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The heat is on

Evaluation of workplace heat stress under a changing climate

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**ERGONOMICS AND AEROSOL TECHNOLOGY | DESIGN SCIENCES
LUND UNIVERSITY**

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Evaluation of workplace heat stress
under a changing climate

Karin Lundgren Kownacki

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Abstract

Background: There are several scientific indications that increasing heat due to climate change is going to become the next big societal and scientific challenge. Climate change is recognized as a significant public health threat. However, there is a lack of research on its impacts on occupational safety and health.

Aims and Objectives: The general aim of the research presented in this thesis was to identify impacts, evaluate assessment tools and explore solutions to the effects of increasing heat at different workplaces. The research had four specific objectives: 1) To identify gaps in the existing knowledge of occupational heat stress and its links with a changing climate (*Papers I, II, V*). 2) To carry out a field study in workplaces situated in already hot areas of the world, namely in Chennai, India, in order to assess the current and future impacts of increasing local heat due to climate change (*Papers II, V*). 3) To evaluate the current standard assessment tools for hot environments (*Papers II, III*). 4) To investigate site-specific sustainable solutions to increasing heat, including technical, managerial and socio-cultural solutions (*Papers II, IV, V*).

Methods: To address the specific objectives, a wide array of research techniques and qualitative and quantitative methods were used. The methods included literature reviews, case studies, heat stress assessment techniques, questionnaire surveys, thermal manikin measurements, application of thermophysiological models and an experimental study conducted in a climatic chamber.

Results: This research showed that occupational heat exposure is already a problem in Chennai, India, affecting workers' health and productivity. The problems are set to worsen due to climate change. Female workers are more prone to heat stress due to the use of clothing that inhibit heat dissipation. Physiological models are also less accurate in predicting heat strain for females. The Predicted Heat Strain (PHS) model (ISO 7933:2004a) can be applied to estimate thermal physiological responses and indirectly to estimate labour productivity loss due to heat exposure. However, caution has to be taken when analysing intermittent work as the PHS over-predicts body cooling at low activity. Traditional methods of coping with heat stress were analysed and the traditional Indian fermented dairy drink, 'buttermilk', proved to be as effective as water in reducing thermal strain. Buttermilk also had a protective effect on renal function. The analysis and evaluation of solutions require transdisciplinary and holistic approaches, including not only technical solutions but also a mix of locally appropriate technologies integrated with a human rights and environmental justice frame.

Conclusion: Occupational heat stress is already a problem, affecting workers' health and productivity. The situation is bound to worsen due to climate change. Because of this, it is important to assess and validate current assessment tools and develop sustainable solutions.

Key words
Occupational heat stress, India, Case studies, Interventions, International standards, Productivity, Climate Change

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'By the sweat of your face shall you drink buttermilk and water'

(modified from Genesis 3:19).

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The thesis at a glance

The aim of this thesis research is to identify impacts, evaluate assessment tools and explore solutions to the effects of increasing heat at different workplaces. The thesis has five appended papers involving a variety of methods and sources of data addressing four objectives:

1. To identify gaps in the existing knowledge of occupational heat stress and its links with a changing climate (*Papers I, II, V*).

2. To carry out a field study in workplaces situated in already hot areas of the world, namely in Chennai, India, in order to assess the current and future impacts of increasing local heat due to climate change (*Papers II and V*).

3. To evaluate the current standard assessment tools for hot environments (*Papers II, III*).

4. To investigate site-specific sustainable solutions to increasing heat, including technical, managerial and socio-cultural solutions (*Papers II, IV, V*).

Paper Title	Objective No.	Sources of Data	Methods
I. Effects of heat stress on working populations when facing climate change.	1	Scientific papers	Literature review
II. Occupational heat stress and associated productivity loss estimation using the PHS model (ISO 7933:2004a): A case study from workplaces in Chennai, India.	2,3,4	5 surveyed workplaces in Chennai, India.	Case study including a questionnaire survey, human thermal assessment techniques: thermal indices and standards, work intensity estimations, testing of clothing properties on a thermal manikin and thermophysiological models.
III. Human responses in heat – Comparison of the Predicted Heat Strain and the Fiala multi-node model for a case of intermittent work.	3	10 subjects (5 males, 5 females)	Comparison of thermophysiological models predictions with experimental data from the climatic chamber.
IV. Exploring how a traditional diluted yoghurt drink may mitigate heat strain during medium-intensity intermittent work – A multidisciplinary study of occupational heat strain.	3,4	12 subjects (6 males; 6 females)	Thermophysiological experiment in a climatic chamber including psychological tests, biomarker sampling and testing.
V. Climate change induced heat risks for migrant populations working at brick kilns in India: A transdisciplinary approach.	1,2,3,4	Scientific papers and data from brick kilns in Chennai, India.	Transdisciplinary case study including a literature review, human thermal assessment techniques: thermal indices and standards, work intensity estimations and climate forecast data.

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Last but not least, I would like to thank my family, especially my husband Witold for his endless support and friendship, and our amazing but time-consuming daughter Maja.

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

Abstract

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Aims and Objectives: The general aim of the research presented in this thesis was to identify impacts, evaluate assessment tools and explore solutions to the effects of increasing heat at different workplaces. The research had four specific objectives: 1) To identify gaps in the existing knowledge of occupational heat stress and its links with a changing climate (*Papers I, II, V*). 2) To carry out a field study in workplaces situated in already hot areas of the world, namely in Chennai, India, in order to assess the current and future impacts of increasing local heat due to climate change (*Papers II, V*). 3) To evaluate the current standard assessment tools for hot environments (*Papers II, III*). 4) To investigate site-specific sustainable solutions to increasing heat, including technical, managerial and socio-cultural solutions (*Papers II, IV, V*).

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Populärvetenskaplig sammanfattning

Tänk dig att du ligger i en solstol på semestern i Thailand. Det är 35 grader och sol. En härlig semesterdag helt enkelt. Men föreställ dig nu att du skulle behöva arbeta fysiskt istället under hela dagen – för så ser många arbetares vardag ut i ett flertal länder. Idag bor hälften av alla människor på jorden i varma områden i den tropiska och subtropiska klimatzonen. Ytterligare ökad hetta i dessa regioner på grund av klimatförändringar kommer att hota folkhälsan och arbetsförmågan. Hårdast drabbade blir de allra fattigaste människorna som ofta arbetar fysiskt utomhus. För dem innebär även en mindre höjning av medeltemperaturen en ökad risk för värmestress (i form av ökad kroppstemperatur), som kan bli livshotande. Avhandlingens forskning angriper denna problematik med olika metoder och frågeställningar.

Första studien är en litteraturstudie som identifierar kunskapsluckor. Andra studien analyserar klimatets påverkan på arbetares hälsa och produktivitet i en fallstudie i Chennai - en region med ett varmt och fuktigt klimat i sydöstra Indien. Klimatförändringarnas framtida påverkan på klimatet i regionen ingår också i analysen. Den tredje studien utvärderar två kända fysiologiska beräkningsmodeller utifrån deras förmåga att uppskatta värmebelastning. Slutligen går de två sista studierna in på möjliga hållbara och regionspecifika lösningar genom en studie i en klimatkammare* på Institutionen för Designvetenskaper vid Lunds universitet och genom en tvärvetenskaplig fallstudie.

Hög värmebelastning är redan idag ett problem som påverkar arbetares hälsa och produktivitet i Chennai. Situationen kommer att försämras ytterligare även vid de lägre prognoserna av framtida klimatförändringar. Studiens resultat visar också att arbetande kvinnor i Chennai är mer utsatta på grund av att de skyddar sina traditionella kläder genom att ha en skjorta utanpå. Det ökar värmebelastningen genom att isolera och försvåra avdunstning av svett.

Vid analys av försämrad arbetsförmåga användes en känd fysiologisk beräkningsmodell för att förutsäga värmebelastning som också är en internationell standard**. Det var första gången som denna modell användes för en analys av detta slag. Tredje studien jämförde standardmodellen** med en mer komplex fysiologisk modell*** gentemot observationer under försök i klimatkammaren. Vi fann att det behövs bättre modeller för att kunna förutsäga värmebelastning vid arbeten som har varierande intensitet under arbetsdagen, vilket är vanligt på bland annat byggnadsarbetsplatser och i jordbruk. Här förutspådde standardmodellen att avkylningen vid låg aktivitet (vila) skulle vara mer effektiv än vad data från klimatkammaren visade. Detta resultat är problematiskt då modellen används specifikt för att hantera och reducera farlig värmeexponering på arbetsplatser. Analysen kom också fram till att modellernas förmåga att förutsäga värmebelastning korrekt var sämre för kvinnor än för män.

Avhandlingens forskning undersöker också en regionspecifik lösning som framgick av svar från frågeformulären som gjordes i Chennai. Många av arbetarna beskrev att den traditionella indiska yoghurtdrycken 'buttermilk' hade en nedkylande effekt. Det visade sig i studien från klimatkammaren att buttermilk var lika effektivt som vatten för att minska värmebelastningen. Detta är ett intressant resultat eftersom många traditionella metoder för att hantera värmebelastning är outforskade.

Sista studien diskuterar och analyserar lösningar mot ökad värmeexponering på tegelbruk i Chennai. Det krävs tvärvetenskapliga och holistiska tillvägagångssätt. Åtgärder måste vidtas på alla samhällsnivåer och flera olika lösningar måste implementeras. Ett helhetsperspektiv behövs också för att säkerställa att lösningar för utsatta arbetstagare innehåller en blandning av lokalt lämplig teknik och att mänskliga rättigheter och miljö respekteras.

Många får en bild av smältande isar och döende isbjörnar när man tänker på klimatförändringarna. Den bilden borde bytas ut mot en bild av oss människor eftersom klimatförändringarna påverkar vår egen hälsa och liv. Hållbara åtgärder krävs, annars kan konsekvensen av reducerad arbetsförmåga bli den mest kostsamma för våra ekonomier, och drabba de allra fattigaste hårdast.

*	Slutna kammare som gör det möjligt att simulera olika termiska miljöer genom reglering av temperatur och luftfuktighet.
**	The Predicted Heat Strain model - ISO 7933:2004a
***	The mathematical model of the human thermophysiology by Fiala

Appended papers

Paper I: Lundgren K (author's birth name), Kuklane K, Gao G, Holmér I (2013) Effects of Heat Stress on Working Populations When Facing Climate Change. *Industrial Health*. 51(1): 3-15.

Paper II: Lundgren K (author's birth name), Kuklane K, Venugopal V (2014) Occupational Heat Stress and Associated Productivity Loss Estimation Using the PHS Model (ISO 7933): A Case Study from Workplaces in Chennai, India. *Global Health Action*. 7: 25283. DOI: 10.3402/gha.v7.25283

Paper III: Lundgren-Kownacki K, Martínez N, Johansson B, Psikuta A, Annaheim S, Kuklane K (2017) Human Responses in Heat – Comparison of the Predicted Heat Strain and the Fiala Multi-node Model for a Case of Intermittent Work. *Thermal Biology*. 70(A): 45-52. DOI: 10.1016/j.jtherbio.2017.05.006

Paper IV: Lundgren-Kownacki K, Dahl M, Gao C, Jakobsson K, Linninge C, Song D, Kuklane K (2017) Exploring How a Traditional Diluted Yoghurt Drink may Mitigate Heat Strain During Medium-intensity Intermittent Work – A Multidisciplinary Study of Occupational Heat Strain. *Industrial Health*. (In Press) DOI: 10.2486/indhealth.2017-0030

Paper V: Lundgren-Kownacki K, Kjellberg S, Goosh P, Dabieh M, Venugopal V (2017) Climate Change Induced Heat Risks for Migrant Populations Working at Brick Kilns in India: A Transdisciplinary Approach. *International Journal of Biometerology*. DOI: 10.1007/s00484-017-1476-0

The author's contributions to the papers

I – Initiated and conducted the majority of the work.

II – Conducted the case study research in collaboration with researchers at Sri Ramachandra University, Chennai. Collected the data, performed the analysis and did the majority of the manuscript writing.

III – Performed the majority of the analysis in the Predicted Heat Strain model and interpretation of the results. Co-ordinated the analysis and manuscript writing with the co-authors.

IV – Planned the experimental study, collected the data, performed the majority of data analysis and did the co-ordination of the manuscript writing.

V – Initiated the work, co-ordinated the analysis and took part as a co-author of the paper.

A selection of associated papers not presented in the thesis

Peer reviewed papers

Lundgren-Kownacki K, Dalholm Hornyanszky E, Tuan AC, Alkan Olsson J, Becker P (2017) Challenges with Using Air-conditioning in an Increasingly Hot Climate. *International Journal of Biometeorology*. DOI: 10.1007/s00484-017-1493-z

Havenith G, Hodder S, Ouzzahra Y, Loveday D, Kuklane K, **Lundgren K,** Fan J, Au J (2015) 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*. 121(1): 197-215.

Kuklane K, **Lundgren K,** Gao C et al. (2015) Ebola: Improving the Design of Protective Clothing for Emergency Workers Allows Them to Better Cope with Heat Stress and Help Contain the Epidemic. *Annals of Occupational Hygiene*. 59 (2): 258-261.

Zhao M, Kuklane K, **Lundgren K,** Gao C, Wang F (2015) A Ventilated Cooling Shirt Worn at Office Work in a Hot Climate: Cool or Not? *International Journal of Occupational Safety and Ergonomics.* 21(4): 457-463.

Lundgren K and Kjellstrom T (2013) Sustainability Challenges from Climate Change and Air Conditioning Use in Urban Areas. *Sustainability*. 5(7): 3116-28.

Conference proceedings

Lundgren K (2012) Exposure to Heat and Occupational Health in a Warming World. Second Nordic International Conference on Climate Change Adaptation. Helsinki, Finland.

Lundgren K and Holmer I (2013) Climate Change and Occupational Health – Populations Exposed and the Sustainability of Methods to Avoid Excessive Heat in Workplaces. International Conference on Environmental Ergonomics. Queenstown, New Zealand.

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

Kuklane K, **Lundgren K,** Kjellström T, Venugopal V, Fan J, Havenith G (2014) Insulation of Traditional Indian Clothing: Estimation of Climate Change Impact on Productivity from PHS (Predicted Heat Strain) Model. Achieving Sustainable Construction Health and Safety. Lund, Sweden.

Hodder S, Au Y, Fan Y, Kuklane K, Loveday D, **Lundgren K,** Ouzzahra Y, Havenith G (2014) The Development of a Non-western Clothing Database. Ambience14 &

10I3M, Scientific Conference for Smart and Functional Textiles, Well-Being, Thermal Comfort in Clothing, Design, Thermal Manikins and Modelling. Tampere, Finland.

Lundgren K, Kuklane K, Fan J, Havenith G (2014) Clothing Insulation and Thermal Comfort in Africa: Current Standards and Applicability. Ambience14 & 10I3M, Scientific Conference for Smart and Functional Textiles, Well-Being, Thermal Comfort in Clothing, Design, Thermal Manikins and Modelling. Tampere, Finland.

Kuklane K, Dahlqvist C, **Lundgren K,** Lucas RAI, Halder A, Gao C, Jakobsson K, Hansson G-Å (2015) Assessment of Workload in the Heat: An Approach with Accelerometers. International Symposium on Firefighters and Heat Strain. Seoul, South Korea.

Lundgren K, Kuklane K, Jakobsson K, Gao C, Dahl M, Graner S, Linninge C, Dahlqvist C, Halder A (2015) What is the Role of Traditional Fermented Foods to Prevent Heat Stress at Work? International Conference on Occupational Health. Seoul, South Korea.

Lundgren-Kownacki K, Samuels M, Goosh P, Dabieh M, Venugopal V (2015) India Livelihood Case Study: Physiological and Social Hardship Faced by Brick Kiln Migrant Labourers from Increasing Heat. RE-DO Sustainability Conference. Aarhus, Denmark.

Lundgren-Kownacki K, Martinez N, Johansson B, Psikuta A, Annaheim S, Kuklane K (2016) Human Responses in Heat – Comparison of the Predicted Heat Strain and the Fiala Multi-node Model for a Case of Intermittent Work. 11th International Meeting on Thermal Manikin and Modelling. Suzhou, China.

Symbols and abbreviations

BMI	Body mass index (kg·m^{-2})
clo	Unit for clothing insulation (1 clo = 0.155 m^2·K·W^{-1})
f_{cl}	Clothing area factor (ISO 9920:2007)
HR	Heart rate (b·min^{-1})
I_{cl}	Intrinsic clothing insulation (m^2·K·W^{-1}) (ISO 9920:2007)
I_{tot}	Total clothing insulation (m^2·K·W^{-1})
$I_{tot,r}$	Resultant total clothing insulation (m^2·K·W^{-1})
I_a	Air layer insulation surrounding manikin (m^2·K·W^{-1})
i_m	Woodcock moisture permeability index (m^2·Pa·W^{-1}) (Woodcock, 1962)
L	Lewis relation (0.0165 °C·Pa^{-1})
M	Metabolic rate (W·m^{-2})
PHS	Predicted Heat Strain model (ISO 7933:2001)
RCP	Reference Concentration Pathway for Climate Change (IPCC, 2013)
$R_{e,T}$	Total evaporative resistance (m^2·kPa·W^{-1}) (ISO 9920:2007)
T_{rec}	Rectal (core) temperature (°C)
T_{sk}	Mean skin temperature (°C)
T_b	Mean body temperature (°C)
T_{nw}	Natural wet bulb temperature (°C)
T_g	Globe temperature (°C)
T_a	Air temperature (°C)
UHI	Urban Heat Island
VO_2	Oxygen uptake (l·min^{-1})
WBGT	Wet Bulb Globe Temperature (°C) (ISO 7243:2017)

Definitions

Acclimatization: the state resulting from a physiological adaptation process that increases the tolerance of an individual when he or she has been exposed to a hot environment for a sufficient period of time (ISO 7243:2017).

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).

Air temperature: dry-bulb temperature of the air surrounding the occupant (ISO 13731:2001).

Air velocity: average velocity of the air, i.e. the magnitude of the air velocity vector of the flow at the measuring point considered over an interval of time (measuring period) (ISO 13731:2001).

Climate change: a change in the state of the climate that can be identified by changes in the mean and/or the variability of its properties, and that persists for an extended period, typically decades or longer (IPCC, 2013).

Clothing insulation (basic): is the resistance of a uniform layer of insulation covering the entire body (ISO 13731:2001).

