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How will Climate Change Working Life?

Impacts of Heat on Productivity and Health

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"We can't solve problems by using the same kind of thinking we used when we created them." - Albert Einstein

Abstract

Heat stress has been studied extensively. However, in the contemporary context of climate change there is a lack of information on the extent of future heat stress and its consequences, especially in occupational settings. The main aim of the research was to identify the current knowledge gaps by conducting a literature review (paper I) together with the collection of empirical data to examine the implications for labour productivity and occupational health in already hot workplaces in Chennai, India (paper II). Finally, it also looked at adaptation options for cooling and sustainability challenges from air conditioning use (paper III).

The literature review found the main factors to exacerbate heat stress in current and future workplaces to be the urban heat island effect, physical work, individual differences, and the developing country context, where technological fixes and certain control measures are often not applicable. There is also a lack of information regarding the effects on vulnerable groups such as the poor, elderly and pregnant women.

The field study in Chennai gathered data from measurements, observations and questionnaires. Climate measurements were combined with estimations of workload and measurements of the properties of the work clothing. Health risks, preventive methods, productivity impacts and the links to climate change were also explored. All workplaces surveyed, representing the industrial, service and agricultural sectors, had very high heat exposure, often reaching the international standard threshold (ISO 7243:1989) for working safely. Most workers had moderate to high workloads, some in direct sun exposure. Females were found to be more vulnerable due to the extra insulation added from wearing a protective shirt on top of traditional clothing when working. Most workers reported health problems due to heat exposure, including tiredness, dizziness and headaches. Problems in meeting production targets in the hotter months were usually compensated for by overtime work. When analyzing productivity loss and heat strain in a physiological model – the Predicted Heat Strain Model (ISO 7933:2004) – the parameters showed significant impacts, especially when a couple of extra degrees were added to the climate change scenario. Water provision and rehydration were critical parameters in the outcome.

Locally in workplaces, there were numerous approaches used to reduce heat exposure. Apart from taking rests, traditional methods, which included mainly drinks and diet, dominated the coping mechanisms.

Air conditioning as a technical solution has experienced high growth in India as a means of protection from heat exposure. It is effective in reducing heat exposure but creates many sustainability challenges. In paper III, it was found that air conditioning use triggers an increase in energy consumption when the outdoor temperature increases, resulting in greenhouse gas emissions and therefore affecting climate change. In addition, the direct heat rejected from the air conditioning units adds to street level heat and thus, the urban heat island effect. If not abated, it has the potential to intensify climate change, and place extra loads on future energy supplies, especially during heat waves.

The issue of increasing heat and associated productivity loss could impact working people's health and livelihood. Further research needs to look at all aspects and impacts, taking an interdisciplinary perspective.

Svensk Sammanfattning

Vårt samhälle är beroende av ett stabilt klimat och förändringar av temperaturen påverkar direkt ekonomisk aktivitet. Att vår hälsa påverkas negativt och att vi har svårare att arbeta produktivt under värmestress är ingenting nytt utan det har studerats ingående. Dock i det samtida sammanhang som överskuggas av ökad värmestress på grund av klimatförändringarna, saknas mycket information på omfattningen av framtida värmeexponering och dess konsekvenser.

Syftet med forskningen var att genom litteratur och en fältstudie studera denna aspekt av klimatförändringarnas påverkan på arbetsmiljön. Den inledande litteraturundersökningen (artikel I) identifierade de faktorer som kan förvärra värmebelastningen i nuvarande och framtida arbetsplatser; den urbana värmeö effekten, fysiskt arbete, individuella förutsättningar och begränsningar i utvecklingsländer där tekniska lösningar ofta inte är tillämpbara. Det finns också en brist på information om effekterna på sårbara grupper som äldre, fattiga och gravida kvinnor.

Empirisk data samlades in från mätningar, observationer och frågeformulär för att uppskatta värmebelastning och tillhörande produktivitetsförluster på varma arbetsplatser i Chennai (Madras), Indien. Klimatmätningar kombinerades med uppskattning av arbetstyngd och mätningar av arbetsklädernas egenskaper. Hälsorisker, anpassningsstrategier och kopplingarna till klimatförändringarna var aspekter som också utforskades.

Samtliga studerade arbetsplatser, bestående av industri, service och jordbrukssektorn, hade mycket hög värmeexponering som ofta gick över de internationellt etablerade gränsvärdena för att kunna arbeta på ett säkert sätt (artikel II). Arbetsuppgifterna hade måttlig till hög arbetstyngd, där jordbruks- och byggnadsarbetare också arbetade i direkt solstrålning. De flesta arbetare rapporterade hälsoproblem på grund av hettan, inklusive trötthet, yrsel och huvudvärk. Problem att uppfylla produktionsmål i de varmare månaderna kompenserades ofta genom att arbeta övertid. Vid analys av produktivitetsminskning i en fysiologisk modell visade alla parametrarna betydlig värmebelastning. Tillgång till vatten var en kritisk faktor i resultatet. Det visade sig att kvinnor är mer sårbara på grund av att de har en skyddande skjorta ovanpå de traditionella kläderna de arbetar i, vilket ökar isoleringen och därmed värmebelastningen.

Lokalt på arbetsplatserna fanns det många tekniska, beteendemässiga och administrativa anpassningsstrategier för att minska värmeexponeringen. Bortsett från att ta raster vilket dominerade anpassningsmetoderna, tillkom många traditionella metoder, däribland främst drycker och kost.

Luftkonditionering av inomhusmiljön ökar snabbt i Indien för att skydda mot hetta och på grund av ökad konsumtionskraft av medelklassen. Det är en effektiv metod för att minska värmeexponering men skapar många problem som ökad elförbrukning. I artikel III, kom vi fram till att användningen av luftkonditionering utlöser en ökning av energiförbrukningen när utomhustemperaturen ökar, och därmed utsläppen av växthusgaser. Detta förvärrar klimatförändringarna och ökar risken för elavbrott under värmevågor. Dessutom pumpas värme direkt ut på gatunivå från luftkonditioneringssystemen och påverkar den urbana värmeön.

Sammanfattningsvis är en god arbetsmiljö en av de grundläggande rättigheter som arbetstagare ofta inte har tillgång till i Indien. Arbetsproduktiviteten kan komma att påverkas med ökande temperaturer och resultera i att Indiens ekonomiska produktivitet minskar. För att lösa denna problematik måste lösningar ta hänsyn till de sociala, ekonomiska, etiska, miljö- och tekniska aspekterna av problemet. Utbildning och medvetenhet är viktigt för att skapa engagemang på alla samhällsnivåer.

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My final thoughts are with the workers in Chennai, whom were all positive and curious, despite their hardship. I hope this project made some improvements in your situation.

Summaries of Appended Papers

Paper I: Lundgren, K., Kuklane, K., Gao, G., Holmér, I., Effects of Heat Stress on Working Populations when Facing Climate Change. *Industrial Health,* 2013. **51**: p. 3-15.

Aim: To provide an overview of existing research findings about the effects of heat stress on working populations in relation to climate change.

Method: Due to the extensive amount of information on heat stress, a strategic literature search was carried out to find key articles. A 'pearl picking' method was combined with strategic keyword searches in selected databases.

Main results: It was found that although heat stress has been researched extensively in the past, in the contemporary context of climate change, information is lacking on its extent and implications. The main factors found to exacerbate heat stress in current and future workplaces are the urban heat island effect, physical work, individual differences, and the developing country context where technological fixes are often not applicable. There is also a lack of information on the effects on vulnerable groups such as the poor, elderly people and pregnant women. As increasing temperatures reduce work productivity, world economic productivity could be reduced, affecting developing countries in the tropical climate zone disproportionately. Future research is needed taking an interdisciplinary approach, including social, economic, environmental and technical aspects.

Paper II: Lundgren, K., Kuklane, K., Chandran, M., Venugopal, V., The Present and Future Climate Change Productivity Decline Projections in Chennai, India Due to Heat Stress Using the Predicted Heat Strain (ISO 7933) Model. *Global Health Action* (submitted).

Aim: During the afternoon in the hottest month in South India, Wet-Bulb Globe Temperature (WBGT) levels are already high enough to cause major loss of hourly work capacity and this situation will become extreme for many jobs when facing future climate change. The aim was therefore to measure heat stress in hot workplaces and related productivity loss in Chennai (Madras), India by comparing the hotter and cooler months. Health risks, preventive methods and the links to climate change were also explored.

Method: Data was collected in the cooler and hotter seasons in the industrial, service and agricultural sectors to evaluate the current occupational heat situation. The study was conducted using the heat balance equation and the Wet Bulb Globe Temperature (WGBT ISO 7243:1989) index. Reduced labour productivity between the seasons and in a future impacted by climate change was assessed using the International Standard ISO 7933:2004, which employs a physiological model: the Predicted Heat Strain (PHS) model.

Main results: All workplaces surveyed had very high heat exposure, often reaching WBGT values above the 27°C threshold for working safely. Most workers had moderate to high workloads, some in direct sun exposure. When analyzing productivity loss in the PHS model all parameters showed productivity losses, with water provision and rehydration being critical aspects. In the canteen, the working conditions were already unhealthy in the cooler season and critical parameters, such as excessive water loss, were reached in only 3 hours in the climate change scenario. The predicted core temperature reached 40.2°C, which is significantly above the international 38°C guiding occupational limit value. It was also found that female workers were more vulnerable due to the traditional clothing worn, with extra insulation added from wearing a protective shirt on top of traditional wear and head cover at work. This was the first time this physiological model was used for this purpose. An exploratory approach was taken for further development of the model.

Paper III: Lundgren, K., Kjellstrom, T. Sustainability Challenges from Climate Change and Air Conditioning Use in Urban Areas. *Sustainability*, 2013. **5**: p. 3116-3128.

Aim: To explore the high growth of the use of air conditioning, especially in South and Southeast Asia to protect from high heat exposure and its implications, interactions and feedback from a sustainability perspective.

Method: A literature search using selected key words in a wide range of information sources was carried out. The literature laid the foundation for a sustainability analysis of causes and feedback and further research needs and methodologies.

Main results: Studies have linked increased total hourly electricity use to outdoor temperatures and humidity. They have also modelled future predictions when facing additional heat due to climate change, related air conditioning to increased street level heat, and estimated future air conditioning use in major urban areas. However, there is a lack of global and localized studies that link climate variables with air conditioning alone.

More research and detailed data are needed that examine the effects of increasing air conditioning use, electricity consumption, climate change and interactions on the urban heat island effect. Climate change mitigation is needed to make future urban areas more climate resilient. Examples of this include using renewable energy sources, particularly photovoltaic electricity generation, to power air conditioning and other sustainable methods to reduce heat exposure.

1. Introduction

Civilizations have been historically dependent on a stable climate. Changes in climate have destabilized civilizations, typically via food shortages, hunger, disease, and unrest (McMichael, 2011). In the modern world, temperature is still closely linked with per capita income as hot countries are usually poorer (Horowitz, 2009) and heat waves cause reductions in economic growth (Dell et al., 2014; Interfax, 2010). Currently, we live in an important decade when it comes to decision making about the kind of climate we leave for future generations.

Increasing global average temperature is the most predictable outcome of climate change. The Intergovernmental Panel on Climate Change (IPCC) in its latest report has deemed this to be ‘virtually certain’, representing a >99% scientific certainty. The report also states that hot days, hot nights and heat waves have become and will become more frequent over most land areas (IPCC, 2013). Since the preindustrial age, the global mean temperature has risen by almost a degree Celsius, due to greenhouse gas emissions. Not only the average temperature has risen, but also the number of warm days and nights has increased. The frequency of heat waves has amplified in some parts of the world, with recent examples from Europe, Russia, the United States and Australia (Coumou et al., 2013).

This thesis presents the link between climate change and health effects. Heat waves, in particular, have already affected some aspects of human health, such as excess heat-related mortality in Europe during the summer of 2003. During that heat wave, recorded temperatures did not go below 30°C for more than seven consecutive days in some regions in France during August (Poumadére et al., 2013). The heat wave was estimated to have caused up to 70 000 excess deaths in Europe (Costello et al., 2009). Responses to some recent extreme climate events reveal high levels of vulnerability in both developing and developed countries (WHO, 2013). There is also increasing evidence of greater vulnerability of specific groups, such as the poor and elderly people, in all countries (Ford & Berrang-Ford, 2011). These trends will continue (Rummukainen, 2012; 2013), with widespread and ever more negative effects on the health of populations, societies and ecosystems. It is expected that European summer temperatures as high as those experienced in 2003 will be the norm by the middle of the century.

High ambient temperature is a leading cause of weather-related mortality in many regions of the world (Ford & Berrang-Ford, 2011). In addition, the continuous rise of absolute humidity in the lower troposphere has also been reported in many regions due to evaporation from the oceans, which has strong implications for human thermal environments (Dunne et al., 2013). In particular, this adds substantial risk in already humid countries, where a small increase in temperature and humidity can have profound consequences on heat stress (Willett & Sherwood, 2012).

Arguably, climate change can no longer be considered simply an environmental issue as it puts at risk the protection of human health. Climate change will affect and is already affecting local living environments in multiple ways, either directly or indirectly, and impacts a wide range of sustainable development issues. Overall, negative health effects from climate change stem from heat stress, communicable diseases, air pollution, lack of food and water security, extreme weather events, malnutrition, stress, mental health issues, vulnerable shelter and population migration, among others (Nilsson & Kjellström, 2010).

The link between high heat exposure and negative effects on human health and performance has been well established through physiological, medical, public health and epidemiological research where it has been made clear that high exposure to heat may decrease life expectancy (Parsons, 2003). However, in the contemporary context of climate change, information is insufficient in terms of the extent of future heat stress and its consequences. To date, the social impact of climate change on occupational health and on many other social dimensions is not well understood. This thesis focuses on this aspect, through review of the literature and collection of empirical data from fieldwork, presented in the three appended papers.

People who carry out outdoor heavy physical labour are at particular risk because their work creates major intra-body heat together with exposure to high solar radiation (Kovats & Hajat, 2008). In its latest report on impacts, adaptation and vulnerability, the IPCC makes the following conclusion with high confidence:

> ‘There is a risk of mortality and morbidity during periods of extreme heat, particularly for vulnerable urban populations and those working outdoors in urban or rural areas (IPCC, 2014).

The main sectors that are directly affected by climate change include agriculture, industry, fisheries, forestry, small businesses and construction work. Tourism, health, and finance/insurance sectors can be affected indirectly from e.g. extreme events (Nilsson & Kjellström, 2010). Climate change will result in the increased prevalence, distribution, and severity of known occupational hazards such as heat stress and accidents even though there is no evidence of unique or previously unknown hazards.

However, such a possibility should not be excluded, since there is potential for interactions of known hazards with new conditions leading to new hazards and risks. Eventually, this could hamper economic and social development (Auliciens, 1992; Kjellström et al., 2009).

Human societies have a capacity to adapt technologically, socially and behaviourally and somewhat physiologically to environmental stresses including extreme heat (Berrang-Ford et al., 2011). For people living in hot environments, the employment of behavioural and cultural mechanisms such as less movement, clothing, seeking shade and building design is powerful in reducing exposure and has served as a buffer (Hanna, 1983). These adaptations are still of dominant importance in daily survival. A population has varying abilities to tolerate heat stress and it is increasingly recognized that social determinants and personal characteristics affect the vulnerability of people to heat exposure (Hollowell, 2010). In France, data from the 2003 heat wave on causes of deaths showed that psychiatric, cardiovascular and pulmonary illnesses were associated with a higher risk of death in heat waves, while good social contacts in the community, the use of fans, air conditioning and showers were associated with lower risk (WHO, 2013). The increasing use of air conditioners, though, may hinder natural acclimatization and potentially increase the risk due to negative side effects, such as increased electricity use (see paper III) (Ford & Berrang-Ford, 2011).

To sum up, coping with climate change (adaptation) is already unavoidable due to past emissions of greenhouse gases. Thus, it is important to come up with solutions to reduce vulnerability to the negative effects of climate change and to enhance the capacity at the individual and societal levels to adapt, respond to and prepare for climate change. As work ability is reduced with increasing heat, it can result in reduced economic productivity, affecting developing countries disproportionately as most of these are already located in warm climates (Dunne et al., 2013; DARA, 2013). This will become reality unless essential mitigation efforts are combined with adaptation to protect populations from increasing heat levels.

The research results presented in this thesis attempt to deal with aspects of this overwhelming global complex problem by looking at historical and current research on occupational heat stress, combining this with future implications of climate change, and identifying knowledge gaps (paper I). The thesis goes on to examine the implications for labour productivity and health at local level workplaces in a hot climate (paper II). Finally, it also looks at adaptation options for cooling (paper III).

1.1 Definitions

Heat stress: when human thermal environments in terms of air temperature, radiant temperature, humidity, air velocity, clothing and activity provide a tendency for body heat storage (Parsons, 2003).

Heat strain: the human thermoregulatory system’s response to heat stress causing strain on the body, with risks of developing heat illness (Parsons, 2003).

Productivity: output per unit of labour input (persons engaged or hours worked) (ILO, 2013).

Health: health is a state of complete physical, mental and social well-being and not merely the absence of disease or infirmity (WHO, 1948).

Adaptation: the process of adjustment to actual or expected climate and its effects. In human systems, adaptation seeks to moderate or avoid harm or exploit beneficial opportunities (IPCC, 2014).

