Susanti I, Homma H, Matsumoto H (2011). A naturally ventilated cavity roof as potential benefits for improving thermal environment and cooling load of a factory building. Energy and Buildings 42: 211-218.

Tawatsupa B, Yiengprugsawan V, Kjellstrom T**,** Berecki-Gisolf J, Seubsman SA, Sleigh A. Association between heat stress and occupational injury among Thai workers: findings of teh Thai Cohort Study. Ind Health 2013, 51, 34-46.

Wakabayashi H, Wijayanto T, Lee J-Y, Hashiguchi N, Saat M, Tochihara Y (2010). Comparison of heat dissipation response between Malaysian and Japanese males during exercise in humid heat stress. Int J Biometeorol, (online).

Wyndham CH (1965). A survey of the causal factors in heat stroke and of their prevention in the gold mining industry. J S African Inst Mining and Metallurg 65: 125-155.

Wyndham CH (1969). Adaptation to heat and cold. Env Res 2, 442-469.

Yaglou, CP, Minard D (1957) Control of Heat Casualties at Military Centers, AMA Arch. Ind. Hlth 16: 302-316.

Yardley J, Sigal RJ, Kenny GP (2010). Heat Health Planning: the importance of social and community factors. Global Environmental Change 21: 670-679.

Zhao J, Zhu N, Lu S (2009). Productivity model in hot and humid environment based on heat tolerance time analysis. Building and Environment 44(11): 2202–2207.