Core temperature: mean temperature of the thermal core of the body (ISO 13731: 2001).

Dew-point temperature: temperature at which moist air becomes saturated (100 % relative humidity) with water vapour when cooled at constant pressure (ISO 13731:2001).

Globe temperature: temperature indicated by a temperature sensor placed in the centre of a globe having standard characteristics (ISO 13731:2001).

Heat strain: the human thermoregulatory system's response to heat stress causing strain on the body, with risks of developing heat illness (Parsons, 2014).

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, 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).

Heart rate: number of heartbeats observed per one-minute time interval (ISO 13731:2001).

Interdisciplinary: problem-specific integration of knowledge and methods. Integration refers to scientific questions at the interface of different disciplines (Jahn et al., 2012).

Local skin temperature: skin temperature measured at a specific point of the body surface (ISO 13731:2001).

Mean skin temperature: sum of the products of the area of each regional surface element and its mean temperature divided by the total body surface area (ISO 13731:2001).

Metabolic rate: rate of transformation of chemical energy into heat and mechanical work by aerobic and anaerobic metabolic activities within an organism, usually expressed in terms of unit area of the total body surfaces (ISO 13731:2001).

Multidisciplinary: features several academic disciplines in a thematically based investigation with multiple goals (Stock and Burton, 2011).

Natural wet-bulb temperature: temperature indicated by a sensor covered with a wetted wick which is naturally ventilated (ISO 13731:2001).

Oxygen consumption: rate at which the lungs take up oxygen (ISO 13731:2001).

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

Rectal temperature: temperature measured by a transducer inserted in the rectum at least 100 mm past the edge of the anus (ISO 13731:2001).

Relative humidity (RH): ratio ($\times$ 100) of the partial pressure of water vapour in the air to the water vapour-saturation pressure at the same temperature and the same total pressure (ISO 13731:2001).

Transdisciplinary: is an extension of interdisciplinary research. Integration refers to the interface of scientific questions and societal problems (Jahn et al., 2012).

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

Introduction

Background

The climate science community is convinced that climate change will cause increasing heat exposure globally and there are several scientific indications that it is going to become the next big societal and scientific challenge (WMO, 2017; IPCC, 2013, 2014; Rummukainen, 2012, 2013, among others). Since the pre-industrial era, the global mean temperature has risen by almost one degree Celsius, mainly due to greenhouse gas emissions. The latest report from the Intergovernmental Panel on Climate Change (IPCC) titled "Climate Change 2013: The Physical Science Basis" (IPCC, 2013), states that not only has the average temperature risen, but there has also been an increase in the number of warm days and nights. To date, the warmest year since the measurements began in 1880 was recorded in 2014, and was exceeded in 2015 and 2016 (NOAA, 2017). Extreme weather and climate conditions have continued to be measured and reported in 2017 (WMO, 2017). Since the start of the research presented in this thesis in 2012, several heat waves have swept across the world, increasing mortality rates and causing health problems (e.g. NOAA, 2015; BBC, 2015; The Guardian, 2015; Australian Government Bureau of Meteorology, 2013; BBC, 2013a; BBC, 2013b; BBC, 2012).

Increasing heat has already had notable social and economic impacts (Hansen and Sato, 2016). For example, Mora et al. (2017) found that around 30 % of the world's population is currently exposed to extreme heat for at least 20 days every year. By 2100, this percentage is projected to increase to ~48 % under a low emissions scenario and ~74 % under a high emissions scenario (Mora et al., 2017). Forzieri et al. (2017) analysed the risk of mortality on the European population and concluded that weather-related disasters could affect two-thirds of the population annually by 2100 and cause 50 times more deaths compared with today (Forzieri et al., 2017). If the warming continues unabated, regions of the world will become uninhabitable, for example, in the Middle East (Hansen and Sato, 2016).

The range of impacts on society from increasing heat levels is wide, from those that affect students' learning abilities (Sheffield and Landrigan, 2010) to psychological outcomes resulting in aggression and riots caused, in part, by the disruption of cultural norms and traditions (Hsiang et al., 2013; Klinenberg, 2002). The effects of increasing

heat levels alone would be taxing on a society that existed in an unaltered environment, but the anthropogenic nature of the world we live in is exacerbating the impacts even more. For example, continuing urbanization exacerbates the negative impacts of increasing heat worldwide (UN DESA Population Division, 2014). Urban areas create urban heat islands due to their physical features and the activities taking place, which further increase the local temperature compared to that of the surroundings (Oke, 1982). Furthermore, the social context also worsens heat exposure, an example being living in sub-standard housing with poor roofing and little green surroundings (Harlan et al., 2006).

The societal impacts of increasing heat generate new research questions and a need for more collaboration between disciplines. Climate change and health studies to date have focused on epidemiology and public health (e.g. Forzieri et al., 2017; Gasparrini et al., 2015; Åström et al., 2015), as well as the identification of vulnerable groups, including young children, elderly, disabled and those on certain medications due to their altered physiology (e.g. Kjellström and Lemke, 2017; Bunker et al., 2016; Sheffield and Landrigan, 2011; Kovats and Hajat, 2008; Canouï-Poitrine et al., 2005; Gouveira et al., 2003; Klinenberg, 2002). The research presented in this thesis has studied the impacts of increasing heat globally on local occupational health. These impacts have received limited attention despite workers being a vulnerable sub-population to climate change (Gubernot et al., 2014). The occupational heat exposures may even be more hazardous than community exposures as the individual often has less control over the situation (Gubernot et al., 2014). In 2014, the Intergovernmental Panel on Climate Change's (IPCC) report on impacts, adaptation and vulnerability came to the following conclusion for the first time 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 p. 12).

Due to the current lack of research and methodological approaches, the research presented is exploratory and the methods applied are diverse. However, since the start of the research in 2012, more papers have been published in the subject area including: Kjellström et al., 2017; Kjellström et al., 2016; Kjellström, 2015; Zander et al., 2015; Dell et al., 2014; Crowe, 2014; Lucas et al., 2014; Dunne et al., 2013; DARA, 2013; Tawatsupa et al., 2013; Sahu et al., 2013; and Kjellström and McMichael, 2013. These papers have, among other findings, identified severe health impacts on workers but have also recognized that labour productivity decline due to increasing heat stress, is one of the costliest impacts of climate change on society.

Increasing heat and health effects

Many researchers now recognize climate change as a significant public health threat with substantial health burdens (e.g. Watts et al., 2015; Åström et al., 2013; Costello et al., 2009; Ebi et al., 2006; McMichael et al., 2004). In 2009, the Lancet Commission on Health and Climate Change identified climate change as the biggest public health threat of the 21st century (Costello et al., 2009). In 2015, the same Commission viewed climate change mitigation and adaptation efforts as the greatest public health opportunity due to the many co-benefits to health that can arise from it (Watts et al., 2015).

The link between high heat exposure and negative effects on human health and performance is well established through physiological, medical and epidemiological research where it has been made clear that high exposure to heat may decrease life expectancy (Dell et al., 2014). Examples of health impacts include heat stroke, dehydration, respiratory and cardiovascular ailments, kidney failure, thermoregulatory system failure and death (Parsons, 2014) (see more information under section 'occupational heat stress and heat strain'). High ambient temperature is a leading cause of weather-related mortality in many regions of the world (Ford and Berrang-Ford, 2011), and strong epidemiological evidence of the negative health impacts of environmental heat has been produced (e.g. Forzieri et al., 2017; Gasparrini et al., 2015; Åström et al., 2015; Anderson and Bell, 2009; Bartnett, 2007; Chesnut et al., 1998; Whitman et al., 1997). In addition, a 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 heat exchange (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 human health (Willett and Sherwood, 2012).

Impacts on labour productivity and economies

A natural reaction of a working person to heat is to reduce physical activity, which reduces the body's internal heat production. One outcome of this preventive reaction is the person's reduced hourly work capacity and economic productivity during heat exposure. The link between the climate and economic performance is thousands of years old, dating from the writings of the Ancient Greeks, to the Arab historian Ibn Khaldun's Muqaddimah in 1377, to the Enlightenment and Montesquieu's The Spirit of Laws from 1748 (Dell et al., 2014). Weather fluctuations affecting economic activities (such as agriculture, industry output, labour productivity) and heat waves are

correlated to reductions in economic growth (Dell et al., 2014). Whilst more research is needed, micro-level studies on labour productivity losses to date centre around a 2 % loss per additional degree above a baseline of 25 °C (Dell et al., 2014). Heat stress models suggest productivity may decrease by 11-27 % by 2080 in hot regions such as Asia and the Caribbean (Kjellström et al., 2009), and globally by up to 20 % in hot months by 2050 (Dunne et al., 2013).

Thermophysiological 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). It has been found that worker performance is impacted at moderate elevations in core temperature during cognitive tasks (Simmons, 2008). There are also specific effects of dehydration on cognitive performance, when 2 % or more of body weight is lost (Kenefick and Sawka, 2007; Lieberman, 2007; Granjean and Grandjean, 2007; Chia et al., 2005; Hancock and Vasmatzidis, 2003; Brake and Bates, 2003). Heat stress impairs mental function and alertness (loss of concentration), but also physical performance including muscle fatigue (Hunter, 2002; Razmjou, 1996), aerobic capacity (Cheuvront et al., 2010), manual dexterity (Meese, 1984), psychomotor proficiency (Ramsey, 1995) and finally, affects the work rate (Nybo, 2008). Thermal comfort studies estimate that in workplaces that maintain the population-average neutral temperature of between 20-24 °C, there is approximately a 7 % increase in productivity (Wyon, 2004; Fisk, 2000).

Reduced productivity is especially affecting workers who carry out heavy physical labour outdoors because their work creates major intra-body heat together with exposure to high solar radiation (Kovats and Hajat, 2008). Outdoor physical work is often the occupation of poor people, bringing in an inequality dimension (Kjellstrom et al., 2009).

Occupational heat stress and heat strain

Research on occupational heat exposure has historically been a military concern (Hanna et al., 2011) and the physiological basis for the effects of heat on humans is well understood (e.g. Parsons, 2014; Hales and Richard, 1987; Ramsey et al., 1983; Fernandez, 1980; Budd, 1974; Bell and Watts, 1971; Schrier et al., 1970; Leithead and Lind, 1964; Hellon et al., 1956; Ladell, 1955; Weiner and Van Heyningen, 1952; Burton, 1933). Human heat tolerance is the result of a series of physiological adaptations that are genetically encoded. Humans are born with a highly specialized thermoregulatory system including sweat glands, vasomotor functions, thermoreceptors, thermoeffectors and sensitive body core temperature control. On the other hand, factors such as pre-existing disease, medications, clothing, age, gender, pregnancy, infections, heat acclimatization, level of physical fitness and body size, body

mass index (BMI), and body composition can influence this system and induce or reverse health impacts (Kjellström and Lemke, 2017; Parsons, 2014).

Above an ambient temperature of about 35 °C, people undertaking heavy manual labour are likely to experience heat stress (Parsons, 2014). When the ambient temperature reaches or exceeds the human core temperature of 37 °C, there are well-documented acute physiological effects on the human body, posing risks to health (Bennett and McMichael, 2010). After a core temperature increase of about 0.2-0.3 degrees, skin blood flow increases and sweating is initiated (Gagge and Gonzales, 1996). At core temperatures between 38-39 °C, there is an increased risk of heat exhaustion and beyond 39 °C, heat stroke can occur with a consequent failure of the thermoregulatory system. At core temperatures beyond 42 °C, death can occur (Jay and Kenny, 2010). Health consequences range from dehydration, injuries and heat fatigue, to a higher burden of respiratory and cardiovascular ailments, kidney failure and weakening of the immune system (Parsons, 2014). There are also chronic effects of continuous heat exposure combined with physical labour; however, there is not much research on the topic. For example, a chronic kidney disease (CKD) epidemic has spread among agricultural workers in many Central American countries with hot and humid climates (Wesseling et al., 2016; Garcia-Trabaino et al., 2015). The workers are healthy, young, normotensive and lean; however, they have been exposed to repeated daily dehydration and hard physical labour, which may constitute a major causal factor (Wesseling et al., 2016; Garcia-Trabaino et al., 2015).

There are also indirect effects of heat exposure, including increased accident risk and adverse impacts on worker behaviour (Park et al., 2009; Ramsey, 1995). It can induce irritation and anger, leading to spontaneous acts by people working in hazardous occupations (Gubernot et al., 2014).

A heat stress evaluation at a workplace involves three major components: the environmental heat, the physical activity (or metabolic heat production), and clothing (Parsons, 2014; Epstein and Moran, 2006). The environmental heat has four major thermal climate parameters: air temperature, radiant temperature, humidity, and air movement (Parsons, 2014; Epstein and Moran, 2006). Radiation emerges primarily from the sun in outdoor work situations, but can also come from workplace specific sources, such as furnaces in steel mills. Furthermore, surface temperatures interact with the human body by radiation but also by direct contact with surfaces. This means that in those situations, one has to take into consideration heat exchange by means of conduction (ISO 13732-1:2006). The thermal assessment techniques applied in this research are based on the body heat balance equation by which the balance between body heat production and body heat exchange with the environment can be calculated. The human body is in heat balance when the metabolic heat production and the heat loss to the environment are equal and result in no change in the body's heat content (S=0). If the heat storage is positive, the core temperature will increase and vice versa.

The body heat balance equation is as follows:

$$S = (M - W) - (H_{res} + E + R + C + K)$$ (Parsons, 2014)

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, 2014). 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). This heat exchange is affected by climate factors, clothing thermal insulation and evaporative resistance, and by the body's metabolic rate (Kuklane and Gao, 2017). Clothing affects the transfer of heat from and to the body through resistance to air movement, dry heat exchange and sweat evaporation (Holmér, 2006). The largest source of heat results from metabolic heat production, which adds to heat stress in hot environments (Parsons, 2014). Acclimatization, hydration status, body posture among 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. It commonly occurs after 7-14 days of at least two hours daily heat exposure (NIOSH, 2013). The evaporation of sweat is extremely effective and therefore becomes more and more critical with increasing environmental temperature. Given the importance of sweat evaporation, 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 (Parsons, 2014).

Summary and organization of the thesis

The focus of this thesis research is on the impact of increasing heat due to climate change on occupational health. The aim is to develop further understanding, through literature reviews and empirical data collection from case studies and an experimental climatic chamber study. The research examines the implications for labour productivity and health in workplaces in Chennai, India, representing a hot and humid climate. It also investigates site-specific sustainable solutions, including low-tech ones such as clothing, diet and hydration practices in combination with socio-cultural solutions. The research process has been exploratory, mixing methods such as literature reviews, case studies, thermophysiological experimental techniques and models, and working across disciplines. This is a compilation thesis consisting of a comprehensive summary of six chapters and a set of five appended papers. The first chapter provides an overview of the research problem. The second chapter presents the aims, objectives and guiding concepts. The third chapter introduces the case study area and workplaces studied. The fourth chapter introduces the research methods. The fifth chapter presents and discusses the main results from the five appended papers. It also reflects on the exploratory approach of the research studies conducted and discusses limitations in the research. Finally, the sixth chapter draws conclusions from the research and offers suggestions for further research needs.

Aim, Objectives and Guiding Concepts

Aim and objectives

The main driver for the research is the knowledge gap concerning the impacts of increasing heat caused by global climate change on local occupational safety and health. A deductive approach was taken with the underlying hypothesis: Occupational heat stress has negative effects on workers' health and productivity. Climate change will worsen the situation. The aim is to identify impacts, evaluate assessment tools and explore solutions to the effects of increasing heat at different workplaces. Subsequently, the research has four objectives:

1. To identify gaps in the existing knowledge of occupational heat stress and its links with a changing climate (*Papers I, II, V*).

2. To carry out a field study in workplaces situated in already hot areas of the world, namely in Chennai, India, in order to assess the current and future impacts of increasing local heat due to climate change (*Papers II and V*).

3. To evaluate the current standard assessment tools for hot environments (*Papers II, III*).

4. To investigate site-specific sustainable solutions to increasing heat, including technical, managerial and socio-cultural solutions (*Papers II, IV, V*).

To achieve the first objective, a literature review was conducted (*Paper I*). Scholarly information was collected from a variety of sources because climate change and occupational health is a highly interdisciplinary field of study.

To achieve the second objective, a case study was conducted in Chennai, India. It involved quantitative measurements of heat stress, workload estimations, and laboratory testing on thermal manikins of the work clothing, together with workplace questionnaire information on health impacts, productivity loss and impacts on daily lives (*Paper II and V*). Heat strain and associated impacts on labour productivity between the seasons were assessed using the International Standard ISO 7933:2004a), which applies the Predicted Heat Strain (PHS) model.

To achieve the third objective, all five papers but the initial literature review applied tools for assessing work in hot environments in various ways. However, *Paper III* specifically compared two mathematical models of human thermal regulation: the Predicted Heat Strain (PHS) model and the Fiala thermophysiological model. The aim of the study was to compare and analyse predictions of the two models against experimental data from the climatic chamber. *Paper II* specifically discusses the applicability of the PHS model for labour productivity analysis. In the initial stage of the research, four pre-studies were conducted involving various comparisons of Wet Bulb Globe Temperature (WBGT) measuring equipment. The studies mainly compared non-standard with standard equipment and incorporated aspects such as the globe diameter, shielded vs non-shielded sensors, comparisons at various air velocities and radiation, the wick-thickness impact on the natural wet bulb sensor (T_{nw}) and finally, an equipment comparison in a the hot-humid climate of Chennai. The details of these pre-studies can be found in the author's licentiate thesis (Lundgren, 2014).

To achieve the fourth objective, three separate studies were conducted (*Papers II, IV, V*) consisting of two case studies and a climatic chamber study. *Paper II* explored practices of handling heat by using a workplace questionnaire. *Paper IV* was based on the answers from the questionnaire where it was found that a fermented dairy drink, 'buttermilk', was widely consumed as a way of coping with heat strain. Consumption of similar diluted yoghurt drinks are seen in other hot regions and the aim was to investigate if buttermilk could mitigate heat as described. *Paper IV* also explored the impacts of moderate work in a hot environment on the gut microbiota, renal and cognitive functions. *Paper V* was a transdisciplinary study looking at brick kiln workers in Chennai with the aim of identifying new pathways for change and soft solutions by both reframing the problem and expanding the solution space. The case study data was largely built on a transdisciplinary literature review complemented by heat stress measurement data, workplace questionnaires, observations from brick kilns and climate forecast data.