Maladaptation: an adaptation process that results in increased vulnerability to climate change and/or undermines the capacity for future adaptation (Peou, 2013).

Resilience: the capacity of social systems to cope with a hazardous event or trend or disturbance, responding or reorganizing in ways that maintain their essential function, identity, and structure, while also maintaining the capacity for adaptation, learning, and transformation (IPCC, 2014).

Vulnerability: encompasses a variety of concepts and elements including sensitivity or susceptibility to harm and lack of capacity to cope and adapt (IPCC, 2014).

Heat wave: extended periods of unusually high atmospheric temperature that cause temporary modification in lifestyle and which may have adverse health consequences for a population (White-Newsome et al., 2012).

2. Aims and Theory

The main driver for the research is that the relationship between global climate change and occupational safety and health has not been comprehensively characterized. A deductive approach is taken with the hypothesis: **Occupational heat stress has negative effects on workers and affects health, productivity and daily lives. Climate change will worsen the situation.**

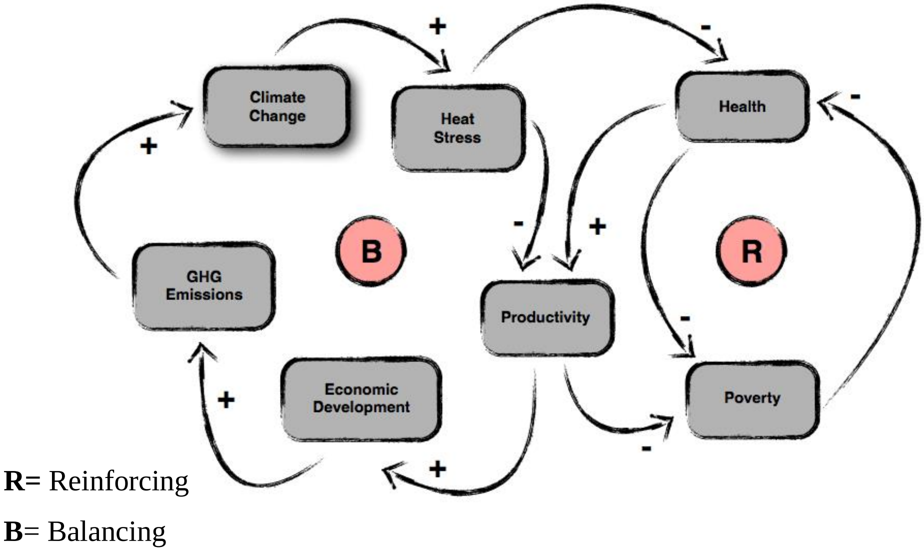
Aims:

- To identify the current knowledge of occupational heat stress, productivity and the linkages with a changing climate by conducting a literature review (paper I).
- To validate low cost heat stress measurement equipment against standard equipment as a pre-study for appropriateness in the field.
- To carry out a field study in already hot local workplaces in Chennai, India, to assess productivity loss between the seasons, including the impacts of increasing heat due to climate change (paper II).
- To examine vulnerability, cooling options and maladaptations, including conventional air conditioning as a technical solution to protect from heat exposure (paper III).

2.1 Problem Framing

Figure 1 illustrates a causal loop diagram (CLD) that was generated to provide a simplified conceptual framework and an overview of the research problem. A CLD is used to understand the complex web of influences that often result in various forms of feedback loops. Such loops add a time dimension to system complexity and often magnify or dampen the intended effect of an action. It is important to understand the causes and effects of a problem, and how different aspects of society and the natural environment interrelate through feedback loops. The concept of feedback shows how factors can reinforce (R) or balance (B) each other. With a CLD it is possible to construct the circular connections and feedback of a problem.

The system boundary in this case is hard to define as climate change is an overarching global phenomenon. The focus, though, is on occupational health.



R= Reinforcing

B= Balancing

Figure 1: Causal-loop diagram of the interactions of climate change, heat, health and productivity.

As can be seen in Figure 1, heat stress reduces productivity and exacerbates poverty and poor health. A reduction in productivity will also reduce economic development with negative impacts, such as lower wealth creation. However, as economic development is currently directly linked to growth in greenhouse gas (GHG) emissions (Ford & Berrang-Ford, 2011), reduced productivity will mitigate climate change. This balancing loop is referred to as the B in the CLD. Additional factors such as a future increase in the use of air conditioning and other technological fixes will have some positive effects in reducing heat exposure but will increase greenhouse gas (GHG) emissions (see paper III). Moreover, poverty and health are linked in a reinforcing relationship (R) due to poor people often being exposed to environments that make them sick, lack decent shelter, clean water or adequate sanitation (WHO, 2014).

2.2 Climate Change Adaptation Research and Interdisciplinarity

The scientific theory of climate change is accepted and it is clear that human intervention is the major cause (IPCC, 2013; Rummukainen 2012; 2013). Even if radical mitigation efforts are made, an additional warming is indisputable. However, scientific uncertainty and the complexity of the problem present challenges for researchers. The present climate change projections exhibit large uncertainties arising from among others, assumptions of emissions of greenhouse gases, incomplete climate models, and human development pathways and downscaling. Most uncertainties about impacts are epistemic, but uncertainties on adaptation measures are complex, with ambiguity often being added. Gaining more knowledge can reduce epistemic uncertainties and dialogue and knowledge sharing can reduce uncertainties related to ambiguity, whilst some uncertainties are non-reducible (Refsgaard et al., 2012).

Occupational health and climate change in relation to heat stress exposure is a research area in the field of climate change adaptation. Adaptation research is a interdisciplinary field of research and is still characterized by an evolving epistemological base. It is widely recognized that there are crucial barriers to adaptation, but a comprehensive set of theories to explain these is still undeveloped. Adaptation to climate change can be aimed at changing contextual conditions or at reducing damage (Eisenack & Stecker, 2011). The research presented in this thesis is primarily aimed at the latter by integrating social and biophysical vulnerability. The primary motivation for the research is to be more prescriptive than analytical, taking an action-oriented perspective. The research also focuses on direct adaptation where the purpose of action is to improve the situation rather than to enable indirect systematic change. The research also constitutes planned adaptation which makes use of information about expected future conditions; promoting anticipatory rather than reactive adaptation. Finally, the research is exploratory and emphasizes the identification of barriers and solutions.

Climate change adaptation presents a unique set of problems that do not originate from within science. The problems of society are becoming increasingly complex and interdependent. Environmental problems – the interaction between human and natural systems – exemplify complexity as they comprise several sub-problems that fall into the domains of different disciplines and sectors. Environmental problems entail non-linear dynamics, uncertainties, and high political stakes in decision making.

Interdisciplinarity breaks free from reductionist and mechanistic assumptions about the ways things are related and the ways systems operate; it challenges normative social values made uninformed by stakeholder and community input; and the expectation that science can deliver final estimates with certainty. In addition, rational knowledge comes out of not only ‘what we know’ but ‘how we communicate’ and this underscores the emergent quality of interdisciplinarity. However, interdisciplinarity does present an epistemological challenge and requires certain skills (Thompson, 2004). This research by its nature requires interdisciplinarity, involving various disciplines and associated methods including occupational health, thermal physiology, human development and climate science.

3. Background

3.1 Thermo Physiology

The physiological basis for the effects of heat on humans is well understood (Burton, 1933; Weiner & Van Heyningen, 1952; Ladell, 1955; Hellon et al., 1956, Bell & Watts, 1971; Budd, 1974; Fernandez, 1980; Ramsey et al., 1983; Hales & Richard, 1987). Extensive research has been carried out especially in military settings (Schrier et al., 1970; USDAAF, 2003; Parsons, 2003). Human heat tolerance is the result of a series of physiological adaptations that have been genetically encoded. Humans are born with a highly specialized complex of thermoregulatory sweat glands and a sensitive control system. On the other hand, factors such as pre-existing disease, clothing, age, gender, heat acclimatization ability, level of physical activity, and body size, can influence this system and cause health impacts (Hanna, 1983). When the ambient temperature reaches or exceeds the human core temperature of 37°C, there are well-documented physiological effects on the human body, posing risks to some organ systems and also making it progressively harder to work productively (Bennett & McMichael, 2010). As the core temperature begins to rise above its ‘set-point’ of 37°C, skin blood flow increases and sweating is initiated. At core temperatures beyond 38-39°C, there is an increased risk of heat exhaustion and beyond these temperatures, heat stroke can occur with a consequent failure of the thermoregulatory system (Jay & Kenny, 2010). Health consequences range from dehydration, injuries, and heat fatigue to a higher burden of respiratory and cardiovascular diseases, kidney failure, weakening of the immune system and finally, death (Parsons, 2003).

The body heat balance is determined by these six fundamental factors:

Climate Parameters:

1. Air temperature
2. Radiant temperature
3. Humidity
4. Air movement

Non-climatic parameters:

5. Clothing
6. The metabolic heat generated by human physical activity (Parsons, 2003)

The heat balance equation by which the balance between heat production and heat exchange of the human body with the environment can be calculated is (can be modified to account for clothing):

$S= (M- W) - (H_{res} + E + R + C + K)$ (Parsons, 2003)

S = body heat storage
M = metabolic heat production
W = external mechanical work
H_{res} = respiratory heat exchange
E = evaporative heat exchange
R = radiative heat exchange
C = convective heat exchange
K = conductive heat exchange

Heat is transferred between the body and the macro environment by means of radiation, conduction, convection, and evaporation at the skin surface and the lungs (Parsons, 2003). Humans can maintain normal body (core and skin) temperatures within a wide range of environmental conditions, assuming heat transfer is not impaired. Heat dissipation occurs through dry heat loss (radiation and convection) and evaporative heat loss (sweating) (O'Brien et al., 2011). Acclimatization and hydration status, body posture, clothing permeability and other factors also affect this balance (Kampmann et al., 2011).

Acclimatization results in an increased sweat rate, leading to a lower core temperature and heart rate at the same work level and environmental heat load (ILO, 1998). Clothing affects the transfer of heat from and to the body through resistance to air movement, dry heat exchange and sweat evaporation (Bernard et al., 1994). The largest source of heat results from metabolic heat production, which adds to the heat stress in hot environments. The evaporation of sweat is extremely effective and therefore becomes more and more critical with increasing environmental temperature. Given the importance of sweat evaporation, it is not surprising that air velocity and humidity are critical environmental factors in hot conditions. If the humidity is high, sweat is still produced but evaporation is reduced which further reduces the cooling effect. Sweat drips off without providing an additional cooling effect and this can further result in dehydration (ILO, 1998).

The thermoregulatory response can be powerful and effective but it can also result in a strain on the body, which can lead to heat illness (Parsons, 2003). Heat disorder occurs for one or more of the following reasons: dehydration, lack of acclimatization, lack of proper appreciation of the dangers of heat, and accidental and unforeseeable circumstances leading to exposure.

Many deaths are attributed to neglect and lack of consideration (Parsons, 2003). Heatstroke has a high fatality rate and even nonfatal heatstroke can result in long-term effects. Sweating imposes the greatest strain on the body. Severe dehydration may lead to heat exhaustion and circulatory collapse (ILO, 1998). Together with water loss, sweating produces a loss of electrolytes. If electrolytes are not replaced, cramps may develop due to the malfunction of nerves and muscles. Dehydration of over 3% of body weight should always be treated with replacement (ILO, 1998).

3.2 Literature Review Summary

The extensive amount of information on heat stress made it necessary to develop a strategic information search to find key articles. Climate change and occupational health is a interdisciplinary field of study and requires information from a variety of sources. That is why the ‘pearl picking’ method was initially applied followed by strategic searches in selected databases and search engines.

It was found that workers in the outdoor occupations with high physical workload are most at risk for severe heat exposure. Also at high risk are workers that wear semipermeable or impermeable protective clothing and/or personal protective equipment (PPE) that severely impedes heat exchange through evaporation (Bernard et al., 1994; Bernard, 1999). There are also possible heat implications for indoor workers in buildings without air conditioning or proper ventilation systems. Most of the heatstroke deaths reported have been associated with occupational exposure at construction sites, agricultural settings, and hot industrial jobs requiring heavy work (Holmér, 2009). The total physiological burden and the potential susceptibility to heat disorders will be much higher if heat stress continues during off-duty hours through work at second jobs, long commutes, strenuous leisure activities, or living in hot dwellings. In addition, nutritional status and hydration is critical (ILO, 1998). Fluid requirements generally depend on work rate, the ambient climatic conditions, and on individual physiological and biochemical characteristics. The implementation of strategies to maintain adequate hydration and work-rest schedules are the most important interventions in the management of work in heat (Parsons, 2003).

Yet, it has been found that even if water is readily available, men working in the heat will drink less than they lose through perspiration, referred to by researchers as ‘voluntary dehydration’ (Parsons, 2003; Hanna, 1983). Therefore, workers in hot environments must also be educated regarding the importance of drinking enough water while working and continuing generous rehydration during off-duty hours (ILO, 1998; Miller & Bates, 2010).

The Urban Heat Island Effect

In 2007, the world’s population living in towns and cities surpassed 50% for the first time in history and this share is continuously growing; by 2050 it could be as high as two thirds (WHO, 2013). Built-up areas influence the absorption and reflection of solar radiation, the ability to store heat, the absorption and remittance of long wave radiation and so on. The built environment is also characterized by human activities affecting the climate, such as the heating and cooling of buildings, motor traffic and industrial production. These activities release heat and moisture but also pollute the air, which affects incoming and outgoing radiation. A limited number of trees and vegetation in urban areas also decreases the capacity to cool the air (Ford & Berrang-Ford, 2011). The urban heat island effect is thus the heat absorption in cities and refers to the difference in nocturnal temperatures measured inside and outside the city. These elevated temperatures, especially during the night, can increase the magnitude and duration of heat waves (Kovats & Akhtar, 2008) and cause significant additional heat exposure of urban workers. This is discussed further in papers I and III.

Individual Aspects

Individual factors such as physical fitness and health status play a fundamental role in heat tolerance (Parsons, 2003). When working in heat, people with the highest risk are those with small body size, overweight, children, elderly and people with medical conditions such as cardiovascular diseases, diabetes, skin, liver, kidney and lung problems, and pregnancy. Additional factors affecting heat tolerance include intake of alcohol, caffeine and nicotine (Gavhed & Holmér, 2006). Individual differences include the effects of age, gender, body morphology, disability, aerobic capacity, acclimatization, state of health, clothing and personal protective equipment (Brake & Bates, 2002). How ethnic origin and cultural differences, including human behaviour, influence heat tolerance, is not fully understood (Parsons, 2003).

Productivity Loss and Economic Impact

Productivity is strongly dependent on thermal conditions, in particular during physically demanding work (Lloyd, 1994). Cognitive and physical performance declines can occur at hyperthermic and/or dehydration levels lower than those causing heat injuries (O'Brien et al., 2011). Studies of the influence of high ambient temperature on performance have examined variables such as reaction time, tracking and vigilance, as well as memory and mathematical calculations (Bell et al., 2005).

When the body is hot, vasodilation (a widening of blood vessels) enhances ease of body movement although sweating may affect grip, cause distraction due to discomfort, fatigue and psychological strain. Thermal conditions can affect output, accident rates and behavioural and cognitive performance (Parsons, 2003). The results of many studies indicate that changes in temperature of a few degrees can significantly influence performance in several tasks including typewriting, factory work, signal recognition, time to respond to signals, learning performance, reading speed and comprehension, multiplication speed, and word memory (Fisk, 2000; Wyon, 2004; Balakrishnan et al., 2010). It is also estimated that productivity is affected after about one hour of moderate physical work in temperatures above 32°C (Bell et al., 2005).

A natural reaction of a working person to heat is to reduce physical activity, which reduces the body’s internal heat production. An outcome of this preventative reaction is reduced hourly work capacity during the exposure to heat. As a result, the worker’s action to prevent ill health will lower productivity and a loss of daylight work hours will occur. An enterprise can compensate for this by carrying out heat sensitive work during the cooler night hours or by scheduling such work in the cooler season, but as climate change progresses the duration of cooler periods will be shortened. In any case, some work has to be carried out during daylight hours (Kjellström et al., 2011).

Kjellström (2009) found that by the 2080s, the greatest absolute losses of population based labour work capacity (in the range 11% to 27%) will be seen in Southeast Asia, Andean and Central America, and the Caribbean (Kjellström, 2009) according to the IPCC A2 climate change scenario (IPCC, 2007). Dunne et al., (2013) estimated that environmental heat stress has already reduced the global labour capacity significantly in peak months with a further predicted reduction of 80% by 2050 (Dunne et al., 2013). Without adaptation, the economic losses of reduced labour productivity relative to baseline could be significant (Kjellström, 2009) and become the most costly impact of climate change (DARA, 2013).

The Developing Country Context

The IPCC forecasts substantial increases of future annual average temperatures in areas populated by billions of people (IPCC, 2013). It is estimated that workers in the low- and middle-income tropical countries are likely to be at the highest risk of excessive heat exposure because these areas are densely populated and are expected to get the highest temperature increases. In many of these countries the maximum temperatures during the hottest part of the year are already close to 40°C and an additional 3-5°C will make outdoor physical work (e.g. in agriculture and construction) very difficult during the hottest periods (Kjellstrom et al., 2009).

Conditions are in some countries worsened by intense solar radiation and high humidity (Costello & Abbas, 2009). Most tropical countries are developing countries and most are experiencing rapid urbanization. The impacts of climate change on vulnerable employment, working poverty (income below the poverty line), youth and women, wage losses and working conditions may be exacerbated. This hits the most vulnerable even harder because of their exposure and least adaptive capacity (Kjellstrom et al., 2009). Despite this, few comprehensive assessments of the effects of climate change on health have been completed in low-income countries (Costello & Abbas, 2009).

In general, developing countries also have higher occupational injury fatality rates compared to developed countries. Many workers lack work security and are paid according to output; as a result, workers have to work longer hours to reach production targets. When working in the heat, which limits the ability to produce, stress and serious mental and physical health problems may be a negative outcome. In addition, outside of paid work, many workers also engage in water and firewood collection, residence building and repair, small-scale agriculture, fishing, cooking and so on. These tasks can sometimes be more hazardous than formal employment, and add to the heat strain and exhaustion (Högstedt & Kjellström, 2009). Moreover, commuting to and from work is a daily source of heat exposure for many people. In developing countries people may be more or less acclimatized to heat although health and nutritional status, access to drinking water and widespread precarious work are decisive factors (Holmér, 2009).

3.3 Heat Stress Indices

A heat stress index is a single number that integrates the effects of the basic parameters in any human thermal environment such that its value will vary with the thermal strain. Heat indices can be used in working practices or be designed to establish safe limits for work (Parsons, 2003).

Heat stress indices are categorized as rational, empirical or direct. Rational indices are centred on calculations involving the heat balance equation; empirical indices are based on establishing equations from the physiological responses of human subjects (e.g. sweat loss), and direct indices are founded on the measurements of instruments used to simulate the response of the human body (ILO, 1998).

Although progress has been made scientifically in understanding human thermophysiological responses to various hot environments, it is still a great challenge to predict heat strain accurately. Heat stress evaluation requires knowledge of the role clothing plays as well as the environment and work demands.

Despite the fact that more than 60 heat stress indices have been developed over the last century, no index has achieved widespread acceptance in the field (Wang et al., 2011). Prescribing suitable heat stress limits and guidelines continues to be highly problematic for most authorities, and most industrial indices currently in use were developed in the more temperate (Western) nations of the Northern hemisphere where occupational work generally takes place in cooler conditions (Brake & Bates, 2011). In addition, indices are difficult to apply or are poorly applicable in many situations (Miller & Bates, 2007). Overall, there is a need to develop an international agreement on the best heat stress index to use in analyzes of climate change impacts on the health of working people in order to be able to compare results worldwide (Dash & Kjellström, 2011).

The Wet Bulb Globe Temperature (WBGT) is a direct index that is widely used in the assessment of occupational heat stress (Bernard, 2005) and was therefore chosen as the heat stress index to be used in this study. The WBGT (ISO 7243:1989) is an index of heat stress that incorporates environmental temperature, humidity and solar radiation (Kleim et al., 2002). The US military carried out extensive research in the 1950s and 1960s into the physiological ability of soldiers to tolerate high temperatures, which led to the adoption of the WBGT as a measure of health and work capacity (Hyatt et al., 2010).

The international standard for the WBGT uses a formula based on measurements of three temperature variables: T_a, the air temperature measured with a shielded thermometer; T_g, the globe temperature which is the temperature inside a black globe representing the heat radiation input; and T_{nw}, the natural wet bulb temperature, which is measured with a wet cloth over the sensor representing the impact of sweat evaporation on heat loss (ISO, 1989).

WBGT equations:

Indoors: $\text{WBGT} = 0.7\ T_{nw} + 0.3\ T_g$

Outdoors with solar radiation: $\text{WBGT} = 0.7\ T_{nw} + 0.2\ T_g + 0.1\ T_a$

(ISO, 1989)

A WBGT at 27°C can be seen as a threshold for the need for actions to protect workers, depending on the intensity of the work (ISO, 1989). However, there are some limitations in using the WBGT system. For example, it only directly evaluates the environmental parameters and incorporates personal factors such as clothing insulation, acclimatization and metabolic heat production by estimations from tables (Jay & Kenny, 2010).

Current heat stress standards are generally conservative and problems become evident when they are introduced into a workplace where workers are mobile and work at varying tasks and metabolic rates during their work shift.

Consequently, there is currently an effort to develop an improved individualized heat stress risk assessment tool to improve heat stress risk prediction. The International Standard, ISO 7933:2004 (ISO, 2004a), employs the Predicted Heat Strain (PHS) model, which is one of the more sophisticated heat strain models. It was built on the required sweat rate index that was previously used. The PHS rationally accounts for the individual factors known to influence heat stress response (Jay & Kenny, 2010) and is based on an analysis of body heat balance and sweat rate for the maintenance of a stable core temperature (Malchaire et al., 2000; Malchaire et al., 2001). On this basis, both ISO 7243:1989 and 7933:2004 were used in the heat stress and strain analysis of this research.

3.4 Equipment Pre-Studies Summaries

The WBGT index is a method for estimating the heat stress on the human body for both indoor and outdoor environments. It is widely used, but the standard instruments are expensive and inexpensive alternatives do not always correspond to the standard. Development and validation of low cost alternatives with acceptable accuracy are needed, especially for use in the field. Different WBGT equipment was compared in four pre-studies with differing climate conditions. Air, natural wet bulb and globe temperatures were measured from the different instruments for the calculation of WBGT in outdoor and indoor conditions, including comparisons of globe sizes and thickness of wick on the wet bulb sensor. This section presents summaries of the studies conducted. The first two studies were conducted by Mr. Salman Butt, a public health master's student before his field work in Pakistan together with Dr. Kalev Kuklane and Dr. Chuansi Gao from the Department of Design Sciences. Based on the findings from these studies, I (the author) carried out the last two in preparation for my field work in India.

Study 1: Comparison of Equipment for WBGT Measurements

The aim of the study was to compare different measuring equipment to a standard WBGT instrument, Bruel & Kjaer (type 1219), and to recommend equipment for field measurements. Other objectives were to compare direct measurements vs. calculations; shielded vs. unshielded sensors and globe diameters. A difference of ±1°C WBGT was considered acceptable based on the ISO 7243 standard.

Method and Procedure

Eleven different instruments and/or instrument combinations were placed in the outdoor condition and ten sets were used for the indoor condition. The sensors for measuring the air, natural wet bulb and globe temperatures were arranged according to ISO 7243. The instruments were categorized into three groups: standard, traditional and alternative equipment. Requirements for the alternative instruments included factors such as being relatively new and handy instruments on the market and that were independently able to log data over an extended period of time. All globes were placed at about the same height. They could be of different sizes (e.g. 3.5 cm for the heat stress meter as manufactured and 9.5 cm for the modified Testo 177-T4) in order to compare the effect of size of globes on measuring the globe temperature. All other instruments were equipped with the standard globe size of 15 cm. The WBGT index was recorded directly from some of the instruments and indirectly by measuring the variables required for calculating the index.

Instruments were compared for two indoor conditions at 30°C with RH = 45 and 75%, and one outdoor ambient temperature of around 25.1 ± 1.5°C with RH = 38.2 ± 2%. Measurements were carried out under a cloudless, clear sky between 12 and 14 hours in June. Air velocity was 0.91 ± 0.46 m/s for the outdoor condition. Indoor air velocity was kept constant at 0.45 ± 0.08 m/s.

Standard instrument

The Bruel and Kjaer WBGT instrument, type 1219 (B&K) with a 15 cm globe, was considered as standard equipment. The B&K is equipped with ambient air (T_a), a globe (T_g), and a natural wet bulb (T_{nw}) temperature sensor with a built in algorithm to calculate WBGT.

Traditional instrument

A combination of a mercury thermometer with a 15 cm globe and psychrometer with an unshielded natural wet bulb sensor, and a shielded dry bulb temperature sensor was used to measure T_a, T_g and T_{nw}. Momentary data for these variables was visually recorded every 10 minutes.

Alternative equipment

Testo 177-T4

Testo loggers (accuracy ± 0.3°C, set to sampling time 10 seconds) with T-type thermocouples (average tip diameter 0.3 mm) were used. Two thermocouple sensors were connected to globes of 15 and 9.5 cm respectively to compare globe sizes (T_g). One thermocouple sensor was a modified natural wet bulb sensor to measure T_{nw}. The final thermocouple sensor was hanging in the shade with an aluminium cover to protect it from direct solar radiation to measure T_a.

Heat Stress Meter

Extech Heat Stress Meter is a self-display instrument with a slightly elliptic globe with a diameter of 3.5 cm. It displays the momentary values for T_a, T_g, and relative humidity (RH). It has two modes to measure WBGT for indoor and outdoor environments which were selected for the respective conditions.

Lascar USB easy data logger

Lascar EL USB 2 LCD$^+$ humidity, temperature and dew point data loggers were used to collect the data for air temperature and relative humidity (accuracy of T_a; ± 0.3°C and RH; ± 2%). For outdoor experiments, a second data logger was put inside a 15 cm globe to measure globe temperature.

MSR

The Data logger MSR 145W (MSR Electronics GmbH, Switzerland) includes a temperature sensor, relative humidity sensor with integrated temperature sensor, a pressure sensor with integrated temperature sensor and a 3 axis accelerometer sensor. The MSR has a working range for temperatures from -10°C to + 58°C or -55°C to +125°C with an external sensor (having the accuracy of ±0.1°C or ± 0.5°C depending on temperature range respectively) which was used in this study. The *RH* with integrated temperature sensor has the capacity to measure relative humidity from 0 to 100% with -20°C to + 65°C of air temperature. The MSR was used to measure T_a and *RH* for indoor conditions and the instrument was modified to measure WBGT for the outdoor condition. In the modified instrument the logger body with pressure and integrated temperature sensor was used in a 15 cm globe. The *RH* and temperature sensor was shielded and used for T_a recording. The thermal couple temperature sensor was built in a 6 mm diameter and 30 mm long copper rod covered with a cotton wick and used as a T_{nw} sensor.

Casella

Casella with the model number HSM 100 has the sensor for natural wet bulb temperature (T_{nw}), a sensor in a 15 cm globe (T_g), and a shielded air temperature sensor (T_a). Casella was used only for the outdoor condition. Indoors, especially with high humidity, the instrument experienced technical error and did not allow further investigation with it.

Conclusions

Data collected from the outdoor measurements showed large variation in the readings from the different instruments (differing more than the 1°C WBGT). The heterogeneity between the calculated values and the WBGT Index show that even though these instruments claim to work on the same ISO 7243 standard, they differ in their calculated values. The results from measurements indoors were, however, homogenous. The heat stress meter showed similar WBGT values as the B&K, while the individual parameters could differ to a large extent, especially under solar radiation outdoors. As a drawback, the MSR has no display. Lascar USB data loggers cannot measure T_{nw} and require calculations to estimate T_{nw} from other climatic parameters or equations. Additional instruments are required in this case, for example, a psychrometer. Also, proper shielding, such as by a gill screen, is very important due to the relatively big sensor housing that is not properly shielded from radiation.

Study 2: Comparison at Various Air Velocities and Radiation

Considerable differences were seen in the previous study between instruments in the outdoor uncontrolled condition. It was therefore hypothesized that these differences were impacted by the air velocity and solar radiation. This study aimed to investigate the influence of wind and radiation under controlled conditions and to compare a modified data logger (Testo 177-T4) with a standard WBGT instrument (Bruel & Kjaer).

Methods and Procedure

A wind tunnel was set up at room temperature with a fan sucking air and an IR radiator installed in the pressure chamber past the instruments on the fan side to avoid any heated air moving towards the instruments. This left radiation as the only heat source. The second setup had a chamber fan under a solar lamp because the lamp could not be installed in the wind tunnel. The following conditions were tested.

Radiation sources:

- IR radiator in wind tunnel
- Solar lamp in warm chamber

Air temperature and humidity:

- 21, *RH* 52% and 41°C, *RH* 24% with IR radiator in wind tunnel
- 21 and 41°C, both *RH* 44% with solar lamp in warm chamber

Air velocities:

- 0.2, 0.5, 1, 2 and 4 m/s in wind tunnel
- 0.2 and 0.8 m/s in warm chamber

Position of the globe from the radiation source:

- Centre at the same distance (IR and solar)
- Front edge at the same distance (IR)

When the temperature values were stable for at least 30 min, the condition was changed and values noted.

Conclusions

When correcting the T_g values of a different globe size, the results are close to the standard globe. The position of the globe has an influence, as a globe adjusted to the surface distance from the radiation source gave results that were closer to the standard globe than the centre-point adjusted globe.

The ambient sensor of the Testo T_{nw} showed consistently higher values than the B&K. As the T_{nw} is the dominant parameter in the WBGT calculated index with 70% influence, it therefore needs to be studied further. When there was no radiation, all sensors showed very close values, and overall, the Testo could be used without radiation.

Study 3: The Wet-Bulb Sensor Test

From study 2 it was hypothesized that the T_{nw}, being the dominant parameter in the WBGT calculated index, is affected by the combination of radiation and wind. Possible reasons for this can be different sock material, thickness and tightness on the sensor and/or the test equipment and/or the cabling itself that is affected by the radiation. This study focused on the thickness of the wick and its effect on the readings in a controlled environment.

Methods and Procedure

According to the ISO 7243 standard, the natural wet bulb temperature sensor should be covered with a wetted wick that is ventilated naturally. The sensor should be cylindrical with an external diameter of the sensitive part of 6 mm. The length specified in ISO 7243 is 30 mm with a measuring range of 5°C to 40°C having an accuracy of ± 0.5°C.

The thickness of the wick is not specified in the standard (ISO, 1989). This study focused on the thickness of the wick on two of the instruments, the B&K and the Testo in indoor conditions, under direct solar radiation by a radiation lamp, 2.5 m from the surface of the globe. The B&K instrument had a standard globe size of 15 cm and the Testo had a 9.5 cm corrected globe. T_a, T_g and T_{nw} were measured and compared; however, the T_{nw} was of main interest. Air velocity was not measured but had minimal influence in the indoor condition.

Results

Large differences can be seen on both instruments when the thickness of the wick is changed as shown in Figures 2 and 3.

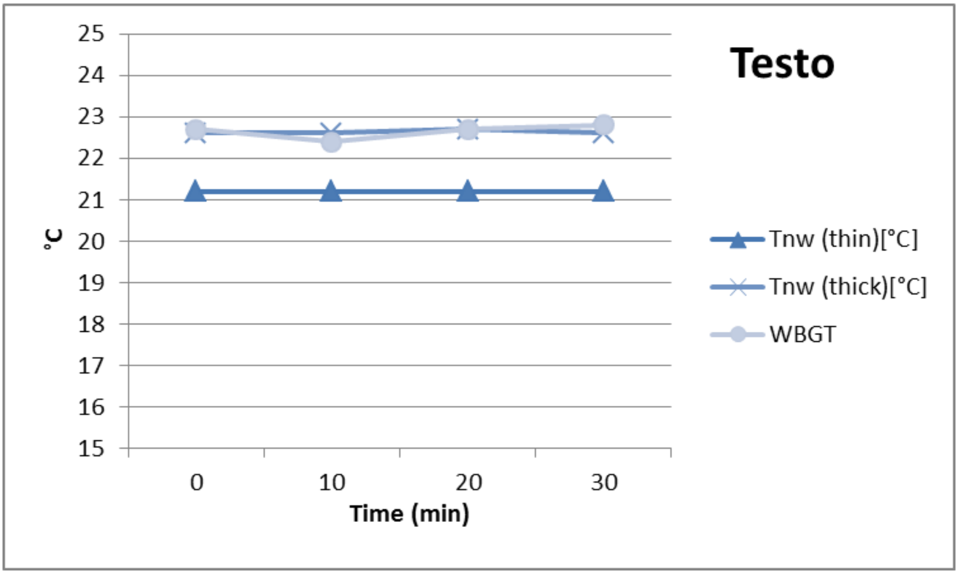


Figure 2. Comparison of wet-bulb sensor's wet wick thickness using the Testo equipment.

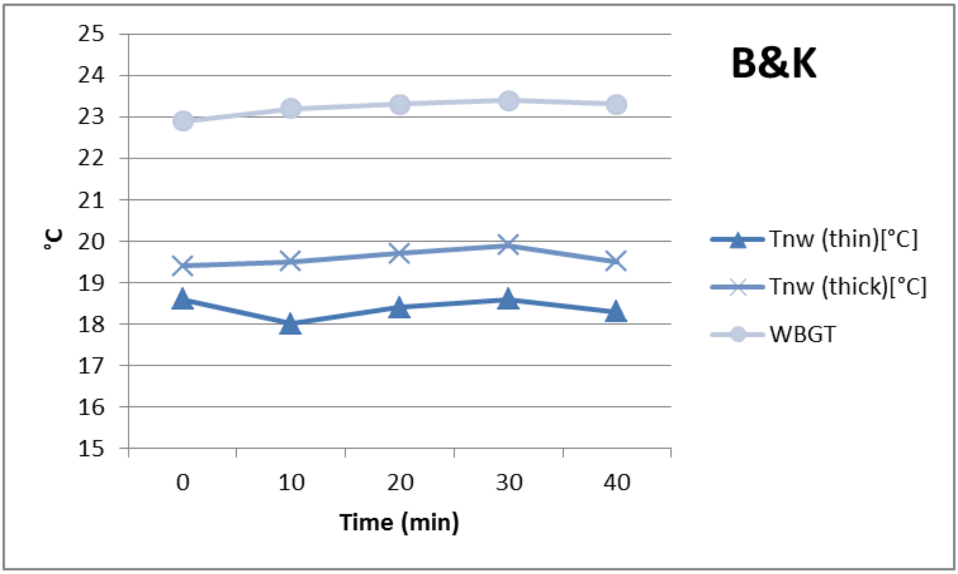


Figure 3. Comparison of wet-bulb sensor's wet wick thickness using the B&K equipment

Conclusions

For both the Testo and B&K equipment, the thick wick generated a higher temperature value: the Testo equipment showed an average 1.4°C difference, and the B&K had a slightly lower difference with 1.2°C. These results present a difference that is too large (higher than the recommended 0.5°C WBGT for the individual sensor) which means that the thickness of the wick does make a significant difference and has to be standardized for reference equipment.