Guiding concepts

The research process has been a journey. It started with a literature review (*Paper I*) and a case study (*Paper II*), the findings of which resulted in new research objectives. The findings from the case study were transformed into a climatic chamber study (*Paper IV*). This experimental study attracted researchers from other disciplines who were interested in impacts of moderate work in a hot environment, resulting in the study's multidisciplinary approach. The collected experimental data were incorporated to evaluate two physiological models (*Paper III*).

Furthermore, an application to the Pufendorf Institute, an interdisciplinary institute at Lund University, resulted in a theme project entitled 'HEAT – Impacts and Solutions of Increasing Heat on Humans and Ecosystems'. One result of this research collaboration was a special issue entitled 'Transdisciplinary Approaches to Climate Change' in the International Journal of Biometeorology where *Paper V* was included. Consequently, the overall research is exploratory in its approach, however, three guiding concepts were integrated into the research process, specifically, climate change adaptation, interdisciplinarity and case study research. The following sections provide more detail on how the concepts were integrated.

Climate change adaptation

The scientific theory of climate change is widely accepted and it is clear that human intervention is the major cause (IPCC, 2013). Even with the most stringent mitigation measures, climate change adaptation is necessary, or even 'unavoidable' (IPCC, 2014). Climate change adaptation was chosen as a guiding concept ahead of mitigation because the thesis hypothesis is responding to current and forthcoming climate changes. However, the importance of mitigation measures to prevent intolerable heat levels in the future were always kept in mind with the understanding that any adaptation measures have to incorporate mitigation.

Climate change adaptation is the response to climate change and the IPCC defines it as, *'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). Thus, it includes both long-term, forward-looking activities and those that address risks and hazards arising from the current climate. Adaptation is concerned with adjustments at different scales and by different actors. To date, though, our knowledge of how human societies can adapt to climatic stresses are limited (Berrang-Ford et al., 2015).

Climate change adaptation research is a challenge to conduct. This is due to the scientific uncertainty related to climate projections and associated assumptions of emissions of greenhouse gases, incomplete climate models, human development pathways and downscaling (Refsgaard et al., 2012). These uncertainties make adaptation research complex because a wide variety of factors have to be considered and a variety of methods applied. Because of the complex problems adaptation research aims to solve, it has naturally become an interdisciplinary field of research. It is also widely recognized that there are crucial barriers to adaptation (Moser and Ekstrom, 2010), partly because of the complexities and uncertainties. However, theories to explain these are still undeveloped (Eisenack and Stecker, 2011).

The investigation of site-specific sustainable solutions to the occupational impacts of increasing heat (fourth objective) consists, in particular, of research associated with the

field of climate change adaptation. Adaptation research can be aimed at changing contextual conditions or at reducing damage (Eisenack and Stecker, 2011). The research presented in this thesis primarily aims at the latter. The main 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 the action is to improve the situation rather than to enable indirect systematic change. The research also comprises planned adaptation which makes use of information about expected future conditions, promoting anticipatory rather than reactive adaptation (Moser and Ekstrom, 2010).

Interdisciplinarity

> 'Ours is a time of both ontological and epistemological revolution where almost all the problems we face nowadays are complex, interconnected, contradictory, located in an uncertain environment and embedded in landscapes that are rapidly changing' (Sardar, 2010).

Traditional within-disciplinary approaches to research have had a positive impact on the development of the scientific method. They are, however, not sufficient when it comes to real world complexity. The insight that the problems of society are complex and interdependent, and that this is an increasing trend has resulted in the need for more collaborations across disciplines (Stock and Burton, 2011). The author's view of interdisciplinary research originates from sustainability science (Thorén, 2015; Lang et al., 2012; Max-Neef, 2005) because it is paramount in order to address society's complex sustainability challenges including climate change.

Interdisciplinarity is inherently about scientific integration and problem solving or as a means of shedding new light on a problem. The combination of disciplines adds value – the total is more interesting than the sum of the individual contributions or parts (Brewer, 1999; Jantsch, 1972). One definition of interdisciplinary studies is that they are '*a process of answering a question, solving a problem, or addressing a topic that is too broad or complex to be dealt with adequately by a single discipline or profession [..] and draws on disciplinary perspectives and integrates their insights through construction of a more comprehensive perspective*' (Klein and Newell, 1997).

Interdisciplinarity requires academic researchers to collaborate across disciplinary boundaries and in this thesis research; it was a necessity when a research problem could only be solved with the help of researchers from other disciplines. The research hypothesis required the involvement of various disciplines and associated methods. Thus, the research process had occupational health, environmental ergonomics/engineering and thermophysiology at its core but included several other disciplines.

It became clear during the research process that conducting interdisciplinary research projects is a challenge that requires certain skills (Thompson Klein, 2004). This was primarily dealt with by being open to other perspectives and by simply inviting interested researchers from different fields. The author of this thesis has a varied background in environmental sciences and sustainability and was therefore familiar with interdisciplinarity and its associated challenges before conducing the doctoral research. The main challenges faced were associated with practical issues including lack of time, project frames, communication difficulties, resources, difficulties identifying quality journals in which to publish, and finally, in the structure of the different university disciplines themselves. In order to handle the mixing of methods and approaches from different disciplines methodologically, the research focused on a specific context and climate. The research primarily achieved multidisciplinarity through its collaborations when a specific knowledge or perspective was lacking. Multidisciplinarity is the least integrative yet, it is arguably the most attainable (Lyall and Fletcher, 2013). *Paper IV* was multidisciplinary and added psychology, food technology and environmental medicine to the study design. The research attempted transdisciplinarity, especially in *Paper V*, through a joint methodological analysis across disciplines by addressing the widespread and complex societal and environmental problems at brick kilns in India. The study included environmental science and engineering, architecture, human ecology, social anthropology and occupational health in its analysis. However, 'transdisciplinarity' is a contested term and there is no universal definition (Jahn et al., 2012). As a result, transdisciplinarity in *Paper V* is understood as being research that addresses the knowledge demands for societal problem solving by improving the understanding of the issue and engaging in the why and how contested practices and institutions have to be changed (Hadorn et al., 2006).

Case study research

The foundation of this research is case study research methodology. This was applied in the initial study conducted in Chennai, India and is integrated into all subsequent studies. Considering the nature of the multifaceted problem underlying the research hypothesis, a case study research methodology was deemed to be the most suitable (Flyvberg, 2001; Yin, 2003). This is because the methodology makes it possible to look more in depth, examine the research problem in action, and include multiple data sources (Bryman, 2008). Chennai was seen as a representative case that exemplified the research objectives. Chennai has a hot and humid climate and many challenges associated with occupational heat stress, which makes it a prime example for analysis. The case allows to address the existing problems and to find solutions where there is an urgent need for these. It also allows analysis and testing of available solutions that could potentially be applied in the other areas where the climate is expected to get hotter.

A case study entails a detailed and intensive analysis of a single example of a class of phenomena (Yin, 2003). The method has high ecological validity and is context dependent, which assists in structuring an analysis of increasing occupational heat stress. This is because it focuses on a specific location, which sets up research boundaries (Bryman, 2008). Further, ecological studies allow many details to be collected that would not normally be easily obtained by other research designs. The data collected is also normally richer and of greater depth. Case studies have the potential to promote ideas and produce novel hypotheses, which is also reflected in this thesis journey leading up to the last two research objectives.

There are discussions about the external validity and/or generalizability of case studies (Bryman, 2008). However, the author is of the opinion that Chennai is a critical case that captures the circumstances and conditions of an everyday situation for many workers elsewhere in India and in other countries situated in hot climates. It exemplifies a broader category of which it is a member (Yin, 2003). As a result, some of the knowledge produced could be transferred to similar contexts and climates. However, this requires a conscious reflection on the similarities and differences between contextual features and historical factors (Flyvberg, 2001). The case study is described in the next section.

Case study: Chennai, India

Occupational health in India

India is a fast growing economy and the world's largest democratic state exceeding 1.2 billion inhabitants (World Bank, 2017). Since independence in 1947, agricultural reforms have transformed the nation from dependence on grain imports into an agricultural powerhouse. Life expectancy has more than doubled, literacy rates have quadrupled, health conditions have improved, and a middle class has emerged. India is also in the middle of a massive wave of urbanization. As a result of these developments, the country is pressured to create jobs, housing, and infrastructure. At the same time, inequality is widespread and more than 400 million people still live in poverty. To meet these challenges, India has pioneered a host of new initiatives, including its 'Skill India' initiative that seeks to equip India's growing young workforce with the skills needed to compete in today's rapidly changing workplace (World Bank, 2017).

India's workforce is the largest and youngest in the world (World Bank, 2017) where 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 are numerous and 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

- lack of a coherent national policy on occupational health (Pingle, 2012).

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. Further, there is no overarching governmental department or agency that deals with occupational health under the Ministry of Labour (Pingle, 2012). As of date, India has not ratified many of the International Labour Organizations Conventions, including C155 – The Occupational Safety and Health Convention, 1981 (ILO, 2017).

Regarding the occupational heat stress situation, it is already an issue in India due to its tropical monsoonal climate. India is also experiencing a warming climate and is at a high risk of excessive heat exposure due to climate change, as it is expected to have some of the highest temperature increases (IPCC, 2013). Kjellström et al. (2017) estimate that even at the lowest pathway for climate change (RCP 2.6), there will be an increased loss of daylight work output in India from about 2 % to 8 % at the end of the century. For the mid-range pathway (RCP 6.0), the annual heat impacts will double (Kjellström et al., 2017).

Case study area description

Chennai, the capital city of Tamil Nadu, is located on the Coromandel Coast of the Bay of Bengal (Figure 1). 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. Over the years, the local government has 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). Due to its location near the equator, Chennai experiences a hot and humid climate throughout the year. The highest temperatures are recorded in the month of May, reaching 45 °C. This causes risks to local workers of developing heat illnesses. Winter occurs during the months of November to February, with January being the coolest. Temperatures are pleasant and vary from 15 °C to 22 °C. During the monsoons, from June to September, Chennai receives abundant rainfall and associated high humidity (The Chennai City Guide, 2013).

Figure 1:
Location of Chennai in India.

Description of workplaces

The workplaces surveyed were mainly fully outdoors or semi-outdoors; 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. Generally, SMEs 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 (ILO, 2013). Figure 2 illustrates the workplaces and short descriptions of them follow.

Figure 2:
Pictures of workplaces: A) outside view of cookie factory, B) food serving area of the canteen, C) drying machines at the laundry, D) agricultural field, E) roof of construction building, F) brick kiln.

A) Cookie factory

This industry is involved in the preparation of cookies with several 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 and bending. The tasks are performed in semi-outdoor conditions. In the next section, the pre-scaling area, different raw materials are received and weighed and then are sent to the mixing area. Mixing is done both manually and mechanically. The cookies are baked in the production area. The finished products are received in the packing area and the work is performed in standing positions. Finally, in the dispatch area, the packed goods are stored and materials are manually loaded into vehicles. Water access, washing and cooking facilities were freely available.

B) Canteen

The canteen is located on the Sri Ramachandra University campus, Chennai. 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 the cleaning workers. Finally, computer billing is carried out in the billing and manager sections at different counters by standing clerks. The canteen is extremely hot, with many cooking stoves with open flames. Water and a variety of drinks were widely available to all employees, however, the washing and sanitary facilities were overcrowded.

C) Laundry facility

The laundry facility at the Sri Ramachandra University campus, Chennai, serves students, faculty and the medical centre. It consists of two sections: hospital and student laundry. The hospital textile products are decontaminated before washing and are then hot pressed. The work area has few fans and little exhaust is provided. Most of the workers are women. In the hot press section, large sheets are fed into the press and the work is performed manually. In the washing section, textile products are fed into the machine and unloaded manually. After washing, the textiles are loaded onto a trolley and taken to the drying section. After drying, textiles are manually ironed with 5 kg non-insulated irons. They are then folded and packed for dispatch.

D) Agricultural site

The agricultural field is located in a village outside Chennai city where crops are cultivated according to the seasons. There are different phases in cultivation, namely: preparation of land for cultivation, sowing, watering, weed clearance, 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 combined with the use of tractors. Manual work is performed in the other phases. Workers spend a substantial part bending during planting and harvesting. There are no washing or sanitary facilities present and the workers have to bring their own water. The work is conducted in extreme heat, with high solar radiation and humidity and many workers are also malnourished, adding to the strain. Agricultural workers are mostly migrants from poorer states and are illiterate. The workers commonly have rich knowledge of traditional practices to cope with heat.

E) Construction site

The construction site is located on the Sri Ramachandra University campus, Chennai. There are different work tasks involved in construction such as intense shovelling, carrying and disposal of debris and cutting of iron bars. There are different categories of workers involved: manual labourers, masons, stonecutters, bar bending workers, painters and electricians. The amount of time spent exposed to solar radiation varies depending upon the nature of the work performed. Most of the workers are migrants from states like Bihar, Andhra Pradesh and Orissa. In addition to working in the construction site, the workers are also 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 are provided on the campus.

F) Brick kilns

Brick making is a traditional, unorganized industry based on manual labour, and can be seen scattered in the landscape of the peri-urban areas of Chennai. The main work tasks include material procurement, tempering, moulding, drying, firing and sorting. Brick production is seasonal as the brick kilns do not operate during the rainy season. Hence, most of the workers migrate. Families, including young children, work under harsh, low paying conditions, commonly compensated as pieceworkers. As a workplace, brick kilns are sites of high levels of heat stress due to the limited cooling options available as well as the heat that is radiated from the brick kiln furnaces. There is typically a lack of basic facilities, such as access to clean drinking water and sanitation. Health impacts mainly originate from breathing in smoke and physically demanding outdoor work causing heat strain and other illnesses such as pneumonia and respiratory infections (Pingle, 2012).

Materials and methods

The research presented in this thesis applied a wide array of research techniques, mixed primary and secondary data, and qualitative and quantitative methods. Due to the mixing of methods, the research faced many challenges and associated limitations. The methods and limitations are discussed in this section.

Literature reviews

The literature review method was applied in both *Paper I and V*. To identify previous research and further research needs, the literature review method was used for the study presented in *Paper I*. The aim was to identify what is already known in the research area and connected fields, and to identify knowledge gaps (Bryman, 2008). That is why the 'pearl picking' review method was initially applied. This method uses one exceptionally useful article (often a review article) to track key articles in the field. A thorough exploration of different databases and search engines (*PubMed*; Lund University's search engine *Summons, Scopus; Google Scholar; Web of Science; Science Citation Index*) was then carried out using a selection of search terms such as 'occupational heat exposure/stress/strain' AND 'climate change', 'heat in/at workplace' and so on.

In *Paper V*, a transdisciplinary literature review method was used to add a detailed and intensive analysis to the specific case. It used different databases and search engines to find key articles in the connected disciplines. It also used specific questions or location to collect relevant papers because this provides the opportunity to synthesize the material in a systematic way. In hindsight, it was a good method to apply to a multi-dimensional problem as it enables the identification of knowledge gaps and the gaining of new insights. It also assisted in the development of a conceptual framework for the research and for finding links between disciplines.

Case studies

In both *Papers II and V*, a case study methodology was applied using a mixed method approach of qualitative and quantitative methods. Considering the respective research questions in both papers, the methodology was found suitable (Flyvberg, 2001; Yin, 2003). The case study data collection for *Paper II* included quantitative measurements of heat stress, workload estimations, and clothing testing combined with information on health impacts, productivity loss, etc., from a questionnaire. Heat strain and associated indirect impacts on labour productivity between the seasons were assessed using the International Standard ISO 7933:2004a, which applies the Predicted Heat Strain (PHS) model.

The case study analysis in *Paper V* used a holistic approach looking at the brick kiln workers' situation from different disciplinary viewpoints. Migrant brick kiln workers in India face heat risks from multiple causes that require a interdisciplinary analysis. The existing literature was reviewed through a critical discourse analysis lens, taking into account the health and environmental risks faced by the people working at the brick kilns. The literature review was complemented with quantitative measurements of heat stress, workload estimations, and clothing testing. Climate forecast data were generated from climate modelling tools, specifically the ClimateCHIP / HOTHAPS Soft toolset (Climate CHIP, 2016). The critical discourse analysis was then directed into a modified framing analysis (Wise et al., 2014; Jerneck and Olsson, 2011; Fletcher, 2009) (see *Paper V* for details) with the aim of uncovering ways of providing locally appropriate solutions.

Human thermal environments – assessment techniques

The assessments of the workplaces' thermal environments in *Papers II and V* were conducted in accordance with International Labour Organization's (ILO) Code of Practice on Ambient Factors at the Workplace, in particular, section 8.2.4. stating that, '*measurements of thermal conditions should take account of: (a) all stages of work cycles and the range of temperature and humidity under which the tasks are performed; (b) the range of clothing worn during the tasks; (c) major changes in physical activity level (metabolic heat production)*' (ILO 2001). The measurement techniques recommended by the ILO are also aligned with the international standards set by the International Organization for Standardization (ISO) for the assessment and monitoring of the thermal environment.

Generally, the advantages of thermal assessment techniques are their reliability and usability, which enhance repeatability of the studies and internal validity. The first phase of assessing the thermal environment according to ILO and ISO is deterministic

through simple measurements of the environmental parameters. Here, the Wet Bulb Globe Temperature (WBGT) limit values determine a boundary for when actions need to be taken. However, the following two phases, the clothing worn and the physical activity level, have limitations associated with individual factors that are flexible. Limiting factors include difficulties in accounting for individual variations, inter-linkages with other impacting factors, and aspects including personal thermal history (Chapells, 2005) and socio-economic status (Harlan et al., 2006). Limitations also include a lack of external validity, one being that physiological databases are mainly based on climatic chamber studies. More details on the WBGT index will follow in the next section.

Environmental parameters and the WBGT index

A heat stress index is a single number that integrates the effects of the basic parameters in any human thermal environment such that variations in thermal conditions will affect its value. Heat stress indices give an indication of the heat exposure and can for example be used to establish safe limits for work. 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 environmental variables (Epstein and Moran, 2006; Havenith and Fiala, 2016). Commonly used heat stress indices are simple to use and the associated field equipment is not expensive. The Wet Bulb Globe Temperature (WBGT) (ISO 7243:2017) is a widespread index and was used in the research presented in *Papers II and V*. It is a direct index of heat stress that incorporates environmental temperature, humidity, wind speed and heat radiation (Havenith and Fiala, 2016). The WBGT index was developed during the 1950's by the US military to control serious outbreaks of heat illness in training camps and is a convenient and comprehensive index (Cook, 1955; Schickele, 1947). 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 7243:2017). The standard was updated in 2017, after the completion of the research in this thesis. Therefore, the new modifications discussed later in this section were not included.