Study 4: Comparison in Chennai, India – Hot and Humid Climate

Two non-standard WBGT instruments were compared to reference equipment in an outdoor hot and humid climate in India during 6 hours (10.40 am to 5.19 pm). The standard equation for outdoor conditions with solar radiation was used. A difference of ±1°C WBGT was considered as acceptable in accordance with the standard.

Methods and Procedure

Three types of equipment were used in this study, see Figure 4: 1) A reliable WBGT instrument as a reference equipment (3M™ QUESTemp°™ 32); 2) a modified Testo (177-T4) data logger unit; 3) and two Lascar EL USB 2 LCD+ humidity, temperature and dew point data logger units (one for T_a and RH, and one modified in a black globe for T_g measurement). All had 50 mm diameter corrected black globes and a probe to measure T_g. T_a sensors were placed in the shade. Two units, the QUESTemp and Testo, measured the T_{nw} while the Lascar logger measured the relative humidity and dew point via a capacitor unit in the logger. The dew point was later calculated to the WBGT index using the Liljegren (2008) formula (Lemke & Kjellstrom, 2012) via the psychrometric wet bulb temperature (T_{pwb}) which is linked to the dew point (T_d) by the formula:

$T_d = 243.5 \ln(\rho/6.112)/(17.67 - \ln(\rho/6.112))$ (p= water vapour pressure)

Figure 4. Equipment set-up for comparison

Results

The close proximity of measured and calculated WBGT of the different instruments can be seen in Figure 5.

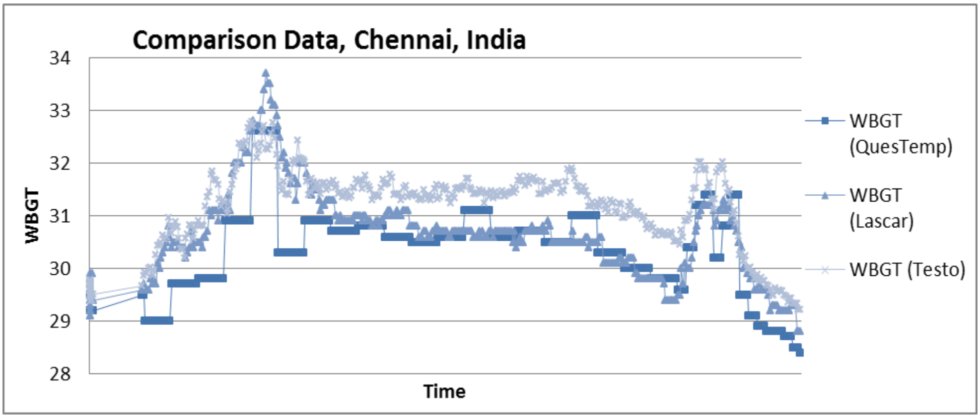


Figure 5. Results from 6 hours of measuring and recording WBGT values from QuesTemp, Lascar and Testo.

Conclusions

During the day, the WBGT fluctuated between 29-34°C. The equipment logged automatically (every 10 seconds) apart from QUESTemp that was manually recorded every 5 min from the equipment. Lascar recorded the highest readings, whilst QUESTemp the lowest, but all instruments never differed more than up to 1°C WBGT throughout the day. Therefore, all instruments give accurate readings. However, due to QUESTemp being considered reference equipment and not standard instrument, exact conclusions cannot be made. Air velocity was not measured but weather data for the day were received from a local weather station (available upon request).

Summary Conclusions

It was found that the Lascar and the MSR data loggers, the Heat Stress Meter and mercury psychrometer instruments can be used to measure the WBGT Index as they showed a variation of less than ±1°C when compared to the standard WBGT calculated value from the standard instrument (B&K) and reference instrument (QUESTemp). However, the modified Testo equipment consistently differed in measurements for the wet bulb sensor in comparison to the standard instrument and therefore need to be checked against standard equipment before use.

The same would apply to all non-standard equipment before field use, especially for outdoor measurements. All instruments gave a reasonable reading in stable, well-defined indoor conditions without a radiation source at relatively low air velocity. When measuring in the field, the selection of globe size and thickness of the wick on the wet bulb sensor has to be evaluated and analyzed in a set-up. The size of the sensor and placement of sensors can also present a small variation, especially in outdoor conditions. Overall, the results of the experiments can only determine a pattern about how selected instruments performed under different indoor and outdoor conditions. More comparison studies under different conditions and with a wider variety of instruments are needed.

4. Case Study: Chennai, India

4.1 The Occupational Health Situation and National Law in India

India is a fast growing economy and the world's largest democratic state exceeding 1.2 billion inhabitants. About 64% are of working age of which, more than 90% work in the informal economy, mainly in small and medium sized enterprises (SMEs), agriculture and services. The formal sector involves mainly larger companies in industry and mining. Occupational health challenges include the quantity of people in the informal sector, availability of cheap labour, lack of reliable data, inadequate public spending on health, lack of enforcement of existing legislation, large numbers of unrecognized/unreported occupational injuries and illnesses, shortage of trained and skilled occupational health professionals, multiplicity of statutory controls, apathy of workers and management towards preventive measures, infrastructure problems, and lack of a coherent national policy on occupational health. In addition, liberalization, globalization, outsourcing and privatization have affected working life in India, introducing new challenges and possibilities. The national policy on occupational safety and health, adopted in 2009, is yet to be implemented. Currently, there is no overarching governmental department or agency dealing with occupational health under the Ministry of Labour (Pingle, 2012). Occupational health is regulated under the Factories Act, 1948 (amended in 1987) and the enforcement of the regulations is the responsibility of the individual states. The act includes regulatory guidelines on health, safety, welfare facilities, working hours, employment of young persons and annual leave with wages among others. Section 13 of the Act, deals with occupational heat stress and states that:

> 'Effective and suitable provision shall be made in every factory for securing and maintaining in every work-room (a) adequate ventilation by the circulation of fresh air, and (b) such a temperature that will secure to workers therein reasonable conditions of comfort and prevent injury to health' (Directorate General, 2013).

The WBGT index is here adopted from the international standard. The maximum WBGT shall not exceed 30°C and adequate air movement of at least 30 m/min should be provided (DGFASL, 2013).

As of date, India has not ratified many of the International Labour Organizations Conventions, including C155 – Occupational Safety and Health Convention, 1981 (ILO, 2013).

4.2 Case Study Area Description: Chennai, India

Chennai, formerly Madras, and the capital city of Tamil Nadu, is located on the Coromandel Coast of the Bay of Bengal (Figure 6). It is the seventh largest Indian city also known as the 'gateway to South India'. Chennai is a major administrative and cultural centre and has also become one of India's major outsourcing destinations. The local government has over the years developed an IT Enabled Service Strategy in the state to promote hi-tech growth (Kobayashi-Hillary, 2005). Other industries such as automobile, electronics and financial services have also relocated to Chennai, which is sometimes also referred to as Asia's 'Detroit' (The Wall Street Journal, 2010).

Figure 6: Location of Chennai in India.

The risks to the Indian subcontinent as a result of climate change are high and multidimensional. There is a risk of increases in both mean, minimum and maximum temperatures of 2-4°C. The predicted regional temperature rises, along with changes in the global climatic system could alter the monsoon system, leading to an increase of 10-15% in monsoon precipitation together with a 5-25% decline in precipitation levels in semi-arid and drought-prone central India (Sharma & Tomar, 2010).

Due to its location near the equator, Chennai experiences a hot and humid climate throughout the year. The month of May records the highest temperatures reaching 45°C, causing risks to local workers of developing heat illnesses.

Winter occurs during the months of November to February, with January being the coolest month. Temperatures are pleasant and vary from 15°C to 22°C. During the monsoons, in the months of June to September, Chennai receives abundant rainfall and humidity is high (The Chennai City Guide, 2013). Figure 7 shows the seasonal temperatures and the calculated WBGT (ISO, 1989) using data gathered from the airport weather station in Chennai, India. During the hottest months and with an increasing heat exposure over time, the threshold of a WBGT of 27°C to maintain health and activity is frequently bypassed (Parsons, 2003).

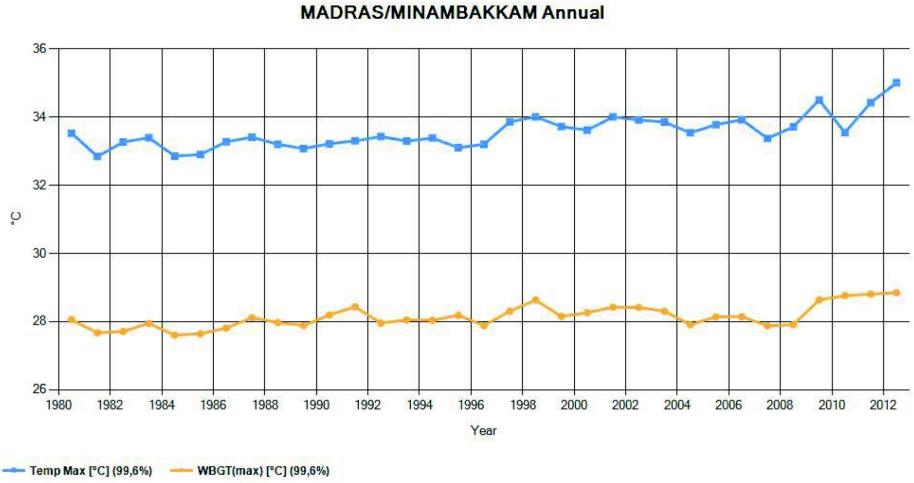


Figure 7: Maximum ambient air temperature and WBGT maximum between 2007-2011 produced by HOTHAPS soft (Kjellström et al., 2013).

Figure 8 shows the monthly average WBGT and work ability with increasing seasonal temperatures in the year 2005 calculated from airport weather station data compared with the year 2050 with modelling data from the University of East Anglia, UK, produced by HOTHAPS soft (Kjellström et al., 2013). The work intensity definitions are from the ISO 7243 standard table on metabolic rate (ISO, 1989). It can be noted that Chennai is situated in one of the most vulnerable areas in India.

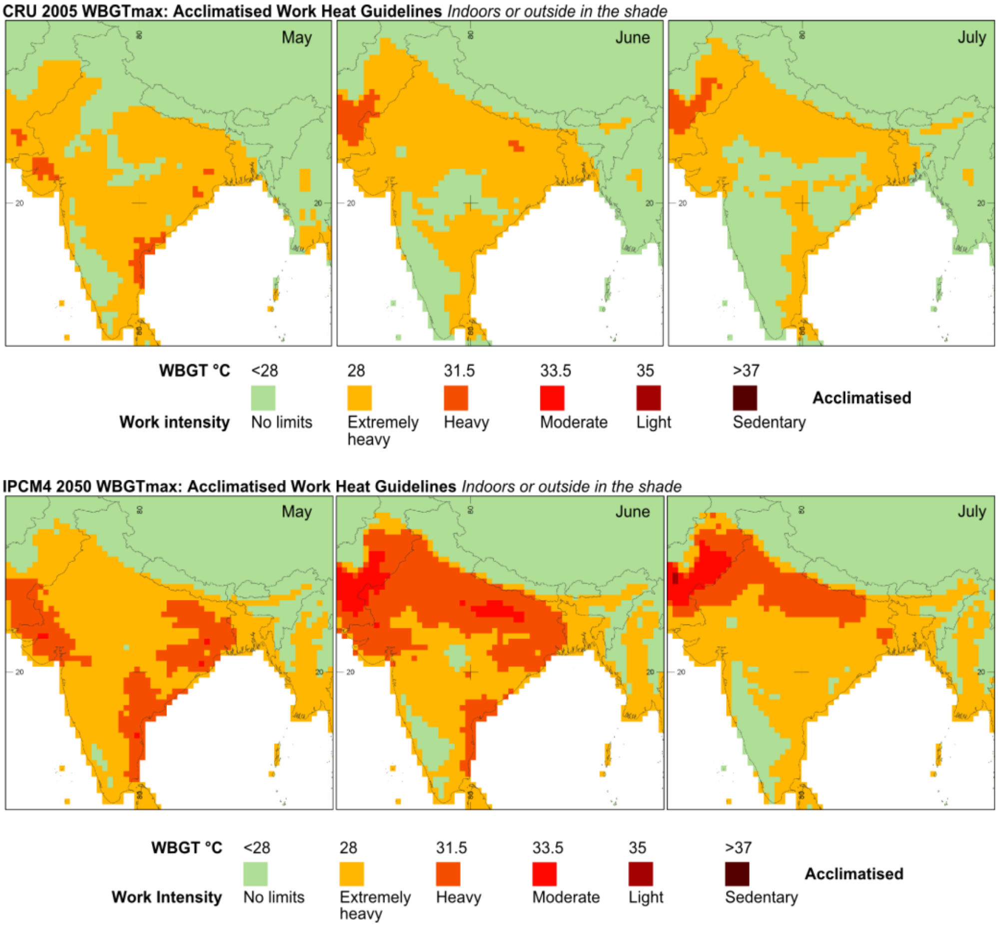


Figure 8: Monthly average WBGT in 2005 and 2050 produced by HOTHAPS soft (Kjellström et al., 2013).

4.3 Fieldwork Sites

The workplaces surveyed were mainly fully outdoors or semi-outdoor workplaces, the latter were sheltered from solar radiation but had walls that prevented the cooling effects of wind. These workplaces were also of poor building design with no air conditioning installed. Most workplaces were small and medium sized enterprises (SMEs), which are the most common employers in India. SMEs generally employ vulnerable groups such as women and poor people, have greater accident rates than larger companies and are more economically constrained when it comes to investing in preventive measures or technology. It is essential to improve the working conditions in SMEs (ILO, 2013).

Cookie Factory

The industry is involved in the preparation of cookies that are of export quality. There are different sections and work tasks in the production line. The first section is the raw material receiving and storage area, involving tasks such as lifting boxes, carrying, bending, etc. The tasks are performed in semi-outdoor conditions. In the next section, the pre-scaling area, different raw materials are received and weighed and raw materials are sent to the mixing area. Mixing is done both manually and mechanically. In the production area, the cookies are baked. The finished products are received in the packing area. Mostly women work in this area and work is performed in standing positions. Finally, in the dispatch area, the packed goods are stored and materials are loaded into vehicles manually. Overall, the facility has many tight spaces with lots of boxes and no windows. Boxes are used to sit on instead of chairs for manual tasks. Buttermilk, a traditional fermented milk drink, is commonly ingested for cooling and rehydration. Water access, washing and cooking facilities are freely available. The storage room is air conditioned, but inefficient. There was a cooling room for cookies and chocolates however, employees are not allowed inside.

A hot air exhaust fan is stationed above the baking unit. This room, however, is still notably hot and the baker reported health problems. Rotation of work tasks does not take place, however, older workers tended to do less strenuous work, such as being security officers. No emergency exits/first aid equipment or fire extinguishers were observed. Some workers reported commuting over two hours to and from work.

Canteen

The canteen is located inside Sri Ramachandra University campus, Chennai (Figure 9). The canteen has different sections that prepare western and South Indian food items. In the raw material receiving and storage area, vegetables and food items are received and stored and a clerk maintains the records. In the vegetable cutting area, vegetables are cleaned and cut. In the food preparation area, breakfast items and rice, vegetables and other items are cooked. Tea and coffee are served throughout the day. In the rice preparation area, rice is cleaned and fed into boilers. In the food serving area, plates are collected and cleaned manually by cleaning workers. Finally, in the billing and manager sections, computer billing is done in different counters that are operated by standing clerks. The canteen is extremely hot, with many cooking stoves with open flames. It was constantly crowded and noisy with customers and thus also messy and dirty. Water and a variety of drinks appeared widely available to all employees, however, the washing and sanitary facilities were overcrowded. Fans were used in the ceiling but did not provide efficient relief. An exhaust system is needed as the particles from cooking cause airway irritation (coughing). The employees are designated to carry out one task, and many stand all day or sit in awkward positions. One big entrance was used for an escape route.

Figure 9: Picture from the canteen.

Laundry Facility

The laundry facility serves students, faculty and the medical centre and consists of two sections: hospital and student laundry (Figure 10). Contaminated/soiled sheets and clothing materials from the hospital are brought to the hospital laundry. The clothes from the hospital are decontaminated before washing and hot press. The work area has few fans and exhaust provided, and most of the workers are women. In the hot press section, large sheets are fed into the press and work is performed manually. In the washing section, clothes are fed into the machine and unloaded manually. After washing, the clothes are loaded into a trolley and taken to the drying section. After drying, the clothes are manually ironed with 5kg non-insulated irons. They are then folded and packed for dispatch. Strong fans and exhaust stacks are present providing some relief from the heat. Chemical data sheets and fire extinguishers are present.