WBGT equations:

Without solar radiation (indoors and outdoors without solar load):

WBGT = 0.7 T_{nw} + 0.3 T_g

Outdoors with solar radiation:

WBGT = 0.7 T_{nw} + 0.2 T_g + 0.1 T_a (ISO 7243:2017)

Figure 3 shows a typical modified field instrument for measuring WBGT by Quest Technologies (3M) that was used in the case studies. It has a 5 cm diameter globe for a faster response time whilst the standard WBGT index is based on the response of a 15 cm diameter globe (ISO 7243:2017). The use of a smaller globe result in larger convection coefficients and hence a different reading. This is because small globes equilibrate more rapidly than the standard globe and is therefore more sensitive to fluctuations (Budd, 2008). Some authors argue that the smaller globe is a reasonable approximation of the standard size as the globe plays a small role in the determination of outdoor WBGT (Bernard and Barrow, 2013). To deal with this limitation, Quest Technologies (3M) performed an independent evaluation and developed a method to calculate the values from the 5 cm globe to that of the standard globe of 15 cm (Bernard and Barrow, 2013). This method was used in this thesis.

Figure 3:
QUESTemp WBGT meter by Quest Technologies (3M).

Determining the WBGT threshold for the need for actions to protect workers depends on acclimatization status, the intensity of the work and the clothing worn (ISO 7243:2017). Here, the index has some limitations and there are those who criticize its global use. For example, the index only directly evaluates the environmental parameters and incorporates personal factors such as acclimatization and metabolic rate by indirect estimations from tables (Havenith and Fiala, 2016). Firstly, the error margin for estimation of the metabolic rate can be up to 50 % (Parsons, 2014). Secondly, it fails to incorporate situations where evaporation is restricted, that being by clothing, high humidity or low wind speed (Budd, 2008). Thirdly, it responds inadequately to humidity due to the constant weighing of 0.7 for T_{nw}, which is excessive in low temperatures and inadequate in high temperatures. Consequently, some researchers propose two sets of WBGT; one for hot-humid and one for hot-dry conditions (Budd, 2008). Fourthly, the index also responds inadequately to wind due to the unreliable cooling of T_{nw} and T_g (Budd, 2008). Due to these limitations, the WBGT index is best used as a general guide or for an initial screening.

Some authors argue for a more simplified threshold system than the WBGT index to facilitate a more effective response directly at the workplace (Rowlinson et al., 2014). Rowlinson et al. (2014) advocate for the development of local action-triggers to reflect the unique climatic conditions, working practices and acclimatization statuses in the specific geographic region (Rowlinson et al., 2014). Furthermore, all existing heat indices assume an average or standard person who is unmedicated, trained and healthy which is not representable in real-world workplaces. Here, Jay and Kenny (2010) argue for the need to develop an improved individualized heat stress risk assessment tool (Jay and Kenny, 2010).

As discussed above, to achieve a comprehensive heat stress evaluation, knowledge of the local conditions, the role clothing plays as well as of the environment and work demands is vital, which adds complexity. The ISO 7243 standard was updated in 2017 to meet some of these shortcomings and now includes the possibility to add clothing adjustments with the Clothing Adjustment Value [CAV] and effective WBGT [$WBGT_{eff}$] (ISO 7243:2017). Further, Sakoi et al. (2017) has proposed a widened [$WBGT_{eff}$*] to include vapour impermeable clothing (Sakoi et al., 2017). The US National Institute for Occupational Safety and Health (NIOSH) has also established 'no work at all' WBGT levels (NIOSH, 2016). Table 1 presents the recommended maximum WBGT exposure levels for the average worker based on the updated ISO standard.

Table 1:
Recommended WBGT$_{eff}$ reference values for acclimatized and unacclimatized people for five classes of metabolic rate (ISO 7243:2017).

Metabolic rate (class)	Metabolic rate (W)	WBGT reference limit for person acclimatized to heat (°C)	WBGT reference limit for person unacclimatized to heat (°C)
Class 0 Resting metabolic rate	115	33	32
Class 1 Low metabolic rate	180	30	29
Class 2 Moderate metabolic rate	300	28	26
Class 3 High metabolic rate	415	26	23
Class 4 Very high metabolic rate	520	25	20

The analyses in *Papers II and V* complemented the WBGT index by adding clothing data from thermal manikin testing (Havenith et al., 2015). Metabolic rate was estimated from tables but also complemented with calculations from heart rate data (ISO 8996:2004b) (*Paper II*) or from high validity measurements of oxygen uptake of work task simulations in the climatic chamber (*Paper V*).

Clothing – measurements on thermal manikins

Thermal manikins are heated to represent the human body and the power to maintain that temperature is used to estimate the heat transfer between a person and the environment. If a manikin is clothed in controlled conditions, the thermal properties of the clothing can be derived. Moving and sweating manikins extend the breadth of measurements that can be made to include evaporative resistance and ventilation potential (Parsons, 2014).

Thermal manikins add more accurate data on clothing properties than estimations from tables in the evaluation of body heat balance or heat exchange. They are now routinely used in the development of clothing, for example. Manikins provide a realistic whole body and local heat exchange simulation that enhances the external and internal validity of a heat exposure analysis in a workplace. It is a quick, accurate and repeatable objective method (Parsons, 2014) applicable to local level, in-depth heat stress assessments that can be a part of a broader analysis of increasing heat. However, operating a manikin is expensive and not always possible.

In the research presented in *Paper II*, the work clothing from Chennai was tested for insulation and evaporative resistance on thermal manikins according to the ISO 15831:2004c standard at Lund University in Sweden, Loughborough University, UK and Hong Kong Polytechnic University as part of a connected research project

(Havenith et al., 2015). Each laboratory used different thermal manikins. The dry thermal insulation was determined in Loughborough and Lund. Dry and evaporative resistances were determined in Hong Kong. In Lund, the walking male-shaped thermal manikin *Tore* was used to study posture and motion effects. *Tore* is made of plastic with a metal frame inside to support the body parts and joints. *Tore* is divided into 17 individually controlled zones: head, chest, back, stomach, buttocks, left and right upper arm, left and right lower arm, left and right hand, left and right thigh, left and right leg, and left and right foot. The surface temperature of the manikin's zones was controlled at 34 °C and air temperature in the chamber was set to 22.2 °C ± 0.1 °C. The temperatures and heat losses were recorded. The thermal manikin *Tore* can be seen in the tested work clothing ensembles from Chennai in Figure 4. Female clothing consisted of two sets of traditional clothes (saree and churidar) with or without protective shirt and towel on the head. Male clothing consisted of a shirt and trousers with a towel on the head.

Figure 4:
The thermal manikin *Tore* in the tested work clothing ensembles at the Thermal Environment Laboratory, Lund University (Photos by Kalev Kuklane).

Generally, the thermal behaviour of clothing is dynamic and difficult to quantify. Factors affecting the thermal behaviour of clothing include dry thermal insulation, transfer of moisture and vapour, heat exchange, compression, pumping effects, air penetration, worker posture, and so on. Firstly, the dry insulation is of fundamental importance and can be calculated from a measure of heat flow and temperature. When measuring the Indian work clothes, the total thermal insulation (I_{tot}) ($m^2 \times K \times W^{-1}$) was determined as follows:

$$I_{tot} = \frac{T_{sk} - T_a}{\text{Dry heat loss}}$$

The intrinsic clothing insulation (I_{cl}) describes the property of the clothing itself: resistance to heat transfer by conduction (which depends on surface area), temperature gradient, and thermal conductivity. The intrinsic clothing insulation (I_{cl}) ($m^2 \times K \times W^{-1}$) was determined from the total thermal insulation (I_{tot}), the air layer insulation (I_a) and clothing area factor (f_{cl}):

$$I_{cl} \ = \ I_{tot} \ - \ \frac{I_a}{f_{cl}}$$

1 clo equals a typical business suit to keep a sedentary person comfortable (1 clo = 0.155 $m^2 \times K \times W^{-1}$). The clothing area factor (f_{cl}) is the ratio of clothed area to nude body surface area. It was calculated through the comparison of photographs of clothed and nude manikins. Pictures were taken at a 0° and 90° angles, and the surface areas calculated in Adobe Photoshop using the ratio between clothed and nude projection areas.

In addition, when vapour reaches the clothing surface it transfers to the environment at a rate depending upon the evaporative heat transfer coefficient. The vapour permeability index used in this study was the Woodcock moisture permeability index (i_m), which corresponds to the ratio between the total dry insulation (I_{tot}) and evaporative clothing heat resistance $(R_{e,T})$ for a clothing ensemble, divided by the Lewis constant (Woodcock, 1962). This index was chosen as it makes it easier to compare garments. The observed values for $R_{e,T}$ and I_{tot} were used to calculate the clothing vapour permeability index i_m:

$$i_m \ = \ \frac{I_{tot}}{L \times R_{e,T}}$$

where L = Lewis constant = 0.0165 °C·Pa^{-1}

For further details on the specific study methods, please see Havenith G, et al. (2015) and ISO 9920:2009 and Parsons (2014) for more information on estimation of clothing properties.

Estimations of work intensity in the field

Estimating and gaining an accurate representation of the work intensity over an average working day is a difficult task in workplaces where it is not possible to measure oxygen consumption. Here, estimations from heart rate are seen as the most accurate. In the case study in *Papers II and V*, work activity was calculated from heart rate conversion to metabolic rate according to ISO 8996:2004b. Heart rate was measured using POLAR pulse monitors (Käyttö 4000 RUD 11.93 STK model, with readings every 15 seconds).

The measurement of heart rate with pulse belts to estimate work intensity is a practical and common method in a field setting rather than measuring oxygen consumption with facemasks. The pulse belt is easy to use and relatively inexpensive. Unfortunately, the method relies on several assumptions about the linear relationship between heart rate and oxygen uptake (VO$_2$) at submaximal intensities (Astrand and Rodahl, 1986) and results can deviate up to 20 % from the true value (Spurr et al., 1988). Heart rate recordings are also affected by factors such as physical fitness, daily variations,

environmental temperature, altitude, nutrition, level of dehydration, health status, age, psychological factors and size of active muscle mass. All of these add complexity (Parsons, 2014; Achten and Jeukendrup, 2003; Spurr et al., 1988). For example, Sidery and Macdonald (1994) found that the heart rate increased by 5-10 bpm after food intake and the effect lasted for about 2 hours (Sidery and Macdonald, 1994). One specific problematic aspect in this context is the impact of environmental temperature. Many studies have shown that the heart rate can increase by around 10-40 beats per minute (e.g. Wingo, 2015; Kuklane et al., 2015; Lee et al., 2014; Achten and Jeukendrup, 2003). On the other hand, the review by Achten and Jeukendrup (2003) argue that the method provides a satisfactory estimate of energy expenditure on a group level in the field (Achten and Jeukendrup, 2003).

The main uncertainty from the field heart rate measurements is the limited duration (between 3-6 hours) and how representative they are of the complete workday. Moreover, it was not possible to measure heart rate on a number of workers, especially female workers due to cultural barriers associated with intimacy. As a result, metabolic rate calculations from heart rate were complimented by observations and estimations from tables according to the ISO 8996:2004b standard. This method assigns a metabolic rate value to each observed activity and calculates a time-weighted average. This is associated with a plenitude of uncertainties, including the validity of the definition of the various activities (Malchaire et al., 2017). However, despite the large uncertainties, the methods chosen are the most reliable to date in field settings. Further, in *Paper V,* measurements from 114 brick kiln workers were complemented with sweat rate measurements and climatic chamber simulations, adding accuracy to that specific workplace work intensity estimation.

Climatic chamber studies
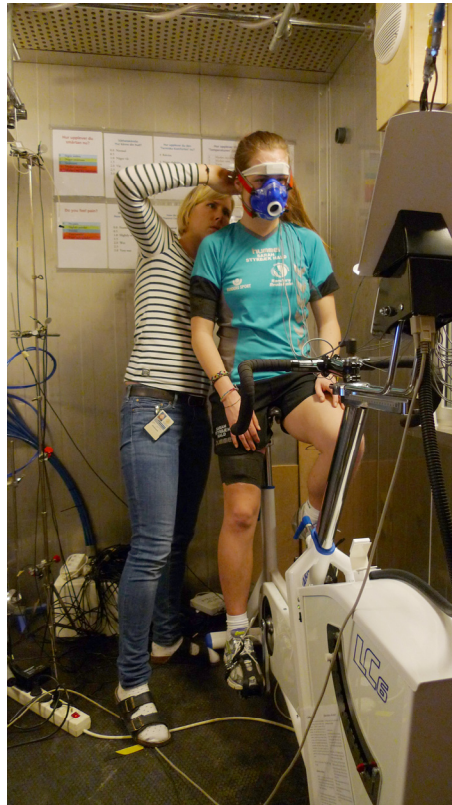
Figure 5.
A test subject (before commencement of the study) in the climatic chamber used for the experimental study (*Paper IV*) at the Thermal Environment Laboratory, Lund University, Sweden (Photo by Erik Andersson).

Chamber studies are deterministic stimulus-response experiments. The subject is regarded as a passive recipient of the thermal stimuli presented by his or her environment. A multidisciplinary experimental study was conducted in the climatic chamber at the Thermal Environment Laboratory at Lund University (see Figure 5) and the results are presented in *Paper IV*. In contrast to the case studies, the climatic chamber experiment was designed to provide far greater control over the exposure settings, such as the key environmental parameters (Bryman, 2008). A climatic chamber experimental design provides a researcher with the ability to analyse specific exposures and responses in a controlled environment. This enhances repeatability and has strong internal validity (Bryman, 2008). It also incorporates the ability to make simulations of future conditions and exposures. The experimental design can be combined with other research methods for rigour, can provide greater transferability

and can be used to determine what is best for the exposed population. However, it does lack ecological validity as it does not correspond to the real world context (Bryman, 2008). For example, climatic chambers cannot simulate the real world weather fluctuations in for example solar radiation and wind speed (Rowlinson and YunyanJia, 2014). Climatic chamber studies can further produce artificial results and may only apply to the specific setting, which is difficult to replicate. Experiments are often time consuming, which makes studying a large number of subjects difficult (in this study 12 subjects were included), and which causes large confidence intervals and difficulties in generalizing.

The results from the case study in Chennai provided the background to the chamber study. The questionnaire survey found that a diluted dairy drink, 'buttermilk', was widely consumed among workers in all the workplaces studied as a traditional way of mitigating heat strain (between 67-100 % of the workers in the workplaces surveyed). Consumption of similar diluted yoghurt drinks are seen in other hot regions, such as lassi in Southeast Asia and ayran in the Middle East. However, buttermilk or similar drinks have not been studied for their potential to mitigating heat strain. As a result, the primary aim of the study was to investigate the benefits of drinking buttermilk on thermoregulation and potential hydration benefits when working physically in a hot environment, compared to drinking plain water and when no rehydration was provided. The effectiveness of buttermilk was assessed from its whole body rehydration, thermoregulation, stress and recovery potential during a 3-hour period of medium load physical workload (average 200 W/m^2, SD ±74). The activities involved loading bricks, stepping, biking and arm cranking at rotating intervals every 20 min in the heat chamber (34 °C, 60 % RH). The thermal condition simulates the hottest measured workplace in Chennai during the study period. The study involved three interventions: water, buttermilk, and no rehydration. Twelve subjects (19-33 years, 6 males, 6 females) were recruited. All subjects were normotensive, non-smokers and with an average BMI of 23.8 kg/m^2. Subjects were not taking any medications that could alter the cardiovascular or thermoregulatory responses in the heat. The subjects performed a VO$_2$ max test before the study to determine suitability. Criteria for participation for women was a maximum oxygen consumption of at least 30 ml/kg/min, and men at least 35 ml/kg/min.

During the experiment, the ambient air temperature was continuously monitored using three sensors (PT 100, Pico Technology Ltd., UK, accuracy ± 0.03 °C) at different heights (0.1 m – 1.1 m – 1.7 m). Body core (rectal) and skin temperatures, heart rate and oxygen uptake were continuously measured during the entire period of each activity. The body weight change, subjective responses by the scales of thirst, thermal comfort and thermal sensation (ISO 10551:1995), and Borg's 15-grade Rating of Perceived Exertion (RPE) scale were recorded at the end of each activity (Parsons, 2014).

The measurements of the temperature of human skin and core followed the method described in ISO 9886:2004d. The rectal temperature (T_{rec}) represented the core temperature in the study and was measured with a *YSI-401 Sensor* (Yellow Springs Instrument, USA). It was inserted by the subjects at a depth of 10 cm above the anal sphincter. The calculation of the mean skin temperature has to be based on several points because the skin temperature can differ in different body regions. During heat exposure the blood vessels are dilated, and in the case of light clothing, the temperature is relatively even at different skin sites. Consequently, the number of measuring points can be relatively small. However, at least four points are usually recommended (Parsons, 2014). Skin temperature (T_{sk}) sensors (YSI-402 [tip 3.0]) were taped with a single layer of 3M *Blenderm^{TM}* surgical tape type 1525 on the forehead and left side of the chest, upper arm, thigh and calf. The mean skin temperature value was calculated according to the 4-point Ramanathan equation ($T_{sk}=0.3*{}^{Chest}+0.3*{}^{UpperArm}+0.2*{}^{Thigh}+0.2*{}^{Calf}$) (Ramanathan, 1964). T_{rec} and T_{sk} were recorded at 10 s intervals by a NI data acquisition hardware and *Labview* program (National Instruments, USA). The mean body temperature is the average temperature of the human body and reflects the heat storage. It includes both the mean skin and core temperature and changes in mean body temperature reflect the change in heat content of the body. Mean body temperature was calculated according to the formula, $T_b= 0.8*T_{rec}+0.2*T_{sk}$.

Subjects also rated their whole body thermal sensation, thermal comfort, thirst and perceived exertion at 20 min intervals. Further, a short questionnaire was conducted during the final test day designed to make the subjects reflect on the interventions and experiences regarding potential cooling effects, thirst relief and refreshment potential, stomach sensations and taste.

Oxygen uptake (VO_2) was measured continuously during the exercises (18 min) with *MetaMax I* (CORTEX Biophysik GmbH, Germany). Heart rate was recorded at 5 s intervals using *Polar Heart Rate Monitors* (RS400, Polar Electro, Finland). Weight was measured nude before and after the test for total body weight loss calculation. During the exposure, weight was recorded every 20 min, after each activity to estimate the dehydration level and evaporation rate. Urine samples were taken before and directly after each test to measure renal function biomarkers. Faeces samples were taken from the single use plastic cover of the rectal probe, inserted into a test tube and weighed at the end of the exposure. These samples were collected to explore the impact of heat stress combined with physical work on the gut microbiota. The cortisol stress hormone was measured from saliva samples taken from the subjects upon their arrival at the climate laboratory, in the beginning, middle and at the end of the test, using *Cortisol Salivette* collection tubes (Sarstedt, Nümbrecht, Germany). The urine and cortisol samples were analysed at the laboratory of Clinical Chemistry (Skåne University Hospital, Lund, Sweden) using a standard luminiscence method.

Thermophysiological models

Mathematical modelling of the human thermal regulation goes back more than 70 years for applications in mainly occupational settings (Malchaire, 2006; Fiala et al., 1999, 2001, 2003; Malchaire et al., 2001; Azer and Hsu, 1977; Fanger, 1973; Stolwijk, 1971; Burton, 1937). It is important to have models for heat stress prediction in order to reduce thermal risk and prevent heat induced illness in different exposure situations. The use of models to predict and quantify heat stress and strain have contributed to a reduction in morbidity and mortality in industrial, military, sports, and leisure activities (Havenith and Fiala, 2016). The advantages with thermophysiological models in climate change and occupational health analyses are their ability to predict response and give personalized exposure profiles. They also provide good indications of a worker's heat strain.

Heat stress prediction models have many different approaches with various objectives and applications. One of the most commonly used models is the Predicted Heat Strain (PHS) simulation model, which is based on the heat balance equation and is also an international standard (ISO 7933:2004a; Malchaire, 2006; Malchaire et al., 2001). The PHS model rationally accounts for the individual factors known to influence the heat stress response (Jay and 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., 2001; Malchaire et al., 2000). The model makes it possible to predict sweat rate, core and mean skin temperatures for an average person and calculate duration exposure limits. The PHS model was built on the previous international standard, the Required Sweat Rate Index (SW_{req}), to which modifications and improvements were added. These include modifications to respiratory heat loss, distribution of heat storage in the body, exponential averaging for mean skin temperature and sweat rate, limits for non-acclimatized persons, and the addition of mean body and rectal temperatures (Malchaire, 2006; Malchaire et al., 2001). The model was validated in both laboratories and in the field in the European Programme BIOMED II. Data from 909 experiments (672 laboratory and 237 field experiments) were gathered to a common database (Malchaire et al., 2001, 2002). One of the most innovative elements of the PHS model included new algorithms for the prediction of the effects of body movements and wind on the heat exchanges through clothing (Havenith et al., 1999; Parsons et al., 1999).

The computer model developed and used in the respective studies presented in this thesis (*Papers II and III*) was based on Annex E in the international standard ISO 7933:2004a. A version of the model used can be accessed from this link: http://www.eat.lth.se/fileadmin/eat/Termisk_miljoe/PHS/PHS.html

The PHS model was used for productivity loss analysis in *Paper II*, which is a new approach when analysing heat stress and productivity decline. The data input consisted of environmental measurements from the workplaces, clothing data, estimates of

average metabolic rates and anthropometric data. The anthropometric data consisted of average values measured on selected workers at the workplaces (66 males and 11 females). The average male was 167 cm (SD 7.4) and 64 kg (SD 12.6), and the average female, 150 cm (SD 4.1) and 56 kg (SD 3.9). It was also estimated that the worker was able to take three 15-min breaks (one in the morning and two in the afternoon) and one 50 to 75-min lunch break during the 8 hours. Resting translates to a metabolic rate of 100 W/m2 (lowest metabolic rate possible in the PHS model). Environmental data input for resting was considered the coolest room or in the shade. An air velocity of 1 m/s, simulating a slow walk, was used in the model as body movement creates airflow over the body (Lemke and Kjellström, 2012). An air velocity of 0.3 m/s was used when resting. All workers were considered acclimatized with free access to water. The analysis applied heat strain limit parameters in terms of core temperature (time to reach 38 °C) and dehydration (maximum water loss) and associated it indirectly to productivity loss. Physiological parameters have previously been found to be indicators of productivity loss (Cheuvront et al., 2010; Nybo, 2008; Hunter, 2002; Razmjou, 1996; Ramsey, 1995; Meese, 1984).

Internationally, the WHO recommends an allowable limit core temperature of 38°C, which was a limit value developed to protect most workers (WHO, 1969). Dehydration also affects productivity by elevating the core temperature by about 0.1-0.2 degrees per percentage of dehydration (Kenefick and Sawka, 2007). Dehydration further causes cardiovascular strain, resulting in elevated heart rates. Dehydration deficits of 2 % of body mass can adversely impact aerobic performance, orthostatic tolerance, and cognitive function (Kenefick and Sawka, 2007; Lieberman, 2007; Granjean and Grandjean, 2007; Chia et al., 2005; Brake and Bates, 2003; Hancock and Vasmatzidis, 2003). The limit used in industrial workplaces is set at 3 % of body mass (Miller and Bates, 2007). Moreover, Wasterlund et al. (2004) found that every percentage water loss in forest workers resulted in a 12 % reduction in productivity (Wasterlund et al., 2004).

The PHS simulation model was also applied in the comparison study in *Paper III.* The aim of the study was to compare a rational simulation model (the PHS model) with a more complex rational multi-node physiological model (the multi-node Fiala model). The Fiala model (Fiala et al., 1999, 2001, 2012) consists of two interacting systems: the controlled or passive system and the controlling or active system. The passive system represents the human body segmented in 20 elements and includes the physical characteristics of the human tissue and the heat and mass transfer occurring within and between the body elements as well as between the body surface and the environment. The outputs of the respective models were analysed against experimental data from the climate chamber study of intermittent work in a hot environment (*Paper IV*). The aim was to analyse how accurately the respective models were able to predict changes in core and skin temperatures during intermittent activities that are common in non-paced industrial jobs.

Ethical considerations

This research involves human subjects, which comprises certain risks, rights and confidentiality in terms of ethics. The research thus follows the Declaration of Helsinki's Ethical Principles for Medical Research Involving Human Subjects developed by the World Medical Association. For *Paper IV*, ethical approval for the climatic chamber study was applied for and granted by the Regional Ethical Review Board in Lund (Dnr 2014/606). The case study in Chennai raised many research questions about ethics and associated considerations. These included how to approach the workers and management properly and to clearly explain what the data was being used for. The Sri Ramachandra University in Chennai received an ethical approval for the study from its Institutional Ethics Committee.

Results and discussion

Current state and future impacts of heat stress on occupational health

Based on the papers reviewed in *Paper I*, one can summarize that the impacts of heat stress on occupational health and performance have been researched extensively in the past. However, in the contemporary context of climate change, information is lacking on the extent of future heat stress and its consequences, especially in an occupational setting. Based on this, the Chennai case study (*Papers II and V*) set out to add to the knowledge base. The papers confirmed the current research and assumptions that occupational heat stress is an issue that already exists, and that the added heat due to climate change will especially make physical work very difficult (Venugopal et al., 2016; Zander et al., 2015; Dunne et al., 2013; Sahu et al., 2013; Tawatsupa, 2010; Balakrishnan et al., 2010; Kjellström et al., 2009). All workplaces surveyed in *Papers II and V* had high heat exposure in the hot season, often reaching the international standard safe work values (ISO 7243:2017) according to which, depending on workload and clothing worn, actions need to be taken to remediate the situation. If not, this could have serious impacts on the workers' income and the country's economy. Table 2 presents a summary of the measurements for each workplace in the cooler season (Jan.-Feb.) and hot season (April-May) (*Papers II and V*) combined with the environment simulated in the chamber study (*Paper IV*).

Table 2:
Summary of the environmental parameters and WBGT indexes from the six field sites and the chamber study (colours indicate the separate studies)

Param-eter	Cookie factory		Canteen		Laundry facility		Agriculture		Construction		Brick kiln		Chamber
	Cooler	Hot	Cooler	Hot	Cooler	Hot	Cooler	Hot	Cooler	Hot	Cooler	Hot	
T_a	30.2 (s.d. 1.3)	35.6 (s.d. 2.4)	33.7 (s.d. 2.3)	36.8 (s.d. 1.7)	30 (s.d. 0.5)	32.7 (s.d. 0.3)	28.9 (s.d. 0.5)	32.0 (s.d. 0.3)	30.0 (s.d. 0.0)	34.2 (s.d. 0.8)	25.3 (s.d. 3.1)	31.8 (s.d. 3.6)	34
T_g	30.5 (s.d. 4.6)	36.0 (s.d. 4.1)	35.2 (s.d. 3.6)	38.1 (s.d. 3.0)	30 (s.d. 1.4)	32.7 (s.d. 0.2)	38.5 (s.d. 2.1)	39.5 (s.d. 0.6)	32.0 (s.d. 1.3)	37.6 (s.d. 5.4)	32.3 (s.d. 6.1)	38.7 (s.d. 6.6)	34
T_{nw}	22.8 (s.d. 0.9)	27.4 (s.d. 1.5)	27.1 (s.d. 1.3)	30.0 (s.d. 0.9)	21.2 (s.d. 0.3)	26.5 (s.d. 0.8)	24.4 (s.d. 0.3)	26.5 (s.d. 0.4)	23.5 (s.d. 0.4)	25.3 (s.d. 0.7)	22.1 (s.d. 2.5)	25.0 (s.d. 2.5)	27.7
RH	54% (s.d. 3.6)	56.4% (s.d. 3.8)	59.1% (s.d. 6.5)	55.6% (s.d. 1.1)	62.3% (s.d. 3.8)	54.3% (s.d. 7.4)	58.5% (s.d. 3.9)	50.8% (s.d. 1.9)	53.6% (s.d. 2.0)	44.4% (s.d. 2.6)	-	-	60%
WBGT	25.0 (s.d. 1.9)	30.0 (s.d. 1.7)	29.5 (s.d. 2)	32.0 (s.d. 2.3)	24.3 (s.d. 0.3)	28.0 (s.d. 0.6)	28.0 (s.d. 0.6)	29.6 (s.d. 0.4)	25.6 (s.d. 0.3)	28.7 (s.d. 1.5)	24.2 (s.d. 2.6)	28.4 (s.d. 2.2)	29.6

Generally, the workers and subjects included in the research had moderate intermittent workloads, averaging between 170-220 W/m^2. Clothing was found to be problematic in the field, with high insulation values in relation to the heat exposure. Females were identified as more vulnerable due to the practice of wearing a protective shirt over traditional clothing (churidar and saree) at work, which increased the insulation and evaporative resistance. The mean insulation from the three laboratories (Havenith et al., 2015) are presented in Table 3.

Table 3:
Clothing ensemble description, moisture permeability index (i_m) and clothing insulation (I_{cl}) measurements. f = female, m = male.

Ensemble	Permeability Index (i_m) (mean of 3 measurements)	Clothing basic insulation (I_{cl}) clo (mean and s.d. of 3 laboratories)
Churidar (f)	0.38	0.58 (s.d. 6.23%)
Churidar + shirt and towel on head (f)	0.34	0.74 (s.d. 4.86%)
Saree (f)	0.34	0.74 (s.d. 7.28%)
Saree + shirt and towel on head (f)	0.31	0.96 (s.d. 7.80%)
Shirt and trousers, with towel on head (m)	0.33	0.61 (s.d. 2.53%)

In regards to future added heat stress due to climate change, the link between meteorological data and the ISO standards related to local heat stress is generally undeveloped (Parsons, 2013). However, Bernard and Barrow (2013) argue that the estimation of WBGT directly from meteorological data can be accomplished with a 95% confidence of 2 degrees WBGT (Bernard and Barrow, 2013). In this research, the future impacts of climate change on the occupational heat stress situation in Chennai was analysed in *Papers II and V* by using the online Climate CHIP tool (Climate CHIP, 2016). The tool is the first of its kind to estimate heat stress globally by using local weather station data to calculate occupational heat stress indices. Future heat stress is calculated using modelling data from the University of East Anglia, UK, produced by HOTHAPS Soft (Kjellström et al., 2013; Lemke and Kjellström, 2012). The data does not account for solar radiation and the contribution of urban heat islands (Kleerekoper et al., 2012). This is mainly due to the lack of data from local meteorological stations and their positioning (commonly at airports outside the urban centre).

Results of future impacts are shown in Figure 6 where the average WBGT (ISO 7243:2017) during the month of May in Chennai over time is combined with future modelling based on the IPCC's representative concentration pathway (RCP) of 8.5 (Climate CHIP, 2016; IPCC; 2013). It can be seen that WBGT temperatures are already high and increasing over time. The heat exposure is further projected to climb above the WBGT limit values for a resting acclimatized worker by the end of the century (Fig. 6). This indicates a challenging future for Chennai with or without significant global reductions in emissions of greenhouse gases.
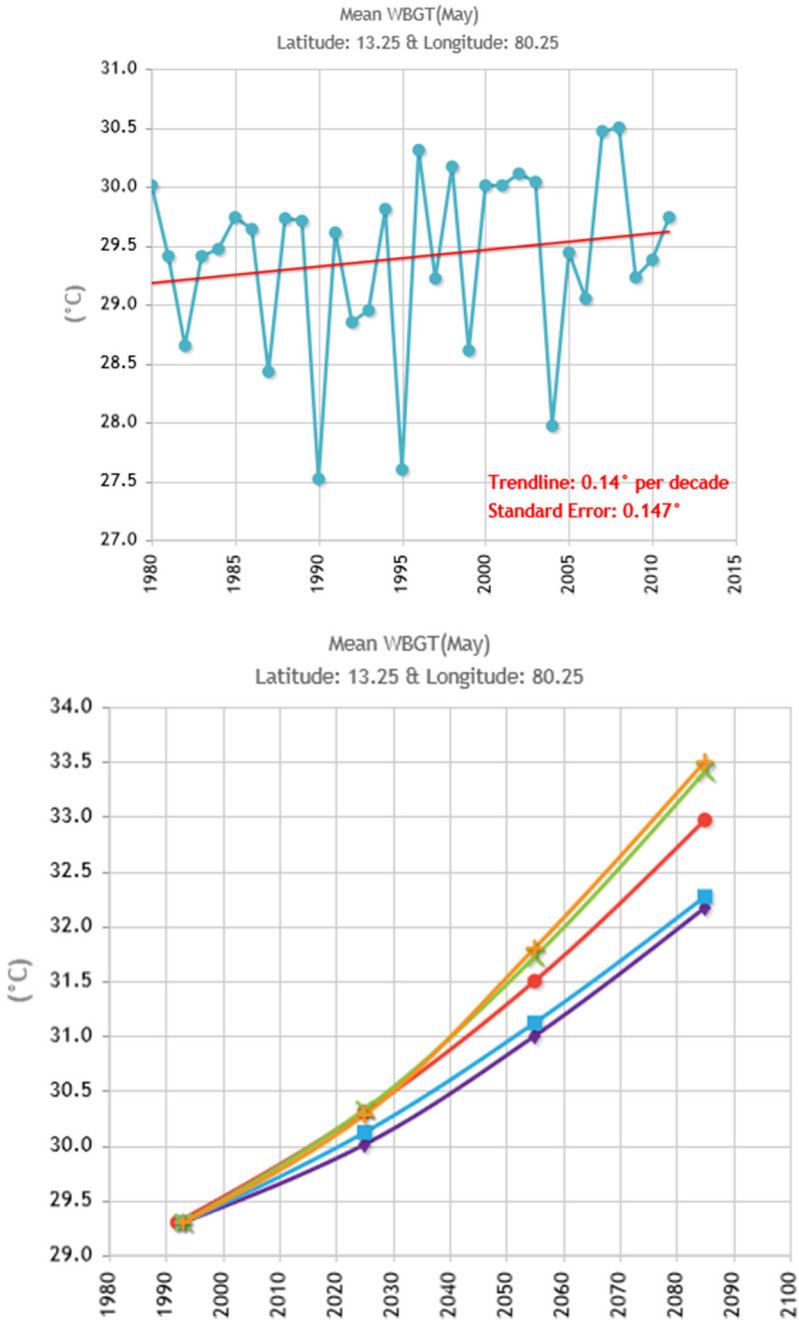
Figure 6:
Historical and future heat stress during the month of May in Chennai according to measurements and simulations. Produced by HOTHAPS soft (Climate CHIP, 2016; Kjellström et al., 2013; Lemke and Kjellström, 2012). The different colours represent different models datasets of RCP 8.5 (HadGem, NORES, GFDL, IPCM and MIROC+).