Figure 10: Picture from the laundry facility.

Agriculture

The agricultural field is located in a village outside Chennai city where crops are cultivated according to the seasons (Figure 11). There are different phases in cultivation namely: preparation of land for cultivation, sowing, watering, clearance of weeds, pest control, fertilization, crop maintenance and harvesting. The work usually starts in the early morning and is completed before noon. In preparing the land, intense shovelling is performed, although nowadays, tractors are also used for this work. Manual work is performed in the other phases. Workers spend most of the time bending during planting and harvesting. Agricultural workers are mostly migrants from poorer states and are illiterate. The workers have rich knowledge of the traditional practices to cope with heat such as ingesting buttermilk and fermented rice. Snakes are common on the paddy and workers are routinely bitten. There are no washing or sanitary facilities present and the worker has to bring his/her own water. Each worker usually brings about one litre for the working day. The work is conducted in extreme heat, solar radiation and humidity; many workers are also malnourished, adding to the strain.

Figure 11: Picture from the agricultural field.

Construction

The construction site is located on Sri Ramachandra University campus in Chennai (Figure 12). There are different work tasks involved in construction such as intense shovelling, carrying and disposal of debris, cutting of iron bars, etc. There are different categories of workers involved: manual labourers, masons, stone cutters, bar bending workers, painters, electricians, etc. The amount of time spent exposed to the hot sun varies depending upon the nature of the work performed. Most of the workers are migrants from states like Bihar, Andhra Pradesh and Orissa. Besides working in the construction site, the workers are also constantly exposed to heat in the temporary housing provided for them on the campus. The houses are made of metal sheets that do not offer relief from heat exposure. Water provision and washing facilities were provided on the campus.

Figure 12: Picture from the construction site.

4.4 Field Study Methods and Results

A longitudinal study was conducted and consisted of visiting the workplaces twice: once in the cooler months and once during the hotter months in 2013. The purpose was to evaluate the heat stress situation and determine the impacts on productivity. Due in part to the inability to conduct a pilot study, a mixed methods approach was taken in order to be able to modify the research in accordance with the field settings. Quantitative methods were mainly used supported by qualitative research. A narrative walk and observations was used in combination with a structured questionnaire and heat stress measurements. The objectives of the study were:

1. To describe and analyze the current workplace heat situation in Chennai, India as well as the ongoing trends using established thermal environment methods.
2. To conduct the study during the cooler and warmer months to establish a baseline for productivity impacts in order to compare current conditions to an expected worsening of the situation with future climate change.
3. To identify and describe health impacts and available preventive interventions.

Narrative Walk and Observations

The aim of the qualitative research was to be more exploratory with the goal to identify health and productivity impacts together with current preventive practices. Exploratory studies are intended to provide understanding of a complex and multi-faceted situation (Bryman, 2008). As piloting the research was not possible due to time and practical constraints, the narrative walk guided the research process and helped overcome barriers. Narrative walks are a method by which a local resident (in this case a local PhD student) will guide the researcher on a visit to a familiar environment (Olsson, 2009). To collaborate with a local PhD student eased barriers of language, access, trust, etc. When meeting people at their workplaces, informal discussions took place and were used as an initial exploratory phase of the research. It is a useful method as it enhances confidence for the respondent because of its informal nature. It can also guide and frame the research. During the narrative walks, observations took place using a selected checklist based on the International Labour Office and International Ergonomics Association Ergonomic Checkpoints (ILO & IEA, 2010). Observations were used to evaluate the overall safety and health situation.

Environmental Factors: WBGT

Air temperature (T_a), natural wet bulb temperature (T_{nw}) and globe temperature (T_g) were collected using the 3M™ QUESTemp°™ 32 heat stress meter (accuracy of T_a, T_{nw} and T_g; ± 0.5°C and *RH*; ± 5%) together with personal exposure measurements using LASCAR data loggers (EL-USB-2-LCD$^+$, accuracy of T_a; ± 0.3°C and *RH*; ± 2%) in the field in Chennai during the colder (Jan.-Feb.) and warmer (April-May) months in 2013. Air velocity was estimated based on the workers' activity. Body movement creates airflow over the body; a standard air velocity of 1 m/s simulates a slow walk, and 0.3 m/s was used for a stationary person (Lemke et al., 2012).

The average WBGT values and standard deviations from all sections in each workplace in the winter and summer were measured. Due to access constrains from employers and other practical issues, measurements were not possible throughout the day or for a number of days. Therefore the measurements are averages from different work sections in each workplace for between 3-6 hours.

The average WBGT values and standard deviations from all sections in each workplace in the cooler and warmer seasons are presented in Table 1 (more detailed workplace data can be found in Appendix III). Environmental data input for resting in the heat strain evaluation was from the coolest room or in the shade, as no workplace had air conditioned resting areas.

Table. 1 WBGT measurements (for reference see Figure 8).

WBGT	**Cookie Factory**	**Canteen**	**Laundry Facility**	**Agriculture**	**Construction**
Jan. - Feb.	25 (SD: 1.9)	29,5 (SD: 2)	24,3 (SD: 0.3)	28 (SD: 0.6)	25,6 (SD: 0.3)
April - May	30 (SD: 1.7)	32 (SD: 2.3)	28 (SD: 0.6)	29,6 (SD: 0.4)	28,7 (SD: 1.5)

Anthropometric Data

Anthropometric data was also gathered at the workplaces for heat strain evaluation. The data consisted of the average values of 66 males and 11 females. The average male was 167 cm (SD: 7.4) tall and weighed 64 kg (SD: 12.6), and the average female, 150 cm (SD: 4.1) and 56 kg (SD: 3.9). All workers were considered acclimatized.

Clothing

The work clothing of the Indian workers was tested for insulation and evaporative resistance on thermal manikins at Lund University, Sweden, Loughborough University, UK and at Hong Kong Polytechnic University, China as part of the ASHRAE Project (Havenith et al., 2014). Five sets of work clothing from Chennai were included in the project (Figure 13) and in this analysis based on their wide use in many workplaces. In Lund, postural effects were evaluated: standing, sitting and walking.

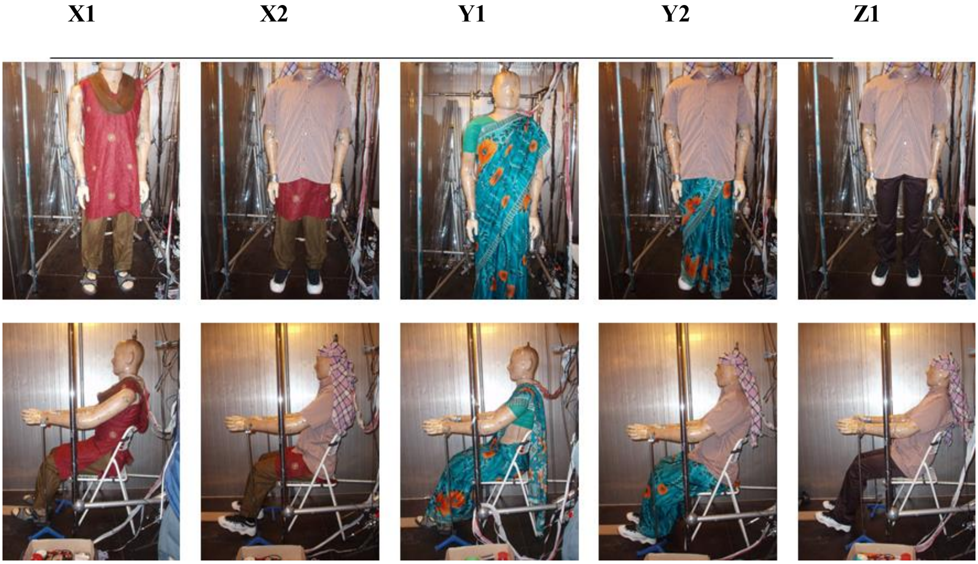


Figure 13: Pictures of the tested work-clothing ensembles.

The mean insulation results from standing measurements from the three laboratories are presented in Table 2.

Table 2: Clothing Descriptions and Data.

Ensemble	**Workplaces**	**Permeability Index (i_m)**	**Clothing Basic Insulation (I_{cl}) clo**
X1: Churidar, with scarf (F)	Cookie Factory and Laundry Facility	0.36	0.58
X2: Churidar + shirt and towel on head (F)	Canteen, Agriculture and Construction	0.32	0.74
Y1: Saree (F)	Cookie Factory and Laundry Facility	0.33	0.74
Y2: Saree + shirt and towel on head (F)	Construction, Agriculture and Canteen	0.30	0.96
Z1: Shirt and trousers, with towel on head (M)	Construction and Agriculture	0.31	0.61
Z2: Shirt and trousers (M)	Cookie Factory, Canteen and Laundry Facility	0.36	0.61

Overall, female clothing without a shirt and head cover had slightly lower insulation values compared to male workwear. In Chennai, it is common for female workers to wear traditional clothing – churidars and sarees – with a protective shirt on top and head cover when working. Such clothing practices trap the saree's layers beneath less permeable fibre, decreasing ventilation. When this was the case, then female workwear had considerably higher insulation and evaporative resistance (Havenith et al., 2014).

Metabolic Rate

Activity was calculated according to heart rate conversion to metabolic rate when possible (ISO, 2004b), and observations using the ISO 7243 activity table to estimate metabolic rate (ISO, 1989). Heart rate was measured using the POLAR pulse monitor (Käyttö 4000 RUD 11.93 STKmodel, with readings every 15 seconds) (ISO, 2004b). Heart rate recordings should be treated with caution because they are affected by factors such as physical fitness, environmental temperature, nutrition, health status, psychological factors (such as stress) and size of active muscle mass, which add complexity (ILO, 1998). On the other hand, heart rate is the most common and practical way of estimating metabolic rate in the field (Parsons, 2003). For this field study, more accurate methods of calculating metabolic rate via measuring oxygen consumption were not possible. The heat and work stress could thus have significantly affected heart rate measurements in this study.

Because of this aspect and due to limited subjects and sampling time, observations using the ISO 7243 activity reference table were also applied (ISO, 1989). The results are presented in Table 3.

Table 3: Estimated average metabolic rates.

Site	Metabolic Rate (W/m^2)*	Work Tasks Involved	Class
Industrial - Cookie factory	188 (178; SD 6.1, 144; SD 5.7, 169; SD 9.1, 260; SD 13.6)	Sustained hand and arm work, pushing/pulling/ lifting light weight boxes, bending, mixing, walking speed 2.4-5.5 km/h.	Moderate
Service – Canteen	170 (170; SD 11.3)	Sustained hand and arm work, standing cooking, preparation, lifting/pushing/pulling light weight boxes, bending, walking speed 2.4-5.5 km/h.	Moderate
Service – Laundry Facility	181 (245; SD 13, 120; SD 17.5, 177; SD 6)	Sustained hand and arm work, manual loading/unloading, ironing, folding and packing, walking speed 2.4-5.5 km/h.	Moderate
Agricultural	190	Preparation of land for cultivation, sowing, watering, weeding, pest control, fertilization, crop maintenance and harvesting, bending, walking speed 2.4-5.5 km/h.	Moderate
Construction	220	Intense arm and trunk work, shoveling, carrying and disposal of debris, cutting of iron bars, pushing and pulling heavy carts, walking speed 5.5- 7 km/h.	Heavy

* Estimation from observation and calculated metabolic rate from the heart rate (HR). In brackets are the average metabolic rate calculated results from the individual subjects' heart rates.

The heart rate of the subjects was recorded only on men due to cultural gender constraints, and they were mostly under the age of 30; two of the subjects were 52 and 60 years of age. Measurement time varied between 3-5 hours. The very high recordings, 260 and 245 W/m^2 were due to very high heat exposure: baker in the cookie factory and dryer in the laundry respectively.

The Questionnaire

The questionnaire substantiated the heat exposure measurements, looking at impacts on health, work capacity and preventive methods. The study used opportunity sampling as the field situation determined accessibility and practicality (Bryman, 2008). Measures to reduce impacts of heat, current heat experiences during travel to/from work and in the household were also explored.

From this analysis, local health and productivity impacts, description of the general heat exposure situation and how people cope with heat were explored. Challenges included language and illiteracy together with manager presence, which impacted the workers' responses. Cooperation with a local academic institution did, however, overcome some of these challenges.

The questionnaire wording is important for reliability and replicability, and had been tested in similar previous studies (Crowe et al., 2009). The questions were developed using largely closed questions for reasons of practicality (access, confidentiality, anonymity, trust, less misinterpretations, etc.) but with the probability to probe further. The closed questions provided data that is easier to process and understand. Easier questions were in the beginning of the questionnaire to relax respondents. The questionnaire is relatively short, using simple language without technical jargon, so that the respondent could easily understand, interpret and complete it (Bryman, 2008). All responding workers signed an informed consent form or if illiterate they confirmed orally, before answering the questionnaire. The questionnaire is available in Annex I.

Overall, the dominant age group in all workplaces represented 20-40 year olds with various educational backgrounds. In the cookie factory, many had finished higher secondary school and university whilst the agricultural workers were mainly illiterate (92%). Most workers had finished primary school and both male and female workers were represented. Most reported having health problems due to heat, including thirst, heavy sweating, muscle cramps, tiredness/weakness, dizziness, headache, and a few reported problems with nausea/vomiting and fainting. For example, in the cookie factory, feeling thirsty, headaches, prickly heat and tiredness almost doubled in summer compared to winter. Many reported having a moderate workload in comfortable, well-ventilated conditions, although acknowledging a problem with heat in the hotter months. In addition, most had productivity targets and difficulties meeting these during this period. Many compensated by working overtime.

Locally in workplaces there are numerous technical, behavioural and managerial approaches to reduce heat exposure. Apart from resting, which dominated the methods, traditional methods, mainly including drinks and diet, dominated the coping mechanisms. Other methods included work-rest regimes, shade structures and ventilation such as fans (Table 4 and Figure 14). Preventive methods must be further studied and adopted (see next chapter and further research).

Table 4: Results on preventive methods from field survey.

Sector	**Preventive Methods**
Agriculture	Face & hand wash; traditional methods (buttermilk, fermented rice, porridge, etc.)
Canteen	Fruit juice and buttermilk + fans, exhaust fans, exhaust ventilation
Cookie Factory	Buttermilk + fans
Construction	Juice, buttermilk, coconut
Laundry Facility	Buttermilk, fermented rice, porridge, etc. + fans, exhaust fans

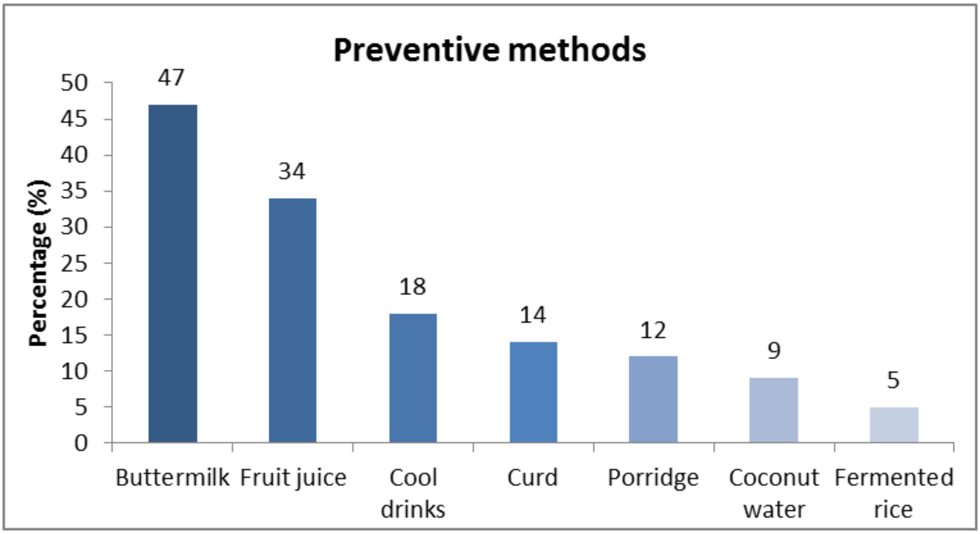


Figure 14: Results on preventive methods from field survey (n=85).

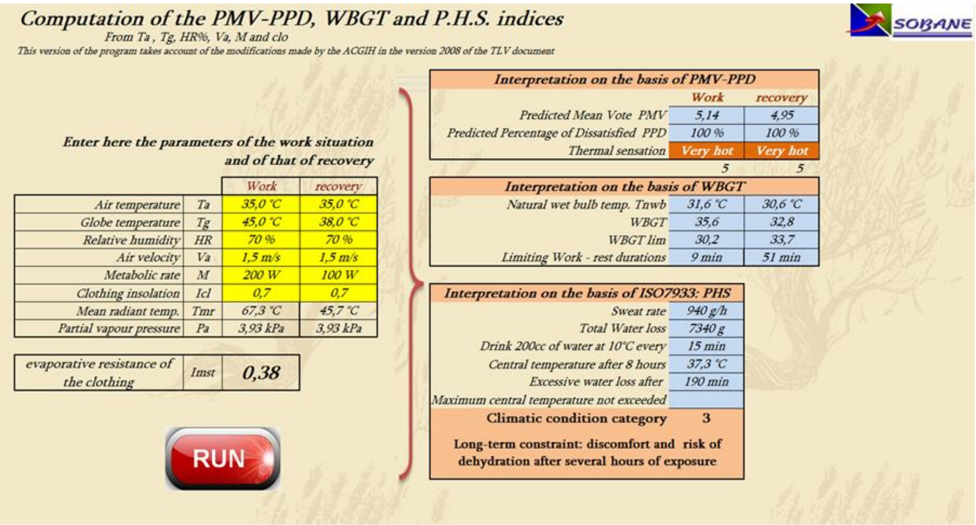
Generally, results from the working conditions and from the productivity questions can be questioned as they represent large varieties between workplaces. For example in the canteen, 89% reported reduced productivity in the hotter months whilst in agriculture, the percentage was 46%. This can partly be explained as the manager was often around, introducing a bias in the results. In addition, misinterpretations, language barriers and time constraints further compromised the data. As a result, it was decided not to rely on the questionnaire data for productivity analysis and to use a physiological model instead: the Predicted Heat Strain Model. The full questionnaire results data can be found in Annex II.

Climate Change Predictions and Labour Productivity

Previous papers examining the links between heat exposure and productivity have used productivity measures such as the collection of ‘bundles’ (Sahu et al., 2013), gross domestic product (GDP) and weather data (DARA, 2013; Dunne et al., 2013), the ISO 7243 standard work-rest guidelines (Dunne et al., 2013; Kjellström, 2009; Kjellström et al., 2009), time to reach production targets, company productivity records, overtime, and the use of interviews and questionnaires about workers’ perception of heat and work productivity (Balakrishnan et al., 2010; Crowe et al., 2009).

Physiological parameters have previously been found to be indicators of productivity loss as well. For example, Nag et al. (2013) found that when the core temperature reaches 38°C, if the worker is able to self-pace, s/he will adjust the pace and slow down (Nag et al., 2013). Based on this, a physiological model was used in the research to estimate productivity loss linked to the heat exposure. The Predicted Heat Strain (PHS) model (ISO 7933) (ISO, 2004a) is a physiological model developed by Professor Malchaire, Université Catholique de Louvain, Belgium together with other European researchers in a EU Project (Malchaire et al., 2001) . The model has been used to predict the decline of productivity between seasons and with climate change. An extra 2°C were added to the current summer measurements for females to simulate future temperatures due to climate change. This is the agreed global average target of the international community to prevent dangerous anthropogenic interference with the climate system (UNFCCC, 2013). However, this is a global average temperature; local climates will respond differently and temperature extremes are becoming more common (IPCC, 2013). Currently, the extra 2°C do not result in unusual temperatures during the hottest months and can therefore be solely seen as an exercise.

The Predicted Heat Strain is an empirical model based on the required sweat rate (Parsons, 2003). It is a method for predicting heat strain on the basis of the sweat rate and the internal core temperature in response to the working conditions. It is used in the present research to estimate productivity loss as a consequence of heat stress. The model is not intended and designed for this, however, but to estimate thermal physiological responses and exposure duration. The individual input and output variables of the PHS model are shown in Figure 15.



Computation of the PMV-PPD, WBGT and P.H.S. indices

From Ta , Tg, HR%, Va, M and clo

This version of the program takes account of the modifications made by the ACGIH in the version 2008 of the TLV document

Enter here the parameters of the work situation and of that of recovery

		Work	recovery
Air temperature	Ta	35,0 °C	35,0 °C
Globe temperature	Tg	45,0 °C	38,0 °C
Relative humidity	HR	70 %	70 %
Air velocity	Va	1,5 m/s	1,5 m/s
Metabolic rate	M	200 W	100 W
Clothing insolation	Icl	0,7	0,7
Mean radiant temp.	Tmr	67,3 °C	45,7 °C
Partial vapour pressure	Pa	3,93 kPa	3,93 kPa

evaporative resistance of the clothing	Imst	0,38

Interpretation on the basis of PMV-PPD		
	Work	recovery
Predicted Mean Vote PMV	5,14	4,95
Predicted Percentage of Dissatisfied PPD	100 %	100 %
Thermal sensation	Very hot	Very hot
	5	5

Interpretation on the basis of WBGT		
Natural wet bulb temp. Tnwb	31,6 °C	30,6 °C
WBGT	35,6	32,8
WBGT lim	30,2	33,7
Limiting Work - rest durations	9 min	51 min

Interpretation on the basis of ISO7933: PHS	
Sweat rate	940 g/h
Total Water loss	7340 g
Drink 200cc of water at 10°C every	15 min
Central temperature after 8 hours	37,3 °C
Excessive water loss after	190 min
Maximum central temperature not exceeded	
Climatic condition category	3

Long-term constraint: discomfort and risk of dehydration after several hours of exposure

Figure 15: The PHS model input and output parameters used for the simulation, updated by Prof. Malchaire in Autumn 2013.

Productivity in the study is based on the following three outputs in the PHS model that indirectly will affect time-weighted productivity: limiting work-rest duration, sweat rate and excessive water loss. Limiting work-rest duration is the most direct measure as it provides guidelines for how to safely work based on the ISO 7243 standard.

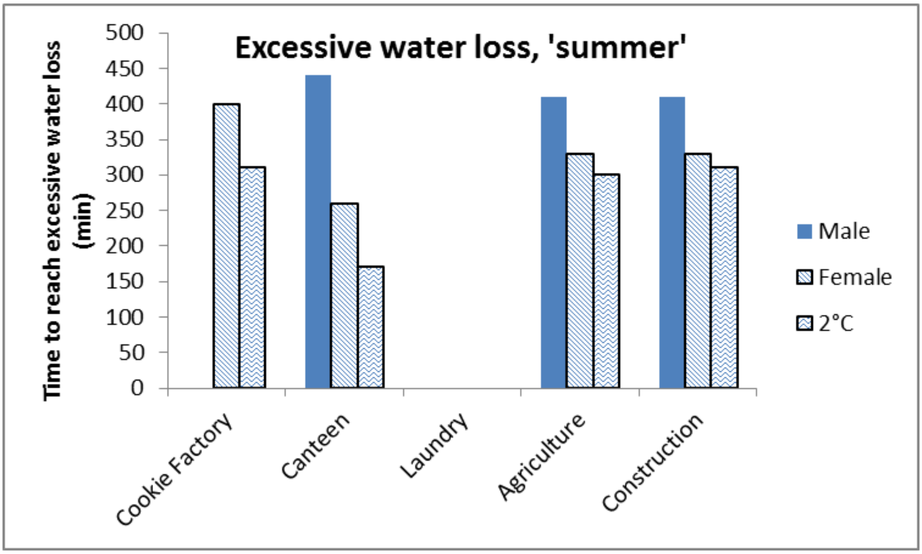


Figure 16: Output from the PHS simulation results; time to reach excessive water loss.

In Figure 16, productivity loss is reflected in time, in accordance with dehydration limits (Malchaire, 2006). In the canteen, excessive water loss is reached in about 4 hours for women, while men can work for almost three more hours before reaching dehydration limits. In the climate change scenario, the dehydration limit is reached in only about 3 hours. The cookie factory, agriculture and construction workplaces showed excessive water loss after about 7 hours in the cold season, 6 hours in the hot season and about 5 hours in the climate change scenario. The results show that females are more vulnerable and under added thermal stress due to the additional shirt and head cover, which add insulation. However, in the real situation females continue working full work shifts, most probably affecting their health. The laundry facility never reached critical thermal conditions.

In the output from the PHS model on predicted sweat rate the effects of different clothing could also be seen. Sweat rates are very high in the summer, especially in relation to the anthropometric data, almost reaching 600 g/h. However, water loss at this level is acceptable if replacement is available (Malchaire, 2006).

The limiting work-rest duration from the PHS output based on the ISO 7243 standard presented some differences in work productivity and ability to work safely in the cooler and hotter months, especially in the canteen and cookie factory. Whilst in the laundry facility the productivity loss was negligible, the conditions in the canteen were already extreme. Adding two degrees will make it almost impossible to work in the hottest months.

The time it takes to reach a core temperature of 38°C for the average worker and dehydration are critical parameters in the model. The WHO 1969 guideline of 38°C is followed to protect most workers (WHO, 1969). In the canteen, the predicted limit core temperature exceeded this 38°C limit in women after 180 min (3hrs); with an additional 2°C, it exceeded the limit already in 73 min. The canteen was also the only workplace that reached climate category 4 in the model, in the climate change scenario, where there is a health risk after 30-120 min of exposure. After a full work shift, the predicted core temperature could reach 40.2°C, resulting in a high risk of developing heat illnesses.

4.5 Discussion

Clothing

Clothing was found to be problematic, with high insulation values in relation to the heat exposure. A gender heat exposure difference was seen as it was found that females are more vulnerable due to the traditional clothing worn under protective layers in the construction, agriculture and the canteen workplaces. Female workers wear shirts over their traditional saree/churidar. Such clothing practices trap a saree’s layers beneath tighter textile decreasing air and vapour permeability, ventilation and increasing the clothing’s insulation. Such clothing practices create a higher heat load for these women. However, it is a cultural practice that is hard to change and requires further research. On the other hand, the ventilation effect of the traditional clothing such as the saree is likely underestimated due to the PHS model being based on western clothing data.

Using the PHS Model to Estimate Productivity Loss

The PHS ISO 7933:2004 model used to predict productivity loss in this study rationally accounts for the individual factors known to influence heat stress response of healthy individuals (Jay & Kenny, 2010). It is based on an analysis of body heat balance and the required sweat rate for the maintenance of a stable core temperature (Malchaire et al., 2000; 2001). Although progress has been made scientifically in understanding human thermo-physiological responses to various hot environments, it is still a great challenge to predict heat strain accurately for most of the existing human thermoregulatory models. For these reasons, a rational model such as the PHS model can mainly be applied as an additional tool to supervise workers to reduce physiological strain by guiding the breaks and rehydration needs. However, letting workers self-pace their work, provision of safe drinking water, regular breaks throughout the day and awareness of heat stress symptoms remain the most critical management practices. The limiting work-rest duration output of the PHS model is aimed at protecting 95% (most) of the working population (Miller & Bates, 2007) and is designed primarily for self-paced workers. These limits represent the sustainable metabolic rate that a well-hydrated, acclimatized worker can maintain in a specific thermal environment within safe limits of core body temperature and sweat rate. The real danger is when the work is externally paced (e.g. by machinery, quotas, peer pressure), as workers will push themselves beyond the safe limit and be at risk of developing heat illness. At most risk is workers who are poorly hydrated, unacclimatized or physically unfit.

Overall, there is a need for a validation of the model, as it is not designed for analyzing productivity loss. Also, it is a human physiological model, and does not account for mental capacity or other factors influencing performance. Hence, it does not include what states of mind, in terms of perceptions, feelings, stress, etc., the workers' experience. As a result, performance may slow down even before it should according to the indicators in the model. Further studies are required to examine the productivity aspect and different methods for estimation. Translating the physiological model output into economic loss would also add value. Although, it was found that due to low-cost labour in India, many managers did not see having to employ additional workers in the hottest months as a problem.

Limitations

In general, practical considerations had a strong influence on the field research and it is important to be aware of its limitation in terms of generalizability. The opportunity sampling conducted both with the questionnaires and heart rate data does bias how representative the sample is of the wider population. It should therefore be used with caution. The study also only provides a snapshot of the reality for these workers as each field visit lasted between 4-6 hours, not for a full working day or over an extended period of time. Additional aspects include worker turnover between the two seasonal studies, psychological aspects, stress factors, and subjective reactivity, such as the Hawthorne effect. The Hawthorne effect is when workers are more productive when being watched as part of a study. This complicates the results, especially in short-term studies (Fostervold et al., 2001).

Uncertainties also include current heat stress standards being naturally conservative, along with problems that become evident when standards are introduced into a workplace where workers are mobile and where work tasks and loads vary during their work shift. In occupational settings that add heat stress, metabolic rates are difficult to estimate. In this study heart rate measurements and observations using the ISO 7243 reference table were applied (ISO, 1989), but not over the full working day. It may therefore be that the metabolic rate is under or overestimated. The average, however, could be reasonably close. In addition, the Predicted Heat Strain (PHS) model does not include a time-weighing option in order to change parameters such as temperature and metabolic rate during the working day. As a consequence, the work-rest schedule may affect the results, as well as availability of cooler/shaded recovery areas.

5. Adaptation and Maladaptation

5.1 Preventive and Control Measures

Humans will have to adapt to warmer temperatures despite uncertainty in climate change impacts. Strategies to reduce the effects of future climate change involve an iterative risk management process that includes both mitigation (reducing emissions of greenhouse gases) and adaptation (coping strategies) (IPCC, 2007). Some risks can be managed by adaptation policies, the success of which will depend on the speed and extent of climate change, the sustainability of measures, and the level of global cooperation to implement measures to support and protect vulnerable regions and populations (Nilsson & Kjellström, 2010). Generally, the aim of adaptation to climate change is to reduce vulnerability and increase resilience to impacts. The heat wave of 2003 in Europe suggests that adaptation is not occurring successfully even in developed countries, and that public health efforts in response to heat are primarily reactive rather than long-term initiatives. The underlying perception that heat is not a high priority prevents learning to avert heat stress. Education and training of workers, employers and the general public is essential for effective risk management.

The two main factors for protection against danger from heat in the workplace are to safeguard from and to control the source of the heat. Heat stress controls can also be divided into two broad categories: general and specific. General controls include thermal audit methods and personal monitoring using heart rate and internal body temperature measuring equipment (Parsons, 2003). General controls should be implemented anytime there is a reasonable potential for heat stress. Specific controls are directed to working practices and include specific training, heat stress hygiene and medical surveillance.

A heat stress assessment follows the traditional hierarchy of hazards control, being in the order of elimination, substitution, engineering controls, administrative controls and finally, personal protection. Overall, there is a large variation in cost, capability and constraints with the different systems (Bernard, 1994).

Engineering solutions include risk alert systems, response plans, water delivery, portable shade structures, water based cooling, air based systems, decreased insulation and ventilated clothes, cooling centres, air conditioning, personal cooling systems (e.g. ice vest), protective clothing and so on (Schenker, 2011). Active cooling systems are widely available such as liquid cooling and air-cooling garments (Parsons, 2003). Active cooling systems include external connections to air or liquid supplies such as ventilated cooled air and circulated liquid cooling. Passive cooling systems utilize phase change materials (PCMs) (e.g. ice, frozen gel, salt, wax) in vests and clothing (Gao et al., 2012). However, these technical fixes may not be applicable to developing countries, especially in small businesses where room for investment is scarce. Measures that reduce thermal stress without compromising performance and productivity, together with being a low cost option, are more likely to be adopted.

As a response to challenges in a warmer world, development of acclimatization procedures, hazard communications, early warning systems and surveillance, and increased emphasis on prevention through design can present vital solutions (Schulte & Chun, 2009). More broadly there are also numerous contemporary urban planning and building design initiatives directed towards sustainability, thermal comfort and energy conservation. Increasing the size of urban parks and gardens, green roofs, reflective surfaces, and enhancing shading and ventilation channels, will result in a reduction in temperatures in urban areas. With appropriate urban planning and design, the urban heat island effect could be considerably reduced (Jusuf et al., 2007; Kikegawa et al., 2006).

5.2 Sustainability and Air-Conditioning Use

During the field work it was discovered that in India, the growth of the adoption of air conditioning (AC) is remarkably high and many new buildings are designed for air conditioning. This development is mostly driven by income growth, modern building design principles and perceived need, but also due to increasing temperatures and protection from heat exposure. Nevertheless, it was found that not many studies have been carried out on the consequences of this development. Therefore, in paper III the aim was to explore this growth in the use of air conditioning to protect from high heat exposure and its implications from a sustainability perspective. A literature search using selected key words in a wide range of information sources was carried out. The literature laid the foundation for a sustainability analysis of causes and feedback and further research needs and methodologies.

The negative impacts of increased energy costs for cooling from AC are projected to be concentrated in the tropics and subtropics where most of the world's population resides and where fast growing, dense urban areas are commonplace. At the regional scale considerable impacts can be seen, particularly in South and Southeast Asia, where energy demand for residential AC could increase more than 40 times by 2100 in comparison to 2000, with a 7% growth per year on average (Isaac & van Vuuren, 2009). AC puts a high burden on the electricity distribution system and increases the risk for electricity power cuts. This has the potential for dire consequences, with increased high health risks from heat stress especially during heat waves. Furthermore, the urban heat island effect will increase the magnitude and duration of heat waves and cause additional night-time electricity consumption from AC units. AC also directly affects the urban heat island effect. It does so by heat ejection, which increases the outdoor ambient air temperature causing additional electricity consumption and worsening the urban heat island. As the urban and global climate changes, the ability of buildings to continue to provide healthy and thermally comfortable environments for inhabitants will be further challenged.

It was found that literature on the subject linking temperature directly to AC use is limited although research has identified climate variables being linked with electricity consumption. Air temperature is found to be the most significant weather variable affecting electricity demand. Above and below the thermal comfort zone, the electricity load becomes sensitive to temperature and electricity consumption increases (Valor et al., 2001). This is highly problematic as the use and cost of AC will increase as a consequence of climate change.