Figure 7 shows the maximum monthly WBGT and work ability with increasing seasonal temperatures in 2005 compared with 2050 for India (Kjellström et al., 2013). The work intensity definitions are from the ISO 7243:2017 standard table on metabolic rate. Note that Chennai is situated in one of the most vulnerable areas in India (southeast).
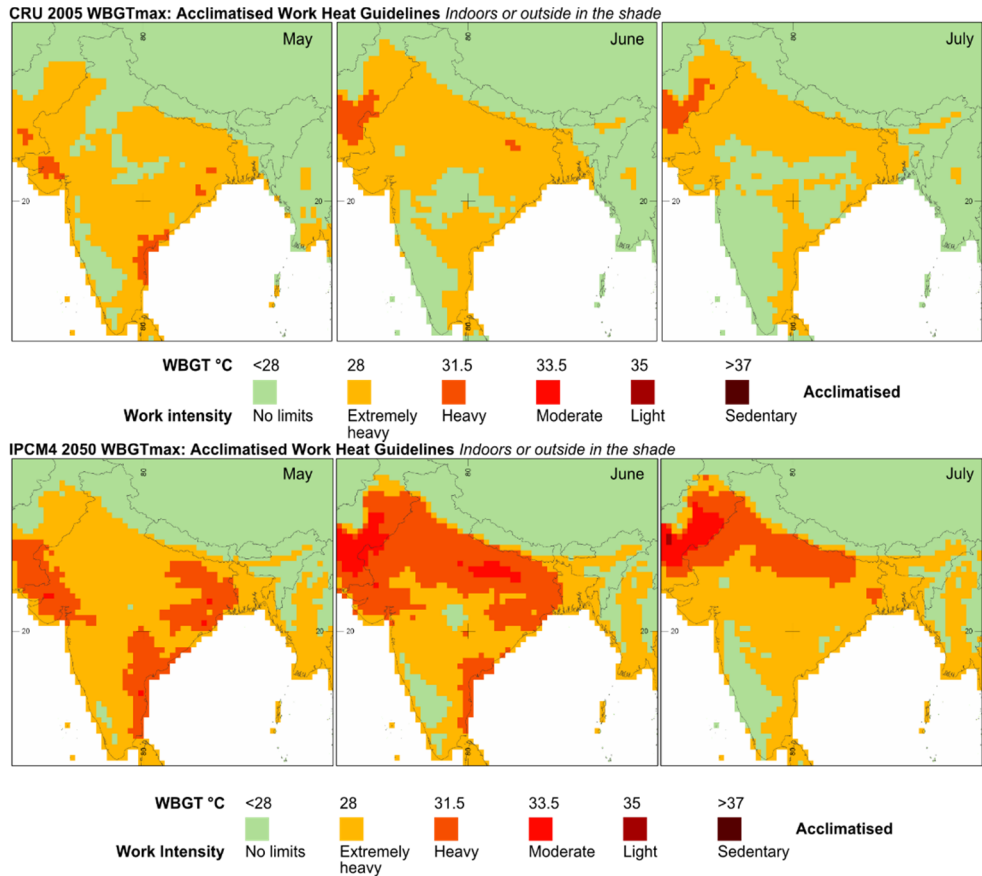
Figure 7:
Maximum monthly WBGT in 2005 and 2050 produced by HOTHAPS soft (Kjellström et al., 2013).

Labour productivity analysis

Productivity is strongly dependent on thermal conditions, in particular during physically demanding work (Lloyd, 1994). Previous studies have examined psychological variables such as reaction time, tracking and vigilance, as well as memory and mathematical calculations (Bell et al., 2005). Thermal comfort studies have investigated the productivity impacts of diverting from neutral temperature (Bell et al., 2005; Wyon, 2004; Fisk, 2000). Research linking labour productivity with climate change have primarily analysed links between weather fluctuations and economic growth globally (Dell et al., 2014; DARA, 2012; Horowitz, 2009). Studies have also:

- applied the thermal work limit (TWL) index which limits the metabolic rate (Brake and Bates, 2002),

- used weather station data and global climate model data to calculate heat stress indices (WBGT/UTCI) and applied their associated reference values (Opitz-Stapleton, et al., 2016; Dunne et al., 2013; Kjellström et al., 2009),

- linked heat stress indices with hourly work output (Sahu et al., 2013),

- applied health economics tools based on work absenteeism and reductions in work performance (Zander et al., 2015),

- used self-reported heat stress impacts from questionnaires (Venugopal et al., 2016; Tawatsupa, 2010; Balakrishnan, 2010), and

- applied time-motion analysis (Ioannou, 2017).

In the research presented in this thesis from *Paper II*, a different approach was taken when analysing productivity loss. Here, the heat strain prediction from the PHS (ISO 7933:2004a) simulation model was applied to indirectly estimate productivity loss. Productivity was based on the following two outputs in the PHS model: time to reach a core temperature of 38 °C and maximum water loss. The worker should rest and drink when these limits are reached, which hypothetically affect productivity. The analysis found that apart from the laundry facility, the parameters showed significant impacts affecting productivity in all workplaces studied, especially during the hot season. For example, in the canteen in the hot season, the predicted limit core temperature of 38 °C was reached in only 64 minutes for women. With expected climate change, actions have to be taken in these workplaces immediately to mitigate further productivity losses and health impacts.

This was the first time the PHS (ISO 7933:2004a) model was used for productivity analysis of this kind and an exploratory approach was taken to assist further development of the model. In particular, the approach is valuable for site-specific analysis of productivity losses due to the detailed physiological input parameters

needed. Limitations of the approach include an inability to conduct a holistic assessment of the work environment's impact on productivity and to include other aspects such as light and noise (Anshel, 2007; Tafalla et al., 1997), air pollution (Duflo et al., 2008), cognitive function (Kenefick and Sawka, 2007), the psycho-social environment, long commutes, lack of sleep and stress. Another limitation of any productivity loss analysis in hot workplaces is that a heat stress initiative does not necessarily lead to a reduction in productivity as it mitigates fatigue and related accidents (Rowlinson, 1997). For example, Washington State performed a cost-benefit impact analysis of heat illnesses prevention programmes and found the economic benefits outweighed the costs (WSDLI, 2008).

Another limitation is that the PHS model is not designed for productivity analysis per se. The model also assumes an initial core temperature of 36.8 °C. However, workers commonly have pre-exposure to heat from travel to work, living in hot dwellings and so on. As a result, performance may be impacted ahead of the simulated output in the model.

Moreover, an aspect to consider is that self-regulation has proven an effective measure to manage heat stress (Miller, 2011; Parikh, 1978). For example, Nag et al. (2013) found in the Indian context that 90 % of workers automatically kept under a core temperature of 38 °C, suggesting that the workers were self-pacing effectively (Nag et al., 2013). This automatic self-pacing complicates any productivity analysis. However, this effect can be constrained by productivity incentives, the workers awareness and physiological factors of individual difference (Rowlinson and YunyanJia, 2014).

Currently, there are no other comprehensive physiological models to estimate productivity loss in hot environments. Validation studies are therefore required on the relationship between PHS predictions and productivity.

Evaluation of assessment tools for work in hot environments

All appended papers to the thesis apart from the literature review in *Paper I* either apply or evaluate assessment tools for work in hot environments. Four initial pre-studies of various comparisons of WBGT measuring equipment were also incorporated in the author's licentiate thesis (Lundgren, 2014). The studies found that non-standard (i.e. *Lascar, modified Testo* and the *MSR Electronics* data loggers, the *Extech 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 instrument (*Bruel & Kjaer*) in stable indoor conditions. However, when measuring in outdoor settings with solar radiation and larger air velocities, the instruments showed great

variations. It appeared that the thickness of the wick on the wet bulb sensor influenced the reading and therefore has to be evaluated in a set-up. Recent support of this result is given by a study on manikin skins (Wang et al., 2017). The size of the sensor and placement of sensors can also present small variations (for further details see Lundgren (2014)).

Paper III specifically evaluates two thermophysiological models. The study compares the Predicted Heat Strain (PHS) rational simulation model, and the more complex rational multi-node physiological Fiala model against experimental data from the climatic chamber study of intermittent work at moderate loads in a hot environment (34 °C, 60 % RH) with low clothing insulation. One goal was to compare the output from the less complex model, PHS (an international standard and available at no cost), to the more complex Fiala model.

The analysis found that the PHS simulation over predicts the cooling effect of low activity and therefore underestimated the thermal strain in the climatic chamber scenario of intermittent work at moderate loads, which is common in workplaces such as agriculture and construction. As the core temperature is a limiting factor for work in hot environments and sets the exposure limits in PHS, the results are problematic. Similar conclusions have been drawn by Bröde et al. (2017) and Brake and Bates (2002) which could be related to the PHS model's inability to consider the thermal inertia of recovery. Further, this underestimation does not seem to be related to modelled sweating as the cumulated sweat profiles in both models were found to be similar. The analysis of variance revealed significant differences in both model simulations and the experimental data for both rectal and mean skin temperatures. Hence, both models showed limitations and the need for improvement and validation, especially of the effects of recovery periods. Moreover, the PHS model is not validated for resting metabolic rates, but should be in order to simulate breaks during a workday, for example.

In summary, the international standard incorporating the PHS model (ISO 7933:2004a) is currently being reviewed and there is a critical need to develop a user-friendly model as it is currently incomprehensive to laymen and not convenient for instant decision-making (Rowlinson and YunyanJia, 2014). There is further a need to add more data on intermittent work to broaden its use and scope. This could also broaden its applicability for employers, occupational health specialists and other stakeholders.

Gender aspects

Gender aspects were incorporated in all studies conducted for this thesis. In *Papers II and V*, a heat exposure difference was observed in the population studied, as females were more vulnerable due to clothing practices. Traditional clothing such as churidars and sarees are commonly worn with a protective shirt on top to protect the clothing. Sarees are a very effective garment to protect workers from heat (Indraganti et al., 2015). However, the protective shirt hampers the traditional clothes effectiveness. The practice of using a shirt traps the layers of the saree or churidar beneath a tighter textile, and in so doing decreases air and vapour permeability, ventilation, and increases the clothing's insulation. This generates a higher heat load for the women. Men usually wear a shirt and trousers, which are not ideal clothing to be worn in a hot environment either. To change these clothing practices, interventions are needed, including the design of new work wear based on industrial safety but to also keep in mind not to simply introduce western styles that may not be optimal for hot environments. More research that investigate cultural norms and practices combined with outreach at the workplaces is also needed.

Another gender aspect was demonstrated in the research conducted for *Paper III*. A confidence interval check of the PHS and Fiala models' predictions, respectively, revealed a gender discrepancy, where males were better predicted in the models against experimental data for both rectal temperature and mean skin temperature. One reason for the gender difference could be that thermophysiological data are largely based on studies of young, fit males, mainly in military settings and male dominated industries (e.g. Parsons, 2014; USDAAF, 2003; Schrier et al., 1970). Thermophysiological models were further developed in western countries (involving western subjects). Because both models under-predicted the thermal stress for females, further development and validation of the models are needed to address this shortcoming.

Collaborations across disciplines

To meet the aim and objectives of the research, collaboration with researchers from other disciplines were necessary. In particular, *Papers IV and V* combined disciplines in innovative ways, and the following sections will describe and reflect on this process in conjunction with a discussion of the results.

The multidisciplinary climatic chamber study

In *Paper II*, the case study identified numerous technical, behavioural, and managerial methods that were applied to reduce heat exposure at the workplaces studied, including self-pacing and rest, ventilation, exhaust fans, and shade structures. Results from the workplace questionnaire found that traditional methods, including mainly drinks and diet, dominated the cooling measures. These were primarily drinking buttermilk followed by fruit juice, coconut water, and fermented rice. Despite the widespread practice, little has been studied on the physiological cooling potential of diets in cultures with hot climates. Diets have the potential to affect thermoregulation, for example, by increasing sweat production for body cooling. However, climate change research to date have focused on the mitigation potential of changing diets (Soret et al., 2014) and its co-benefits to health (Aston et al., 2012) rather than its adaptation potential.

Hydration in various forms is of outmost importance at hot workplaces as the depletion of water and electrolytes decreases the blood volume, extracellular fluid volume and the amount of sweating (Sawka et al., 1989), making heat dissipation difficult (Montain et al., 1995). This reduction in sweat rate is known as 'involuntary dehydration' or 'sweat gland fatigue'. Moreover, there are also discussions in the literature whether or not humans have an inadequate thirst response, an aspect known as 'voluntary dehydration' (Brake and Bates, 2003).

On the basis that buttermilk had not been studied for its potential to mitigate heat strain, the general aim of *Paper IV* was *'to investigate the benefits of drinking buttermilk on thermoregulation and potential hydration benefits when working physically in a hot environment, compared to drinking plain water and when no rehydration was provided.'* The study attracted researchers from other disciplines who were interested in studying questions related to the impacts of work in a hot environment. As a result, the impacts on the gut microbiota, renal and cognitive function were also studied combined with a validation study. The added aims of the multidisciplinary study were:

- To explore the cognitive effects of heat strain and physical work on arousal, working memory performance, and risk-taking.

- To examine the impact of heat strain and physical work on the human gut microbiota.

- To investigate the effects of physical work and short-term heat exposure on renal function.

- A validation study of accelerometers for use in the field of hot occupational settings to estimate the metabolic rate (see Kuklane et al., 2015, as the results are not reported in *Paper IV*).

The results from the study generally confirmed previous literature that keeping oneself hydrated mitigates heat strain in well-nourished subjects (e.g. Kenefick and Sawka,

2007; Sawka and Montain, 2000; Cadarette et al., 1984; McLellan, 1998; Meyer et al., 1995; Cheung and Neufer et al., 1989; Sawka et al., 1988). It was also found that buttermilk performs as well as water in lowering the body heat content. A hormonal stress response at the end of the exposure was seen when the subjects did not drink. However, no differences in cognitive abilities or gut microbiota were found. The exposure lowered the renal blood flow suggesting an acute impact of short-term heat exposure on the kidney. It was also found that buttermilk has a protective effect on this impact.

A complementary intervention study with buttermilk was conducted by Krishnan et al. (2017) on residential complex workers in Chennai. The authors found no significant change in either heart rate or core temperature (Krishnan et al., 2017). However, this could be due to aspects linked to the low heat stress levels and workloads but also due to a small sample size (20 workers).

Furthermore, when looking at the results from the climatic chamber study, one could speculate that the water intervention could prove to have an additional thermoregulatory effect than buttermilk if the study had been prolonged, although it was not statistically significant. On the other hand, if the study design would have been modified to include a longer duration combined with a lighter breakfast and a reduction of the initial water intake, the nutritional benefit of buttermilk may have outweighed the water intervention. Following up on this, a single subject climatic chamber experiment with a slightly modified protocol (lighter breakfast and less initial water intake) was conducted. Interestingly, the results showed an additional physiological cooling benefit of buttermilk on mean body temperature and rectal temperature. As a result, it is motivating to further explore traditional ways of managing heat through drinks and diet in the future.

Despite the lack of statistically significant results in general, the study advanced the research by combining research questions and methods from a variety of disciplines. The researchers involved also experienced increased learning during the collaboration despite the fact that the various research questions were analysed separately. It was also an innovative and explorative approach and few previous studies in the field have combined so many disciplines and research questions, which could pave the way for more interdisciplinarity in the research of occupational health and heat stress.

The transdisciplinary case study of brick kilns

In *Paper V*, it was argued that migrant brick kiln workers in India face heat risks from multiple causes including from occupational and meteorological sources but also from the heated economy. On this basis, the researchers involved in the study all found it an interesting workplace to examine from their respective perspectives. During the initial analysis of the literature, it became apparent that experts have tended to focus primarily

on productivity aspects and technical solutions, such as improved smoke stacks or fuel mix modifications at the kiln furnace, and lacked suggestions for meeting the environmental and human rights challenges that specifically face the migrant workers. For example, the 2012 report of the Clean Air Task Force on brick kilns includes many technical solutions, but only in the final sentence of its recommendations do the authors suggest their technical solutions may lead to an 'improvement of working conditions for millions of workers employed in brick kilns' (CATF, 2012). Because of this narrow solutions space, it is critical that the socio-economic and cultural dimensions of current and potential solutions to increasing heat are considered. They should particularly take into account the workers' experiences, knowledge and perspectives. The objective of *Paper V* was therefore to look at the problems faced at brick kilns from different angles, using a transdisciplinary approach to reframe the problem and identify alternative solutions. On this basis, a case study of heat stress at brick kilns in the Chennai area is the anchor point around which a transdisciplinary approach was applied. The study evaluated current heat risks, and the potential future impacts of heat caused by climate change. To evaluate potential future pathways for brick kilns, a framing analysis was applied. Reframing has the capacity to associate ideas across theoretical, empirical and disciplinary divides (Jerneck and Olsson 2011).

The results revealed that the current situation is problematic since occupational heat exposure in the hot season from March through July is already reaching the international standard limit values for safe work (ISO 7243:2017). The analysis goes on to suggest that more locally 'appropriate' technology is needed, including the use of sun dried mud bricks that could mitigate the worsening of climate change induced heat. The local climate is a perfect heat source for drying the bricks in the sun. The practice is not only environmentally friendly but also provide social and economic benefits by using local skills and material while reducing production costs. Sun-dried bricks can also be effectively returned to earth as soil for vegetation.

There is a need to reframe the discussion away from technical solutions and productivity maximization to be about the protection of people and the environment. Socio-cultural solutions discussed in the paper included decentralized governance and participatory approaches such as open re-localization, and rights-based approaches such as the environmental sustainability and the human rights based approach (ES-HRbA) framework. The framework is a tool to examine how social injustice is inextricably linked with ecological injustice. The analysis suggests that an integrative, transdisciplinary approach could incorporate a more holistic range of solutions in order to protect the health of people threatened by India's brick kiln industry.

The transdisciplinary approach applied quantitative and qualitative methods including climate forecast data, a transdisciplinary literature review and local case study data. This required the co-authors to collaborate across disciplinary, epistemic and methodological boundaries. As a result, the authors represented a diverse range of disciplines, including

environmental science and engineering, architecture, human ecology, social anthropology and occupational health. No previous studies have been found that use this combination of methods and disciplines. The research work was cumbersome in parts due to differences in language and disciplinary cultures. However, overall it was a learning process for all and its innovative method added perspective to the current discourse on improving India's brick kilns.

Quality assessment of the research and limitations

In general, practical considerations had a strong influence on the case study research conducted in *Paper II and V* and it is important to be aware of its limitation in terms of generalizability. The data do suffer from selection bias as the opportunity sampling conducted both with the workplace questionnaires and heart rate data call into question how representative the sample is of the wider population. The data should thus be used with caution and the papers referenced as case studies that are not to be generalized. The studies only provide a snapshot of the reality for these workers as each field visit lasted between 3 and 6 hours, not for a full working day or over an extended period of time. Additional considerations include worker turnover between the two seasonal studies, psychological aspects, stress factors, and subjective reactivity, such as the Hawthorne effect. The Hawthorne effect occurs when workers are more productive because they are being observed as part of a study (Fostervold et al., 2001). This complicates the results, especially in this short-term study.

One problem with assessing workplace heat stress at fixed sites, as is done in this research, is that it does not provide a complete picture of the individual worker's exposure. Future assessments could include personal heat exposure to address this shortcoming directly through wearable monitors measuring air temperature and humidity. Personal heat exposure research does provide more valid and precise insights for heat risk assessments (Kuras et al., 2017).

There are also problems in the research that performs heat exposure assessments in a workplace where the workers are mobile and where work tasks and loads vary during their work shift. This is mainly due to difficulties in estimating metabolic rates (see the methods section on estimations of work intensity in the field). As a result, new methods to estimate metabolic rate in the field are needed, and the use of accelerometers can be one approach (Kuklane et al., 2015).

Additionally, more than 60 heat stress indices have been developed over the last century (Epstein and Moran, 2006; Parsons, 2014) and the chosen heat stress assessment metric impacts results (Bröde et al., 2017). Consequently, there is a need to develop an international agreement on the best heat stress index to use in order to be able to

compare results worldwide (Dash and Kjellström, 2011). There is also a need to link ISO standards with meteorological data to better assess the impacts of climate change locally, but there are also challenges attached to such an assessment (Parsons, 2013). Moreover, indices have been criticized for being developed exclusively in western countries and therefore lack flexibility for application in hot developing countries where morphology, food and living conditions are different (Malchaire et al., 2017). There are several limitations of the WBGT index used in this research as discussed in the methods section on environmental parameters and the WBGT index. On the other hand, it is one of the more widespread indices and an international standard and was therefore chosen as the heat stress screening tool (ISO 7243:2017).

The climatic chamber study (*Paper IV*) has limitations in relation to it being subjected to human error, small sample size, the subjects not being from India and not involving poor under-nourished workers. This makes the sample rather unrepresentative and complementary studies are needed such as a controlled workplace study with advanced measurements of physiological parameters. Another limitation is that in order to improve ecological validity, a test with longer duration is necessary (e.g. simulating an 8-hour working day).

Specific discussions of the advantages and limitations of the methodological approaches can be found in the methods section.

Conclusions

Increasing occupational heat exposure due to climate change is a major societal and scientific challenge. On this basis, the research first set out to identify the current knowledge and knowledge gaps (*Paper I*) and showed that information is lacking on the extent of future heat stress and its consequences. The main factors found to exacerbate heat stress in current and future workplaces were the urban heat island effect, physical work, individual differences, and the developing country contexts where technological fixes and certain control measures are often not applicable. There is also a lack of information on the effects on vulnerable groups (*Paper I*). On this foundation, the main conclusions are as follows:

- Occupational heat exposure is already a problem today in Chennai, India, affecting workers' health and productivity. The problems are set to worsen due to climate change (*Papers II and V*).

- Female workers in Chennai were more prone to heat stress due to the extra insulation added from wearing a protective shirt on top of traditional clothing when working. This practice increases the insulation and evaporative resistance properties of the clothing (*Papers II and V*).

- The Predicted Heat Strain (PHS) Model (ISO 7933:2004a) can be applied to estimate thermal physiological responses and indirectly estimate labour productivity loss due to heat exposure in specific workplaces. Validation, however, is needed (*Paper II*).

- The PHS model over predicts the cooling at low activity (rest) for intermittent work and therefore underestimates the thermal strain. As core temperature is used to limit work exposure, this is problematic and requires further investigations (*Paper III*).

- Two physiological models, the PHS and Fiala, predicted responses more accurately for males than females. Further development of the respective models is needed to address this shortcoming (*Paper III*).

- Traditional methods of coping with heat stress are worth further study as the Indian diluted yoghurt drink 'buttermilk' performed as well as water to reduce the body heat content (*Paper IV*).

- A holistic approach is needed to ensure that solutions for vulnerable workers are not only technical, but also include a mix of locally appropriate

technologies integrated with a human rights and environmental justice frame. Here, a transdisciplinary facilitation of solution framing could provide an invaluable lens when analysing problems and solutions, including technical and socio-cultural ones (*Paper V*).

Future research needs

The impacts on society of increasing heat globally require more research. Based on the results of research presented in this thesis, future efforts should focus in particular on:

- More studies of occupational heat stress in varying contexts, countries and ways of preventing and/or mitigating heat strain.

- Studies that bridge community and occupational heat exposures by including personal monitoring (i.e. through wearable sensors). This would provide a more complete picture of the personal exposure and more valid insights for heat risk assessments.

- Development of heat stress models and indices: validation of the Predicted Heat Strain (PHS) model for productivity loss analysis and the addition of more data on intermittent work to broaden its use and scope.

- Develop more accurate and practical measurements of metabolic rate in hot environmental conditions for field use.

- Develop tools to better link standard meteorological measurement data with the ISO standards.

- Negotiate and develop an international agreement on the best heat stress index to use in order to compare studies worldwide.

- Studies on under-researched vulnerable groups including children, emergency workers, tourists, women and especially pregnant women and malnourished people.

- Analysis of combinations of exposures with heat, for example air pollution and the possible increased evaporation of chemicals at the workplace.

- Analysis of methods to reduce heat stress and strain, including: traditional methods and socio-cultural solutions and sustainable technology (low and high-tech).

- Conducting action research and pilot identified solutions through collaborative interventions in the field.

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Paper I

Effects of Heat Stress on Working Populations when Facing Climate Change

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Abstract: It is accepted that the earth's climate is changing in an accelerating pace, with already documented implications for human health and the environment. This literature review provides an overview of existing research findings about the effects of heat stress on the working population in relation to climate change. In the light of climate change adaptation, the purpose of the literature review was to explore recent and previous research into the impacts of heat stress on humans in an occupational setting. Heat stress in the workplace has been researched extensively in the past however, in the contemporary context of climate change, information is lacking on its extent and implications. The main factors found to exacerbate heat stress in the current and future workplace 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 elderly people and pregnant women. As increasing temperatures reduce work productivity, world economic productivity could be condensed, affecting developing countries in the tropical climate zone disproportionately. Future research is needed taking an interdisciplinary approach, including social, economic, environmental and technical aspects.

Key words: Heat stress, Occupational health, Climate change, Developing countries

Introduction

Climate change affects, either directly or indirectly, a wide range of sustainable development issues such as health, food security, employment, incomes and livelihoods, gender equality, education, housing and poverty. Existing policies and social protection systems are often inadequate to enhance resilience and adaptive capacity or to mitigate negative climate change impacts on employment. Arguably, climate change is also one of the largest environmental and health equity challenges as wealthy energy consuming nations are most responsible for the emissions that cause climate change, yet poor countries are most at risk. Negative health effects from climate change stem from heat stress, communicable disease, air pollution, lack of food and water security, extreme weather events, malnutrition, stress, mental health issues, vulnerable shelter and population migration among others. Examples of climate-related hazards in the workplace include increased ambient temperature, air pollution, ultraviolet radiation exposure, extreme weather and vector-borne diseases such as malaria and expanded habitats[1–3, 31].

Outdoor workers are the most vulnerable and the main sectors that are directly affected by climate change include agriculture, industry, fisheries, forestry, small and medium sized enterprises, indoor workplaces (for example without air conditioning), semi-outdoor workshops and construction work. Tourism, health, and finance/insurance sectors can be affected indirectly from for example extreme events[4].

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Climate change can no longer be considered simply an environmental or developmental issue as it puts at risk the protection of human health and well-being.

In addition, while forecasts exist on the economic impact of climate change, the social impact on enterprises and workers, on employment and income, on working conditions, and on many other social dimensions is considerably less understood. 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 the vulnerability of workers and enterprises to the negative effects of climate change and to enhance the capacity at the individual and society levels to adapt, respond to and prepare for climate change. This literature review concentrates on the effects of heat stress on the working population with a focus on developing countries in relation to climate change. So far, climate change impacts related to heat stress have often been examined in relation to heat wave-mediated effects on the general population, but recognition is lacking that climate change may exacerbate occupational heat-related risks[5].

Methods

The extensive amount of information on heat stress made it necessary to have a strategic information search to find key articles. Climate change and occupational health is a highly multi-disciplinary field of study and requires scholarly information from a variety of sources. That is why the 'pearl picking' method was initially applied. This method uses one exceptionally useful article (often a review article) to track key articles in the field. The article chosen for the 'pearl picking' was: Kjellström, Holmér and Lemke: Workplace Heat Stress, Health and Productivity − an increasing challenge for low-and middle income countries during climate change[6].

A thorough exploration of different databases and search engines was then carried out and several information retrieval tools were selected. Most were broad multidisciplinary platforms and databases covering a wide variety of journals and hence, more likely to have the articles desired. The information retrieval tools chosen were PubMed, Lund University's search engine Summons, Scopus, Google Scholar, Web of Science and the Science Citation Index[7]. Several search words were used such as 'occupational heat exposure', 'occupational heat stress', 'occupational heat strain', 'heat in/at workplace', 'work in the heat', 'occupational heat stress AND climate change' and the more broad search words 'heat stress'.

Relevant articles were then selected. An internal database and library was also used together with the International Labour Organization's Bookshelf on Occupational Safety and Health[35].

Current Status

Climate change and its effects

The Intergovernmental Panel on Climate Change's (IPCC) Forth Assessment Report (AR4) which came out in 2007 stated clearly that 'warming of the climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice and rising global average sea level'. Data records clearly show that the eleven years between 1995–2006, rank among the warmest in the instrumental record of global average surface temperature (since 1850). For the next two decades a warming of about 0.2°C per decade is projected for a range of future scenarios of emissions of greenhouse gases.

The AR4 reports that hot days, hot nights and heat waves have become and will become more frequent over most land areas[8]. The continuous rise of absolute humidity in the lower troposphere has also been reported in many regions which add substantial implications for human thermal comfort and heat-related mortality and morbidity. In particular, this may add substantial risk in already humid countries, where a small increase in temperature can have profound consequences on heat stress[9].

Heat waves are defined as 'extended periods of unusually high atmospheric related heat stress, which cause temporary modification in lifestyle and which may have adverse health consequences for a population'[10]. Heat waves have already affected some aspects of human health, such as excess heat related mortality in Europe during the summer of 2003[8]. This heat wave caused up to 70,000 deaths[11]. In France, data 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[2]. Additionally, deaths and illnesses caused by air pollution (e.g. ozone, particles) tend to increase during extremely warm weather[12]. It is expected that European summer temperatures as high as those experienced in 2003 will be the norm by the middle of the century[2]. Responses to some recent extreme climate events reveal high levels of vulnerability in both developing and developed countries[8]. There is also increasing evidence of greater vulner-

ability of specific groups such as poor and elderly people in all countries[3]. High ambient temperature is a leading cause of weather related mortality in many regions of the world and heat exhaustion is the most common response to prolonged exposure to high outdoor temperatures[3].

As the world gets warmer, populations will acclimatize to some extent, raising the optimum temperature[13]. The possible increased use of air conditioners, though, may hinder natural acclimatization and potentially increase the risk[3, 12]. Human populations have a great capacity to adapt physiologically, technologically, and by behavioural change, to gradual changes in climate. However, sudden changes in weather can have a significant impact on human physiology and therefore health. Assessing the impact of climate change on health is a complex task. There are often difficulties in obtaining data. Among them are the frequent interaction of climatic-environmental influences on health with factors such as level of economic development, the state of public health systems, and individual and population behaviour. Climate change will result in the increased prevalence, distribution, and severity of known occupational hazards such as heat stress and accidents although; 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 and new conditions leading to new hazards and risks. Climate change will affect living and working environments and create health threats for millions of people[14]. For example, in the United States, 423 heat-related fatalities among crop production workers occurred during 1992–2006 and this number was increasing over time. The heat related average annual death rate for these crop workers was 0.39 per 100,000 workers, compared with 0.02 for all U.S. civilian workers[15]. Eventually, this could hamper economic and social development[6, 16].

Health effects and occupational heat exposure
Health effects
The physiological basis for the effects of heat on humans is well understood[17–25] and extensive research have been done in military settings[26–28]. Still, all is not yet understood of the pathophysiology of heat exhaustion and heat stroke. Human heat tolerance is the result of a series of adaptations that have been genetically encoded. Humans are born with a highly specialized complex of thermoregulatory sweat glands and a sensitive control system. For those groups living in hot environments, the employment of behavioural and cultural mechanisms has served as a buffer and it is clear that physiological adaptations

are still of dominant importance in daily survival[29]. 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[30]. Factors such as pre-existing disease, clothing, age, gender, ability for heat acclimatization, level of physical activity, and body size, can influence the health impact of heat stress. Also, the most powerful form of human thermoregulation is behavioural and includes measures such as less movement, clothing, seeking shade and opening windows[29].

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[31]. 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 an eventual failure of the central nervous thermoregulatory system[32]. Health consequences range from dehydration, injuries, and heat fatigue to a higher burden of respiratory and cardiovascular diseases, cataract, kidney failure, weakening of the immune system and death[2].

The body heat balance is determined by these six fundamental factors:
1. Air temperature
2. Radiant temperature
3. Humidity
4. Air movement[6]
Non-climatic parameters:
5. Clothing
6. The metabolic heat generated by human physical activity[6]

The human heat exchange with the environment is pictured in Fig. 1.

In addition, acclimatization and hydration status, body posture, clothing permeability and other factors affect this balance[33]. An initial understanding of how environmental features can affect human heat tolerance may be gained through examination of the processes of heat transference between the body and the macro environment[29]. These processes are radiation, conduction, convection, and evaporation at the skin surface and the lungs[28]. 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
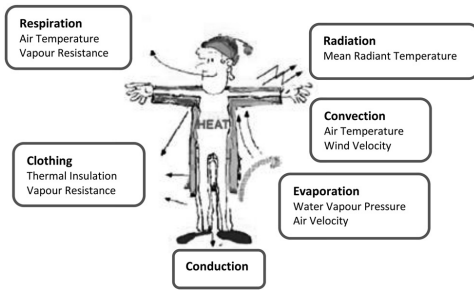
Fig. 1.　Human heat exchange; Holmér, 2007.

dry heat loss (radiation and convection) and evaporative heat loss (sweating)[34]. 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[35]. Clothing affects the transfer of heat from and to the body through resistance to air movement and water, permeability and ventilation. The insulating characteristics influence the transfer of heat[36].

Connected to the human heat exchange is the heat balance equation, through which the balance between heat production and heat exchange can be calculated (can be modified to account for clothing):

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

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

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 wind velocity and air humidity are critical environmental factors in hot conditions. If the humidity is high, sweat is still produced but evaporation is reduced which reduces the cooling effect[35]. The thermoregulatory response can be powerful and effective but it can also incur a strain on the body which can lead to heat illness[28]. Heat disorder occurs for one or more of three reasons: dehydration/lack of ac-

climatization, 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[28]. Heatstroke has a high fatality rate and even nonfatal heatstroke can lead to long term effects. Sweating imposes the greatest strain on the body. Severe dehydration (at a water loss of about 6% of body weight) may lead to heat exhaustion and circulatory collapse[35]. Together with water loss, sweating produces a loss of electrolytes, mainly sodium and chloride, but also to a lesser degree magnesium, potassium etc. If the sweat loss is replaced by water, this may cause cramps due to the malfunction of nerves and muscles. Dehydration of over 3% of body weight should always be treated with water and electrolyte replacement[35].

Occupational heat exposure

Workers in the outdoor occupations with high physical load are most at risk for severe heat exposure. Also at high risk are workers required to wear semipermeable or impermeable protective clothing and/or personal protective equipment (PPE) that severely impedes heat exchange through evaporation[36, 37].

Heat can cause workers to take off protective clothing due to discomfort, putting the worker at high risk for dangerous exposure and injury[38]. There are also possible heat implications for indoor workers in buildings without air conditioning or proper ventilation systems in warm countries. Most of the heatstroke deaths reported have been associated with occupational exposure at construction sites, agricultural settings, and hot industrial jobs requiring heavy work. The increased cardiovascular load experienced during heat stress compromises the capacity for physical work[39]. Cognitive and physical performance decrements can occur at hyperthermic and/or dehydration levels lower than those causing heat injuries[34]. Furthermore, socioeconomic factors such as income and urbanization can compound the adverse health outcomes from heat stress on workers as it may indirectly cause psychological distress due to reduced work productivity, lost income, and disrupted daily social activity[40]. Outdoor work is the most problematic and fatalities due to heat stress are associated with warm nights, hot days and hard physical work. 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, strenuous leisure activities, or living in unremittingly hot quarters. In addition, nutritional status and hydration may reflect patterns of eating and drinking, which may

also change with season or religious observances[35]. Heat exhaustion is most often preceded by dehydration and is usually associated with unacclimatized workers. Heat stroke in otherwise normal and healthy people results from a combination of excessive heat exposure and physical work[36]. Fluid requirements generally depend on work rate, the ambient climatic conditions, and on individual physiological and biochemical characteristics.

Implementation of strategies to maintain adequate hydration is the single most important intervention in the management of work in heat. Where this cannot be achieved, it is necessary to set dehydration limits of the percentage lost in body weight (e.g. a 2% decrease translates into 1–4 litres of liquid[28]). Detailed limiting values for work in hot environments can be found in international standards such as ISO7933 for acclimatized and non-acclimatized workers[41]. Yet, it is found that even if water is readily available, men working in the heat will drink less than that lost through perspiration, referred to by researchers as 'voluntary dehydration'[28, 29]. 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[35, 42]. Another intervention could be to implement traditional work-rest schedules developed for centuries to deal with heat, instead of simply implementing an industrial model, or to develop individual work-rest schedules. Urban workers may also be exposed to additional heat stress as a result of the urban 'heat island effect' of the urban built environments[1].

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[2]. Built-up areas influence the absorption and reflection of solar radiation, the ability to store heat, the absorption and emittance of long wave radiation, winds and evapotranspiration (the discharge of water from the earth's surface to the atmosphere). 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[43]. A limited number of trees and vegetation in urban areas also decreases the capacity to cool the air through transpiration (the loss of water by evaporation in terrestrial plants)[3]. The 'urban heat island effect' is thus the heat
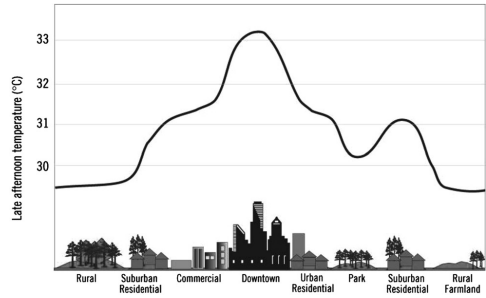

Fig. 2.   Heat island effect profile; US EPA, 2012[45].

absorption in cities and refers to the difference in temperatures measured inside and outside the city[44]. This is primarily a nocturnal phenomenon, as during daytime, urban-rural temperature differences are usually smaller because of the relatively high thermal capacity and energy storage of urban surface materials. After sunset, the energy stored is released causing an additional warming. The severity of the urban heat island decreases with increasing emissivity (emission of energy by radiation) from the sky (e.g. due to increased cloud cover) and with increased wind speed. These elevated temperatures can increase the magnitude and duration of heat waves. Some large cities, such as Mexico City, have shown a heat-island effect measuring an increase of up to 4−5°C in comparison to the surrounding rural areas[43]. Below is The US Environmental Protection Agency's schematic view of the heat island effect profile (Fig. 2).