These trends create additional inequity between low and high income countries as it will increase energy demand in most tropical and sub-tropical countries, while there may be a beneficial effect (less heating needed) in more temperate high income countries (IIASA, 2012). Increases in humidity in combination with temperature will further increase electricity consumption (Ihara et al., 2008) especially in hot-humid climates.

A life cycle and a systems analysis approach are necessary when examining the problem and possible solutions (see paper III). Short-term considerations, such as simply installing inefficient types of AC during hot summers, are not a sustainable solution (IIASA, 2012). Figure 17 conceptualizes the issue of space cooling and electricity consumption. It presents a significant sustainability issue, where linkages and reinforcing feedbacks between the uses of AC, climate change and the urban heat island effect are prominent.

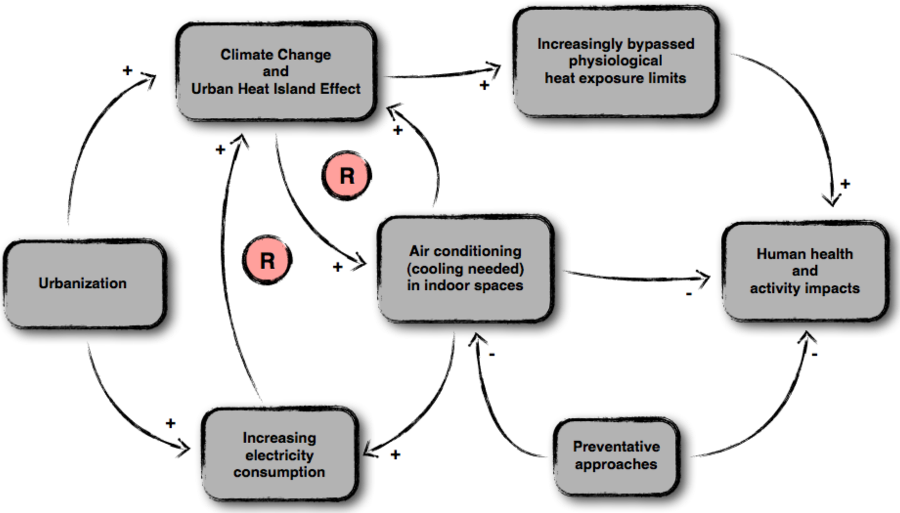


Figure 17: Examples of the links between the different concepts in urban settings and AC use from a systems approach.

The social impacts of increasing heat will hit poor people the most due to lack of access to air conditioned spaces and novel cooling technologies. It is placing an inequitable health and financial burden on vulnerable heat-stressed households. Poor people are also more likely to occupy and perform activities outdoors and/or semi-outdoors and therefore be more vulnerable to the urban heat island. These ethical aspects of increasing heat on the local level from both lack of climate change mitigation and increasing air conditioning use, call for better design and planning solutions and more affordable sustainable cooling technologies. Sustainable methods to reduce heat exposure are needed to make future urban areas more climate resilient. However, there are problems due to the lack of an alternative effective sustainable solution to air conditioning for effective cooling, especially when the temperatures go above 40°C. Here, traditional design may not be sufficient to maintain a comfortable thermal environment (Nguyen et al., 2011). More traditional ways of building according to the climate together with modern technology such as renewable energy have a potential. One has to consider all the drivers and feedback when designing alternatives to AC and it is important to understand innovation systems and how past technological transitions have occurred. This can provide insight into approaches for promoting innovation for greater sustainability.

6. Conclusion

Heat stress has been studied extensively in the past. However, in the contemporary context of climate change, it was found that information is lacking on the extent of future heat stress and its consequences, especially in occupational settings. In the literature review (paper I), the main factors found to exacerbate heat stress in current and future workplaces are the urban heat island effect, physical work, individual differences, and the developing country context where technological fixes and certain control measures are often not applicable. There is also a lack of information on the effects on vulnerable groups such as the poor, elderly people and pregnant women.

On this basis, a field study was carried out to measure heat stress and related productivity loss in heat-exposed workplaces in Chennai (Madras), India. Health risks, preventive methods and the links to climate change were aspects also explored. The WBGT index (ISO 7243:1989) was chosen as the method for estimating the heat stress using reference equipment and simple data loggers. This was based on four pre-studies of WBGT measuring equipment with differing climate conditions. It was found that low cost equipment such as data loggers can be used accurately in stable conditions without a radiation source at relatively low air velocity.

All workplaces surveyed had very high heat exposure; often reaching WBGT values above the 27°C threshold for working safely (paper II). Most workers had moderate to high workloads, some in direct sun exposure. It was also found that females were more vulnerable due to the extra insulation added from wearing a protective shirt on top of traditional clothing when working. Most workers reported health problems due to heat exposure, including thirst, heavy sweating, muscle cramps, tiredness/weakness, dizziness, headaches, and few reported problems with nausea/vomiting and fainting. Problems with meeting production targets in the hotter months were usually compensated by overtime work. When analyzing productivity loss and heat strain in a physiological model – the Predicted Heat Strain Model (ISO 7933:2004) – the parameters showed significant impacts, especially when adding a couple of extra degrees in the climate change scenario. Water provision and rehydration were critical parameters in the outcome.

Locally in workplaces, there were numerous technical, behavioural and managerial approaches used to reduce heat exposure. Apart from taking rests, traditional methods, including mainly drinks and diet, dominated the coping mechanisms. Other methods included work-rest regimes, shade structures and ventilation such as fans.

Air conditioning as a technical solution has experienced high growth in India to protect from heat exposure. It is effective in reducing heat exposure but creates many sustainability challenges. In the research presented in paper III, it was found that air conditioning use triggers an increase in energy consumption when the outdoor temperature increases, and therefore greenhouse gas emissions, exacerbating climate change. In addition, the direct heat rejected from the air conditioning unit adds to street level heat and the urban heat island effect. If not abated, it has the potential to intensify climate change, and put extra loads on the future energy supply, especially during heat waves.

In conclusion, occupational health and safety is one of the basic rights that workers have often no access to in India. In addition, as work productivity reduces with increasing temperatures, India's economic productivity could be affected. To address these current and future occupational problems, solutions must take into account the social, economic, equity, environmental and technical aspects of the problem. Both mitigation and adaptation measures should be considered, sometimes in combination and including both preventive and control solutions to achieve multiple benefits. Capacity building such as education and awareness, and involvement on all levels of society is especially needed to address this.

6.1 Further Research Needs

The issue of increasing heat and reduced productivity can become overwhelming as future increase in heat exposure at work will impact people's health and livelihood. It could have a wide effect on world inequalities, wealth creation, and poverty and if left unmanaged, it could possibly cause social unrest and migration. Further research is needed, in particular:

- Validation and development of the Predicted Heat Strain (PHS) model for appropriateness of productivity analysis.

- Development of research tools to further the development of more accurate estimations of productivity and economic analysis.

- Development of more accurate measurements of metabolic rate in hot environmental conditions for field use.

- More comparison studies of WBGT equipment under different conditions.

- Negotiate and develop an international agreement on the best heat stress index to use in analyzes of climate change impacts on health in order to compare studies worldwide.

- Effects on vulnerable groups such as young and elderly people, women, pregnant women, and poor people.

- Occupational heat stress in different countries, contexts and ways of adaptation.

- Urban heat island effects and combinations of exposure on workplaces in urban areas.

- Downscaling climate modelling data and using weather station data to reflect local living environments and heat impacts, including the urban heat island effect.

- Current adaptation practices (with mitigation benefits) in hot countries and their effectiveness.

- Inequalities and moral dimensions of the problem and adoption of cooling technologies.

- Social, psychological and health effects of heat stress.

The future plans of the PhD project will include testing of the cooling methods currently used in the workplaces studied for their effectiveness but also assessed from developed sustainability criteria. More research on vulnerable groups, heat resilient urban areas, inequalities of cooling technologies and how to analyze productivity loss will be conducted.

Additional Publications not Presented in the Thesis

Articles

Mengmeng, Z., Lundgren, K., Jun, L., Kuklane, K., A Ventilated Cooling Shirt Worn at Office Work in Hot Climate: Cool or Not? *Industrial Health,* 2014 (in progress).

Havenith, G., Kuklane, K., Fan, J., Hodder, S., Ouzzahra, Y., Lundgren, K., Au, Y., Loveday, D., A database of static clothing thermal insulation and vapor permeability values of non-western ensembles for use in ASHRAE standard 55, ISO 7730 and 9920 - results from project 1504-RP, *ASHRAE Transactions*, 2014 (in progress).

Reports

Havenith, G., Hodder, S., Ouzzahra, Y., Loveday, D., Kuklane, K., Lundgren, K., Fan, J., Au, J. Report on manikin measurements for ASHRAE 1504-TRP. 2014 (in progress).

Lundgren, K., Butt, S., Kuklane, K., Gao, C. Technical Report: Comparison Studies of WBGT Index Measurement, Lund University, Faculty of Engineering (LTH), Department of Design Sciences, 2014 (in progress).

Conference proceedings

Lundgren K., Exposure to Heat and Occupational Health in a Warming World. Second Nordic International Conference on Climate Change Adaptation – Adaptation Research Meets Adaptation Decision-making. Helsinki, Finland, August 29-31, 2012.

Lundgren, K., Holmér, I., Climate Change and Occupational Health – Populations Exposed and the Sustainability of Methods to Avoid Excessive Heat in Workplaces. XV International Conference on Environmental Ergonomics. Queenstown, New Zealand, February 11-15, 2013.

Lundgren, K., Kjellström, T., Holmér, I., Lemke, B., Lucas, R., Protecting Against Excessive Workplace Heat as an Outcome of Climate Change – Confronting the Sustainability Challenge from Increased Air Conditioning Use. XV International Conference on Environmental Ergonomics. Queenstown, New Zealand, February 11-15, 2013.

Main Research Projects

1. Swedish International Development Cooperation Agency (SIDA) grant.

Title: Sweden-India Cooperation on Protection of Working People from Health and Productivity Risks Due to Workplace Heat Exposure and the Links to Climate Change

Aim: Contribute to poverty reduction and equitable and sustainable development by fostering healthier working conditions and systems that protect the incomes of the poor when climate change undermines the work productivity due to heat at work.

Main partners: Umeå University, Sweden; Sri Ramachandra University, India; Lund University, Sweden.

2. The American Society of Heating Refrigerating and Air Conditioning Engineers research grant.

Title: Extension of the Clothing Insulation Database for Standard 55 and ISO 7730 to Provide Data for Non-Western Clothing Ensembles, Including Data on the Effect of Posture and Air Movement on that Insulation.

Aim: To extend the current databases of clothing ensemble insulation values used in the comfort standards ASHRAE-55 and ISO-7730. The present databases contain very little non-western clothing ensembles. Hence, the project focuses directly on non-western clothing from major population regions.

Main partners: Loughborough University, UK; Lund University, Sweden; Cornell University, US; Hong Kong Polytechnic University.

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APPENDIX I: Main Study Questionnaire for Industrial Workers

Part 1. General information about person interviewed and the organization she/he represents

1. ID No:
2. Date of interview:
3. Name of the interviewer:
4. Type of the industry
5. Age:
6. Age group: ☐$_1$ 20-30 / ☐$_2$ 30-40 / ☐$_3$ 40-50 / ☐$_4$ 50 and above
7. Sex: ☐$_1$ Male / ☐$_2$ Female
8. Education: ☐$_1$ Illiterate / ☐$_2$ Primary / ☐$_3$ Secondary / ☐$_4$ Higher Secondary / ☐$_5$ University
9. Designation: ☐$_1$ Worker ☐$_2$Supervisory ☐$_3$Manager
10. Smoking: ☐$_1$ Smoker /☐$_2$ Non Smoker /☐$_3$ Ex smoker
11. Consuming alcohol: ☐$_1$ Yes ☐$_2$ No ☐$_3$ Ex
12. Any existing illness: ☐$_1$Diabetes ☐$_2$Hypertension ☐$_3$Respiratory illness, specify ☐$_4$Others, specify

Part 2. Questions concerning the type of work

1. Type of work: ☐$_1$Light ☐$_2$Moderate ☐$_3$Heavy ☐4 Very Heavy
2. What was your previous job and where (relating to temp)? ____________
3. How long you are employed here? ____________years/months (more than 6months means acclimatized)

4. How many hours per day do you usually work excluding regular break timings? --------
5. When and how long are the regular breaks?
6. Do you work near a direct heat source(naked flame/hot air/outdoors/radiant heat)
   ☐$_1$ Yes / ☐$_2$ No
7. Is the place you work well-ventilated? ☐$_1$ Yes / ☐$_2$ No
8. Do you have additional breaks during summer? ☐$_1$ Yes / ☐$_2$ No
9. If yes, mention no. of hours/minutes_________________

Part 3. Questions in relation to heat exposure at work

1. Are you comfortable with the workplace temperature? ☐$_1$Yes / ☐$_2$No
2. How many people work in this area? ________________
3. Is heat exposure a problem during the hot season? ☐$_1$Yes / ☐$_2$No
4. How many months do you feel hot /uncomfortably hot in this workplace?
   a. 1-3 months b. 4-6 months c. 7-9 months d. 9-12 months e. Never
5. Describe how bad the heat stress can be in the hot season.
   a. Extremely bad b. Very bad c. Bad d. Manageable e. No stress at all

Part 4. Questions concerning impacts of heat on health

1. What symptoms do you face during summer months?
   a. Excessive Sweating b. Exhaustion c. Thirst

d. Wanting to go to comfort zone e. Others________________

2. Have you ever had these symptoms at work due to heat?
   a. heavy sweating ☐$_1$Yes / ☐$_2$No
   b. muscle cramps ☐$_1$Yes / ☐$_2$No
   c. Tiredness/weakness ☐$_1$Yes / ☐$_2$No
   d. dizziness ☐$_1$Yes / ☐$_2$No
   e. headache ☐$_1$Yes / ☐$_2$No
   f. nausea or vomiting ☐$_1$Yes / ☐$_2$No
   g. fainting ☐$_1$Yes / ☐$_2$No

3. Have you ever been affected by any of the following?

$_1$Prickly heat $_2$Heat cramps $_3$Heat exhaustion $_4$Heat syncope (fainting) $_5$ Heat stroke

4. To achieve production target or complete do you have to work extra hours?

Part 5. Questions concerning impacts of heat on worker's productivity

1. Have you ever taken sick leave/permission due to heat ? Yes /No
2. If yes, approx. how many hours in a week?---------------- Month-------------
3. Have you ever been advised to take off due to heat related illness? ☐1 Yes / ☐2 No
4. Have you ever been admitted in hospital/medical centre due to heat related sickness? Yes/No
5. If yes, approximately how many days__________________________
6. How does heat affect other aspects of your work (during hot seasons)
   a. Absenteeism b. Less productivity c. Irritation/Interpersonal issues

d. Work related issues with manager e. Take more time to complete same task

7. How much production target do you have? __________________________
8. Do you complete your production target? Yes/No
9. If no, how much target is not completed? __________________________units
10. To achieve production target or complete work do you have to work extra hours?
11. If yes, how many extra hours __________________________
12. Have you lost any wages due to absenteeism in summer months?
13. If yes, how much __________________________?(currency)

Part 6. Questions concerning impacts of clothing on heat stress and productivity

1. Dress material of the workers (Indian equivalent to ACGIH)
   1. Breathable cotton 2. Thick cotton overall 3. Rayon/Nylon

4. Plastic PPE 5. Others______________________

2. Worker perception about dress Material of the worker:

a. Comfortable b. Moderately comfortable

c. Uncomfortable e. Others___

3. If uncomfortable, can you give any suggestions to improve?___________________________

4. Do you feel hotter with uniform/ Does the Dress Material increase heat stress?
   a. Sure b. May be c. Not sure d. No, not at all
5. Does clothing reduce your work output?
   a. Sure b. May be c. Not sure d. No, not at all
6. If clothing impedes your work out put, based on your perception can you tell how much?
   b. About 10% b. 10-25% c. 50% d. No sure

Part 7.Questions concerning coping mechanisms:

1. How do you limit heat exposure, when needed?
   a. Get away for a while b. remove the clothing c. drink water
   d. any other method, do specify____________________
2. If you are feeling unwell from heat exhaustion how do you cope with this?

$_1$take rest $_2$cool shower, bath, or sponge bath $_3$move to an air-conditioned/cooler environment $_4$switch to Light weight clothing $_5$any other method, do specify__________________

3. Do you drink water at work? Yes / No
4. Is sufficient water available at all times when you need it? Yes / No
5. How much do you drink in a day in hot conditions? ____________________ltrs/cups
6. Do you take any traditional special diet to cope with heat? ____________________
7. What traditional or other methods do you adopt for coping with heat?
   ____
8. Do you spend more money during hot seasons to cope with heat? ____________________
9. If yes, specify ____________________ (Currency units)
10. Do you spend more time to cope with heat? If yes how much ____________________ (min/hrs) – convert to % of productivity time or personal time
11. Does the time spent on coping heat impact your social life? Yes/No
12. How does it affect your social life?
    a. Moderately b. Highly c. Extremely d. No impact

APPENDIX II: Questionnaire Results

Cookie Factory

Demographic information (n=13)

Variable	**Characteristics**	**Percent (%)**
Age group	<20	**-**
	20-40	**54**
	>40	**46**
Sex	Female	**8**
	Male	**92**
Education	Illiterate	**-**
	Primary	**15**
	Secondary	**24**
	Higher secondary	**23**
	Polytechnic/Diploma	**15**
	University	**23**

Workplace heat exposure information (n=13)

Variable	**Characteristics**	**Percent (%)**
Type of work	Heavy	**8**
	Moderate	**61**
	Light	**31**
Work near direct heat source (Radiant heat/Hot air)	Yes	**15**
Perception about ventilation	Not well ventilated	**8**
	Well ventilated	**92**
Perception about ambient temp	Not comfortable	**8**
	Comfortable	**92**
Heat exposure a problem in the hot season	No	**92**
	Yes	**8**

Impacts of heat stress on health, productivity and social lives as reported by questionnaires (n=13)

Variable	**Characteristics**	**Winter (n=13)**		**Summer (n=14)**	
		N	**Percent (%)**	**N**	**Percent (%)**
Impacts of heat on health	Excessive sweating/Thirst	10	77	12	86
	Muscle cramps	-	-	-	-
	Tiredness/weakness/dizziness	2	15	7	50
	Headache	3	23	1	7
	Nausea/Vomiting	-	-	-	-

	Fainting	-	-	1	7
	Prickly heat	3	23	7	50
Production target & issues	Have production target	5	39	8	57
	Able to Complete production target	5	39	8	57
	Not able to complete production target	-	-	-	-
Impacts of heat on productivity	Absenteeism/ Taken sick leave due to heat	1	8	2	14
	Less productivity/ More time to complete task/Work extra hours	6	46	11	79
	Irritation/Interpersonal issues	2	15	7	50
	Wages lost in summer	-	-	-	-
Coping mechanisms	Take rest	10	77	3	21
	Drink water	12	92	12	86
	Cool shower, bath or sponge bath	-	-	-	-
	Move to air-conditioned/cooler area	-	-	4	29
	Traditional methods	11	85	9	64
Impacts of clothing on productivity	Clothing-Comfortable	13	100	10	71
	Clothing-Moderately Comfortable	-	-	3	21
	Clothing-Uncomfortable	-	-	1	7
Impacts on Social Life	Yes	2	15	8	57
	Highly	-	-	-	-
	Moderately	2	15	8	57

Coping mechanisms adopted by workers to manage heat stress (n=13)

Variable	**Characteristics**	**Percent (%)**
Type of coping mechanism	Get away for a while	**8**
	Remove/Change Clothing	**-**
	Drink water	**92**
	Take rest	**77**
	Cool shower, bath or sponge bath	**-**
	Move to air-conditioned/cooler area	**-**
	Switch to light weight clothing	**-**
	Traditional methods to deal with heat	**85**

Canteen

Demographic information (n=10)

Variable	**Characteristics**	**Percent (%)**
Age group	<20	**10**
	20-40	**60**
	>40	**30**
Sex	Female	**10**
	Male	**90**
Education	Illiterate	**10**
	Primary	**40**

	Secondary	**10**
	Higher secondary	**20**
	Polytechnic/Diploma	**20**
	University	**-**

Workplace heat exposure information (n=10)

Variable	**Characteristics**	**Percent (%)**
Type of work	Heavy	**-**
	Moderate	**80**
	Light	**20**
Work near direct heat source (Radiant heat/Hot air)	Yes	**60**
Perception about ventilation	Not well ventilated	**20**
	Well ventilated	**80**
Perception about ambient temp	Not comfortable	**50**
	Comfortable	**50**
Heat exposure a problem in hot season	No	**10**
	Yes	**90**

Impacts of heat stress on health, productivity and social lives as reported by questionnaires (n=10)

Variable	**Characteristics**	**Winter (n=10)**		**Summer (n=9)**	
		N	**Percent (%)**	**N**	**Percent (%)**
Impacts of heat on health	Excessive sweating/Thirst	10	100	9	100
	Muscle cramps	1	10	2	22
	Tiredness/weakness/dizziness	6	60	9	100
	Headache	3	30	3	33
	Nausea/Vomiting	-	-	-	-
	Fainting	1	10	-	-
	Prickly heat	8	80	8	89
Production target & issues	Have production target	-	-	9	100
	Able to Complete production target	-	-	9	100
	Not able to complete production target	-	-	-	-
Impacts of heat on productivity	Absenteeism/ Taken sick leave due to heat	7	70	-	-
	Less productivity/ More time to complete task/Work extra hours	3	30	8	89
	Irritation/Interpersonal issues	6	60	7	78
	Wages lost in summer	5	50	-	-
Coping mechanisms	Take rest	10	100	9	100
	Drink water	10	100	9	100
	Cool shower, bath or sponge bath	6	60	-	-
	Move to air-conditioned/cooler area	-	-	-	-
	Traditional methods	9	90	9	100

Impacts of clothing on productivity	Clothing-Comfortable	4	40	2	22
	Clothing-Moderately Comfortable	3	30	6	67
	Clothing-Uncomfortable	3	30	1	11
Impacts on Social Life	Yes	4	40	5	56
	Highly	-	-	4	44
	Moderately	4	40	1	11

Coping mechanisms adopted by workers to manage heat stress (n=10)

Variable	**Characteristics**	**Percent (%)**
Type of coping mechanism	Get away for a while	**90**
	Remove/Change Clothing	**80**
	Drink water	**100**
	Take rest	**100**
	Cool shower, bath or sponge bath	**60**
	Move to air-conditioned/cooler area	**-**
	Switch to light weight clothing	**-**
	Traditional methods to deal with heat	**100**

Laundry

Demographic information (n=13)

Variable	Characteristics	Percent (%)
Age group	<20	-
	20-40	8
	>40	92
Sex	Female	69
	Male	31
Education	Illiterate	15
	Primary	46
	Secondary	15

Workplace heat exposure information (n=13)

Variable	Characteristics	Percent (%)
Type of work	Heavy	-
	Moderate	62
	Light	38
Work near direct heat source (Radiant heat)	Yes	39
Perception about ventilation	Well ventilated	92
Perception about ambient temp	Not comfortable	23
	Comfortable	77

Heat exposure a problem in hot season	No	62
	Yes	38

Impacts of heat stress on health, productivity and social lives as reported by questionnaires (n=13)

Variable	**Characteristics**	**Winter (n=13)**		**Summer (n=23)**	
		N	**Percent (%)**	**N**	**Percent (%)**
Impacts of heat on health	Excessive sweating/Thirst	11	85	22	96
	Muscle cramps	-	-	1	4
	Tiredness/weakness/dizziness	2	15	16	70
	Headache	3	23	12	52
	Nausea/Vomiting	1	8	1	4
	Fainting	-	-	2	9
	Prickly heat	1	8	6	26
Production target & issues	Have production target	1	8	15	65
	Able to Complete production target	1	8	14	61
	Not able to complete production target	-	-	1	4
Impacts of heat on productivity	Absenteeism/ Taken sick leave due to heat	-	-	3	13
	Less productivity/ More time to complete task/Work extra hours	1	8	13	57
	Irritation/Interpersonal issues	1	8	4	17
	Wages lost in summer	-	-	2	9

Coping mechanisms	Take rest	2	15	18	78
	Drink water	10	77	23	100
	Cool shower, bath or sponge bath	-	-	1	4
	Move to air-conditioned/cooler area	-	-	1	4
	Traditional methods	8	62	16	70
Impacts of clothing on productivity	Clothing-Comfortable	11	85	18	78
	Clothing-Moderately Comfortable	2	15	4	17
	Clothing-Uncomfortable	2	15	1	4
Impacts on Social Life	Yes	2	15	15	65
	Highly	-	-	4	17
	Moderately	2	15	11	48

Coping mechanisms adopted by workers to manage heat stress (n=13)

Variable	Characteristics	Percent (%)
Type of coping mechanism	Get away for a while	15
	Remove/Change Clothing	-
	Drink water	77
	Take rest	15
	Cool shower, bath or sponge bath	-
	Move to air-conditioned/cooler area	-
	Switch to light weight clothing	-
	Traditional methods to deal with heat	100

Agriculture

Demographic information (n=12)

Variable	**Characteristics**	**Percent (%)**
Age group	<20	**-**
	20-40	**8**
	>40	**92**
Sex	Female	**50**
	Male	**50**
Education	Illiterate	**92**
	Primary	**8**
	Secondary	**-**

Workplace heat exposure information (n=12)

Variable	**Characteristics**	**Percent (%)**
Type of work	Heavy	**42**
	Moderate	**58**
	Light	**-**
Work near direct heat source (Direct sunlight)	Yes	**100**
Perception about ventilation	Well ventilated	**100**
Perception about ambient temp	Not comfortable	**17**
	Comfortable	**83**

Heat exposure a problem in hot season	No	**8**
	Yes	**92**

Impacts of heat stress on health, productivity and social lives as reported by questionnaires (n=12)

Variable	**Characteristics**	**Winter (n=12)**		**Summer (n=11)**	
		N	**Percent (%)**	**N**	**Percent (%)**
Impacts of heat on health	Excessive sweating/Thirst	12	100	11	100
	Muscle cramps	6	50	4	36
	Tiredness/weakness/dizziness	10	83	7	64
	Headache	4	33	8	73
	Nausea/Vomiting	-	-	-	-
	Fainting	2	17	1	9
	Prickly heat	6	50	2	18
Production target & issues	Have production target	9	75	100	11
	Able to Complete production target	-	-	5	46
	Not able to complete production target	-	-	6	54
Impacts of heat on productivity	Absenteeism/ Taken sick leave due to heat	6	50	2	18
	Less productivity/ More time to complete task/Work extra hours	10	83	5	46
	Irritation/Interpersonal issues	-	-	5	46
	Wages lost in summer	4	33	2	18

Coping mechanisms	Take rest	12	100	10	91
	Drink water	9	75	10	91
	Cool shower, bath or sponge bath	-	-	1	9
	Move to air-conditioned/cooler area	-	-	5	46
	Traditional methods	8	67	9	82
Impacts of clothing on productivity	Clothing-Comfortable	12	100	8	73
	Clothing-Moderately Comfortable	-	-	-	-
	Clothing-Uncomfortable	-	-	3	27
Impacts on Social Life	Yes	2	17	8	73
	Highly	-	-	3	27
	Moderately	2	17	5	46

Coping mechanisms adopted by workers to manage heat stress (n=12)

Variable	**Characteristics**	**Percent (%)**
Type of coping mechanism	Get away for a while	**50**
	Remove/Change Clothing	**-**
	Drink water	**75**
	Take rest	**100**
	Cool shower, bath or sponge bath	**-**
	Move to air-conditioned/cooler area	**-**
	Switch to light weight clothing	**-**
	Traditional methods to deal with heat	**67**

Construction

Demographic information (n=24)

Variable	Characteristics	Percent (%)
Age group	<20	8
	20-40	46
	>40	46
Sex	Female	8
	Male	92
Education	Illiterate	13
	Primary	33
	Secondary	29
	Higher secondary	4
	University	21

Workplace heat exposure information (n=24)

Variable	Characteristics	Percent (%)
Type of work	Heavy	42
	Moderate	42
	Light	16
Work near direct heat source (Direct sunlight/Outdoor)	Yes	38

Perception about ventilation	Not well ventilated	62
	Well ventilated	38
Perception about ambient temp	Not comfortable	50
	Comfortable	50
Heat exposure a problem in hot season	No	42
	Yes	58

Impacts of heat stress on health, productivity and social lives as reported by questionnaires (n=24)

Variable	**Characteristics**	**Winter (n=24)**		**Summer (n=28)**	
		N	**Percent (%)**	**N**	**Percent (%)**
Impacts of heat on health	Excessive sweating/Thirst	7	29	28	100
	Muscle cramps	8	33	4	14
	Tiredness/weakness/dizziness	13	54	24	86
	Headache	6	25	4	14
	Nausea/Vomiting	1	4	-	-
	Fainting	3	13	3	11
	Prickly heat	-	-	13	46
Production target & issues	Have production target	-	-	12	43
	Able to Complete production target	-	-	12	43
	Not able to complete production target	-	-	-	-
Impacts of heat on productivity	Absenteeism/ Taken sick leave due to heat	16	67	7	25
	Less productivity/ More time to complete task/Work extra hours	16	67	24	86
	Irritation/Interpersonal issues	-	-	16	57

	Wages lost in summer	-	-	7	25
Coping mechanisms	Take rest	-	-	26	93
	Drink water	-	-	28	100
	Cool shower, bath or sponge bath	-	-	5	18
	Move to air-conditioned/cooler area	-	-	7	25
	Traditional methods	-	-	25	89
Impacts of clothing on productivity	Clothing-Comfortable	24	100	25	89
	Clothing-Moderately Comfortable	-	-	3	11
	Clothing-Uncomfortable	-	-	-	-
Impacts on Social Life	Yes	-	-	20	71
	Highly	-	-	1	4
	Moderately	-	-	19	68

Coping mechanisms adopted by workers to manage heat stress (n=24)

Variable	Characteristics	Percent (%)
Type of coping mechanism	Get away for a while/Self-pacing	46
	Remove/Change Clothing	25
	Drink water	29
	Take rest	71
	Cool shower, bath or sponge bath	4
	Move to shade/cooler area	25
	Switch to light weight clothing	-
	Traditional methods to deal with heat	45

APPENDIX III: Environmental Data from Workplaces

Cookie Factory

	SUMMER			**WINTER**			Difference WBGT (°C)
Work Location	**Temp. (°C)**	**RH (%)**	**WBGT (°C)**	**Temp. (°C)**	**RH (%)**	**WBGT (°C)**	
Outdoor temperature (for reference)	35	47.5	**34.0**	29	51	**29.8**	4.2
Pre-scaling area	36	43	**31.5**	29	48	**23.8**	7.7
Mixing area	35.5	47.5	**30.8**	29	48	**23.8**	7.0
Packing Area-I	34.5	51	**32.1**	29	48	**26.4**	5.7
Packing Area-II	34.5	51	**30.9**	29	48	**25.7**	5.2
Raw Material storage Area	35	53	**31.4**	29	48	**23.9**	7.5
Dispatch Area	35	54.5	**31.0**	29	49.5	**26.1**	4.9

Canteen

	SUMMER			**WINTER**			**Difference WBGT (°C)**
Work Location	**Temp. (°C)**	**RH (%)**	**WBGT (°C)**	**Temp. (°C)**	**RH (%)**	**WBGT (°C)**	
Rice making area	35.0	47	**34.3**	29.0	55	**32.2**	**2.1**
Storage room	35.5	43	**29.4**	28.0	62	**27.2**	**2.2**
In front of storage room	34.5	48	**29.0**	29.0	50	**26.8**	**2.2**
Kolambu making area	35.5	47	**31.5**	29.0	58	**30.5**	**1.0**
Fried rice making area	35.0	48	**31.8**	29.0	47	**28.2**	**3.6**
Dosai making area	36.0	38	**34.8**	29.0	55	**30.6**	**4.2**
Coffee and tea area	35.5	44	**34.5**	29.0	58	**31.2**	**3.3**

Laundry

	SUMMER			**WINTER**			**Difference WBGT (°C)**
Work Location	**Temp. (°C)**	**RH (%)**	**WBGT (°C)**	**Temp. (°C)**	**RH (%)**	**WBGT (°C)**	
Close to washing machine	35.5	44.0	**27.6**	29.0	66.0	**24.6**	**3.0**
Close to drying machine	36.0	39.0	**27.7**	30.0	58.0	**24.2**	**3.5**
Ironing Area-I	36.0	38.0	**27.8**	30.0	56.0	**24.5**	**3.3**
Ironing Area-II	36.0	38.0	**27.9**	30.0	62.0	**24.6**	**3.3**
Ironing Area-III	35.0	40.0	**29.2**	30.0	62.0	**24.3**	**4.9**
Close to Folding Area	35.5	44.0	**27.7**	29.0	66.0	**24.2**	**3.5**
Close to hydro machine	36.0	39.0	**28.0**	29.0	66.0	**23.7**	**4.3**

Agriculture

	SUMMER			WINTER			Difference WBGT (°C)
Work Location	**Temp. (°C)**	**RH (%)**	**WBGT (°C)**	**Temp. (°C)**	**RH (%)**	**WBGT (°C)**	
Ambient temperature	34.0	46.0	**29.4**	28.5	62.0	**28.0**	**1.4**
Near working area	34.0	46.0	**29.2**	29.0	62.0	**27.6**	**1.6**
Near water pump	35.0	35.0	**30.3**	29.0	62.0	**26.7**	**3.6**
Inside the field	34.5	40.5	**29.5**	29.0	62.0	**28.3**	**1.2**

Construction

	SUMMER			WINTER			Difference WBGT (°C)
Work Location	**Temp. (°C)**	**RH (%)**	**WBGT (°C)**	**Temp. (°C)**	**RH (%)**	**WBGT (°C)**	
Entrance of the building	34.5	36.0	**27.2**	30.0	56.5	**25.9**	**1.3**
Outdoor area inside the building	34.5	36.0	**29.2**	30.0	56.5	**25.9**	**3.3**
Inside the construction area	34.0	38.0	**27.6**	30.0	51.0	**25.8**	**1.8**
1st floor of the building	34.0	39.5	**27.5**	30.0	53.0	**25.1**	**2.4**
2nd floor of the building	34.0	39.5	**27.6**	30.0	55.0	**25.1**	**2.5**
3rd floor of the building	34.0	39.5	**27.8**	30.0	53.0	**25.6**	**2.2**
Top floor of the building	34.0	41.0	**28.1**	30.0	51.0	**25.6**	**2.5**