Individual aspects

Individual factors such as physical fitness and health status plays a fundamental role in heat tolerance[28]. When working in heat, people with the highest risk are those with small body size, overwheight, 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[46]. Individual differences include the effects of age, gender, body morphology, disability, aerobic capacity, acclimatization, state of health, clothing and personal protection equipment[47]. How ethnic origin and cultural differences, including human behaviour, influence heat tolerance, is not fully understood[28]. Knowledge of the mechanisms behind subjective differences is important for risk assessment[44] and the next sections will explore these aspects further.

Children and the Elderly People

Children and elderly people are likely to be more sensitive to over-heating, in particular if they are working. An excess death rate due to heat illness has been reported among elderly people, infants and children[44]. This is partly due to physiological difficulties in regulating heat, and restricted mobility, which decreases the ability to access fluids when needed[48]. Children are included in this review on occupational health as child labour is still common in many countries (this is against international conventions such as the International Labour Organizations Convention nr. 182 on the worst forms of child labour and nr.138 on minimum age[49]). Children may also be present in workplaces, and babies may sometimes be strapped on the back of their mothers as they are working. An excess death rate due to heat illness has been reported among infants and children during heat waves compared with adults[50].

Babies have relatively large heads, large surface area to mass ratios, high blood flows and limited sweating capacity, as their system of thermoregulation is still developing. It is also likely that thermo-neutral temperatures occur within a narrower range of conditions[28]. The limited ability to thermoregulate makes small children more at risk of dehydration[44]. Infants will experience a more rapid rise in body temperature and may not be able to respond by removing themselves from the stress environment or pursuing other behavioural defences[51].

The reason why elderly people are particularly at such an increased risk of thermoregulatory deficits is not a new question, yet still unsolved[52]. Generally, body mass, size, and composition changes with age in addition to the decline of homeostatic responses and the regulation of blood pressure[24]. These changes usually take place around the age of 80[53] and as retirement age is increasing in many countries, or in some, workers continue working until they are unable to do so. As a result, examining the effects of heat stress on elderly people at work is essential. Available data suggest that heat tolerance is reduced in older people as they have lower metabolic rates and aerobic capacity (oxygen uptake) due to sedentary lifestyles (although core temperature remains the same)[28]. Due to a reduced activity level, old people tend to expose themselves less to physical strain which leads to a loss of heat acclimatization, reduced ability to transport heat from the body core to the skin, and a lower cardiovascular stability[35]. Longer periods of hot weather, especially when little relief is given at night have hit primarily the older population. The percentage of people with illnesses and disabilities also increases with age[54].

On the other hand, in a study by Kenney and Havenith in 1993, it was found that when fit healthy older subjects are matched with younger subjects of the same gender, size and body composition, metabolic rate, acclimation state and hydration level, the thermal tolerance is less a function of chronological age than of functional capacity and physiological health status. As a result, what is not so clear is whether aging per se is associated with poor heat tolerance, or whether alterations in other factors associated with the aging process play a larger role[55].

Men and women

Men and women have slightly different physiology, endocrinal physiology and body characteristics; one example being men having on average greater body size, weight and strength. In general, yet with large individual differences, women have a larger surface to mass ratio, which implies that women are more prone to heat loss. On the other hand, women have a higher whole body and subcutaneous fat content than men, which in turn increases insulation. Women are known to have colder skin at distal areas, despite the increased body fat content relative to men. Part of this effect can be attributed to reproductive hormones and the menstrual phase. In general, relative to men, the thermoneutral zone of women is shifted upward (the temperature range at which the person feels 'comfortable')[56]. When comparing the sexes, it has been observed that women tolerate humid heat better as females are superior in suppressing excess sweating and therefore conserve body water. Both sweating and vasoconstriction thresholds are 0.3−0.5°C higher in women than men, even during the first days of the menstrual cycle. Differences are even greater in between menstruations[53]. Males have higher maximal sweat rates, which may enhance tolerance for extremely hot and dry environments[35].

In contrast, some studies have found that there is no or little difference between men and women in either metabolic heat production or in heat exchange by radiation, convection or evaporation. The observed superior capacity of men for sustained exercise in desert heat is rather related to their higher aerobic capacity and not to a difference in capacity for thermoregulation. Differences in heart rate between men and women are mainly dependent on individual differences, fitness and stress level rather than differences in thermoregulation[57].

Although in a study by Havenith in 2005, females had generally higher core temperatures, skin temperature, heart rates, blood pressure, and set points for sweating, in comparison to males[57]. Moreover, Witterseh et al., 2004,
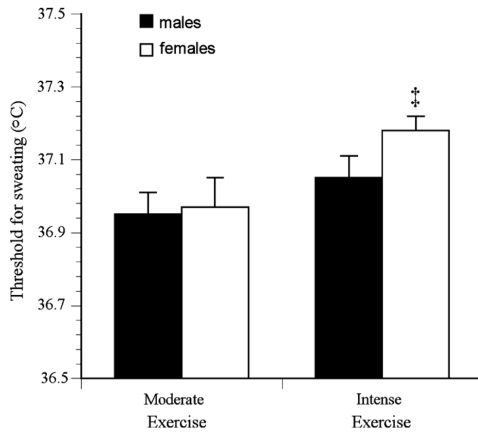
Fig. 3. Gender differences in onset of sweating during exercise, Kenney *et al.*, 2007[59].

found that the effects of heat stress on performance seem to be more adverse for males than for females[58] and Kenney *et al.*, 2007 found that females show a greater increase in the core temperature onset threshold for sweating in both moderate and intense exercise (Fig. 3)[59].

Two specific female processes do affect thermoregulation: the menstrual cycle and menopause, although the effect of the menstrual cycle at rest (a higher core temperature in the postovulatory phase) seems to be almost absent during heat exposure. Postmenopausal hot flashes and night sweating provide anecdotal evidence that thermoregulation is affected by oestrogen withdrawal[57]. The effect of pregnancy on women's heat tolerance is not clear, but altered hormone levels, added weight, reduced adaptive capacity and the increased circulatory demands of the foetus on the mother may increase the susceptibility to fainting. Severe maternal hyperthermia (over-heating) due to illness appears to increase the incidence of foetal malformation[35]. In a study by Hartgill *et al.*, 2011, it was found that human temperature regulation is altered in pregnancy. Maternal core temperature was at its highest in the first trimester but fell during pregnancy with its lowest point 3 months post-delivery and persisted until 6 months after delivery in breast-feeding women. The causes of the delayed return to normal temperature can currently only be speculated on[60]. It also appears that women, especially older women, are more at risk, in both relative and absolute terms, of dying in a heat wave[44]. Whether or not this is due to women generally living longer is not clear.

Ethnicity

Few studies were found in relation to ethnicity and heat tolerance. It is suggested that people living in high altitudes, such as Tibet, in the hot climates of Africa, or in the cold environments of Lapland may have developed special physiological capabilities for coping with extremes. Such adaptations might even be genetic such as the Saharan Touareg, with tall slender bodies that maximize the surface cooling area in proportion to the amount of body tissue that produces heat.

Some adaptations, though, may well be acquired during one's lifetime rather than being genetic[61]. In one study by Meese, 1983, it was found that Afro-American subjects show a performance reduction with falling temperature when compared to Caucasians[62]. In a recent case control study it was found that African-Americans had the highest risk of heat-related mortality, and that Caucasians had a higher risk than Hispanics[48]. On the other hand, this might be more related to socio-economic status than ethnic origin. It has also been found that people from New Guinea have lower sweat rates than Nigerians, showing some genetic factors in variations of sweat rate[28]. There is little evidence, though, of inherent or genetic differences in response to heat stress and all humans appear to function as tropical animals. The ability of humans to live and work in a range of thermal conditions rather reflects adaptation through complex behaviour and the development of housing, clothing and technology. Apparent ethnic differences probably relate more to body size, individual life history and nutritional status rather than to inherent traits[35].

Productivity loss and economic impact

Productivity is strongly dependent on thermal conditions, in particular during physically demanding work[63]. 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[61]. 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, behavioural and cognitive performance[28].

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. It is estimated

that approximately a 7% increase in productivity is present in a workplace maintained at the population-average neutral temperature of between 20–24°C[64–66]. It is also estimated that productivity is affected after about one hour of moderate physical work in temperatures above 32°C[61]. In an analysis of Thai industrial workers by Tawatsupa in 2009, it was found that ~60% of the workers reported loss of working capacity in the heat, and about 20% were more vulnerable to heat illnesses during the summer months[40]. In a study by Kjellström *et al.*, 2009, it was found that by the 2080s, the greatest absolute losses of population based labour work capacity (in the range 11 to 27%) will be seen under the IPCC A2 scenario in Southeast Asia, Andean and Central America, Eastern Sub-Saharan Africa and the Caribbean. The A2 scenario assumes a high population growth and medium rapid economic development and therefore represents a moderately 'high' emissions scenario[68].

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 preventive reaction is reduced hourly work capacity and economic productivity 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. In the long term, this will affect individual, local, national and regional economic productivity.

An enterprise can compensate for this by carrying out heat sensitive work during the cooler night hours of the hot season or by scheduling such work in the cooler season, but as climate change progresses the duration of cooler periods will be shortened. In addition, some work has to be carried out during daylight[67]. Without adaptation, the economic losses of reduced labour productivity relative to baseline could potentially be up to 20% of the gross domestic product (GDP)[68].

Developing country context

The proportion of the world's population living in the tropical climate zone, with normal daytime air temperatures exceeding 30°C, is estimated to be about 40%. Conditions are in some countries worsened by intense solar radiation and high humidity[11]. Most tropical countries are developing countries and most are experiencing rapid urbanization[43]. 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[69]. Despite this, few comprehensive assessments on the effects of climate change on health have been completed in low-income countries, and none in Africa[11].

Occupational health and safety is one of the basic rights that workers are being denied in many developing countries[70]. 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 heat, which limits the ability to produce, stress and serious mental and physical health problems may become a negative outcome. In addition, on the side of paid work, many workers also engage in water collection, 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[71]. Moreover, commuting to and from work is a daily source of heat exposure for many people. Urban growth is extensive in these regions making populations especially vulnerable to climate change[11].

Agriculture is generally a big employer in the developing world. Commonly, farm workers work are at high risk as they work under high pressure, perform extended hours of work in heat and high humidity, suffer dehydration and often do not have sufficient knowledge regarding prevention from heat exposure. Additionally, cultural aspects and malnutrition, poverty and stress add to the high risk environment[72]. For example, fatality due to heat accounted for 11% of farm accidents in India during the heat wave of 1998–1999[73]. Another example is in Central America, where authorities are overwhelmed by the high prevalence of chronic kidney disease (CKD). CKD is a worldwide public health problem and knowledge about the prevalence or incidence of early-stage CKD is scarce. One hypothesis is that heavy workloads in a hot climate lead to chronic dehydration, partly causing the problem[74].

It has been found that this disease has a high prevalence in sugarcane workers where they are under constant heat stress. It may be partially due to chronic dehydration related to working conditions[75].

In developing countries people may be more or less acclimatized although health and nutritional status, access to drinking water and widespread precarious work are decisive factors[39]. In addition, small and medium sized enterprises (SME's) are the most common employer. It is estimated that SME's have a 33% greater accident rate than companies with 200 employees and more. It is

therefore essential to increase the likelihood of improvements of the working conditions in SME's[76]. In a study by Ayyappan *et al.* in 2009, multiple locations and industries were measured around India (400 measurements). The study showed that many processes even in organized large-scale industries have yet to control heat stress related hazards adequately[5]. Additional examples from industries in Thailand and Tanzania have shown that the workplaces frequently exceed international guideline values for heat[40], such as ISO7243 and ISO7933, which describes appropriate heat stress indices and guidelines[41, 77]. These guidelines, however, have been assessed in developed countries and therefore are not fully applicable in warm developing countries where workers are more acclimatized[78].

Preventative and control measures

Despite uncertainty in climate change impacts, it is assumed that humans will have to adapt to warmer temperatures. 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). Whether or not humans will be able to adapt to future increasing heat is uncertain, although humans already inhabit various climatic spaces[8].

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[4]. 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 public health efforts in response to heat focus primarily on reactive measures rather than long-term adaptation. The underlying perception that heat is not a high priority prevents the uptake of relevant information to avert heat stress. On the other hand, working practices for hot environments are well established (for example NIOSH, 1986[79]), including the use of appropriate heat stress indices, acclimatization programmes, and the importance of water replacement, although, lessons seem to have to be re-learnt[28].

The main factors for the protection against danger from heat at the workplace are to safeguard from and control the source of the heat[40]. 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[28]. General controls should be implemented anytime there is a reasonable potential for heat stress on the job and are applicable across all heat stress jobs. Specific controls are directed to individual jobs and include specific training, heat stress hygiene practices and medical surveillance[36]. 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[36].

Engineering control measures

Engineering solutions include those of risk alert systems, response plans, water delivery, portable shade structures, water based cooling, air based systems, decreased clothing insulation (e.g. through smart textiles), ventilated clothes, cooling centres, air conditioning, personal cooling systems (e.g. ice vest) protective clothing, wearing white and loose-fitted clothing, etc.[72]. Active cooling systems are widely available such as liquid cooling and air cooling garments[28]. Active cooling systems include external connections to air or liquid supplies such as ventilated cooled air and circulated liquid cooling[80]. A practical solution is that of increasing ventilation in clothing by using air permeable clothes that are designed to increase possibilities for ventilation or by using fans for active ventilation. Passive cooling systems utilize phase change materials (PCMs) (e.g. ice, frozen gel, salt, wax) in vests and clothing. PCMs are latent heat storage materials and absorb or release heat when they change phases, such as from solid to liquid (heat of fusion), and back to solid (heat of crystallization). Therefore, a PCM has two types of thermal effects: a cooling effect when it melts and a heating effect when it solidifies[81, 82]. Wearable personal cooling integrated with PCMs has the advantage of cooling the human body's micro-environment in contrast to stationary personalized or building cooling, thus providing greater mobility and saving energy[80]. Selection of the optimum active clothing system will depend upon the requirements of the task and consideration should be given to work organization and design. Any effective cooling system should be placed where a heat exchange occur, for example, by the neck, wrists and under arms, and should not restrict thermoregulation.

For instance, when wearing a cooing vest running up a hill, the metabolic cost of carrying the vest might offset the

benefit of cooling. The vest can also restrict the evaporation of sweat, add weight, increase the metabolic rate, and so on. For a sedentary task in a hot environment, however, it may be useful if it does not cause too much cooling[28]. Moreover, these technical fixes may not be applicable to developing countries, especially in small businesses where room for investment is scarce. For instance, the price of a cooling vest ranges between \$200−300, which is why preventative and managerial methods may be more appropriate in a developing country context. On the other hand, all workplaces around the world should follow the widely accepted traditional hierarchy of controls mentioned earlier[36].

Dehumidifying and cooling the indoor air may reduce heat stress and increase productivity in hot and humid indoor work places in developing countries. However, many work situations are such that air conditioning is not feasible and fans are not sufficient when the heat exposure is very high. In addition, air conditioning is costly as it uses plenty of energy, which also adds to the climate change problem. Moving the person to a cooler area and cooling off the person's body may be an essential preventive action[40]. An innovative solution is a solar-powered system for supplying dry air in offices, providing a low-cost alternative to traditional air conditioning in hot and humid regions. The system can also be produced using local skills and resources, representing a low-cost alternative to high-tech air conditioning[83].

Preventative control measures

Preventative interventions include design of urban areas, trees in industrial areas[83], design of housing and workplaces to reduce heat exposure, increase shading, and public and occupational health programmes that protect individuals at risk, among others[40]. One general control is that of work-rest regimes. However, determining safe work-rest regimens based on heat stress criteria is challenging. Relying on the self-pacing of the workers is not recommended especially when the task has an urgent character or involves productivity incentives. Studies have shown that self-paced work-rest regimes were poorly related to physiological parameters[84]. Self-chosen rest periods are too short to dissipate heat[38]. Therefore, self-paced workers must be associated with close supervisory surveillance or predetermined work-rest schedules, which may constitute a better solution[85]. 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[1]. Finally, education and training of workers and employers is essential for effective risk management. Measures that reduce thermal stress without compromising performance and productivity, together with being a low cost option, are more likely to be accepted[23].

Conclusion and Future Research Needs

On the basis of the reviewed articles, it can be summarized that heat stress has been researched extensively in the past. However, in the contemporary context of climate change, information is lacking on the extent of future heat stress and its consequences, especially in an occupational setting. It was also found that heat stress is often an overlooked problem and that lessons seem to have to be relearnt. The main factors found to exacerbate heat stress in the current and future workplace 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 elderly people and pregnant women.

Occupational health and safety is one of the basic rights that workers are being denied in many developing countries. In addition to this, as work productivity reduces with increasing temperatures, world economic productivity will be condensed, affecting developing countries disproportionately as most of these already are located in warm climates. To address these current and future occupational health problems, sustainable solutions must be interdisciplinary and take into account the social, economic, environmental and technical aspects of the problem. Both mitigation and adaptation measures should be considered, sometimes in combination and including both preventative and control solutions, to achieve multiple benefits. Capacity building such as education and awareness, and involvement on all levels of society is needed to address this.

From the review it became apparent that research is needed in these areas:
- Occupational heat stress in different countries and ways of dealing with it; studies are especially needed in Africa.
- Heat island effects on workplaces in urban areas.
- Current adaptation practices in warm countries.
- Heat stress control options and possible sustainable solutions (low cost).
- Analysis of future productivity losses due to heat stress and economic analysis.

- Social and health effects of heat stress.
- Effects on vulnerable groups such as young and elderly people, women, pregnant women, and poor people.

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Paper II

ORIGINAL ARTICLE

Occupational heat stress and associated productivity loss estimation using the PHS model (ISO 7933): a case study from workplaces in Chennai, India

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Background: Heat stress is a major occupational problem in India that can cause adverse health effects and reduce work productivity. This paper explores this problem and its impacts in selected workplaces, including industrial, service, and agricultural sectors in Chennai, India.
Design: Quantitative measurements of heat stress, workload estimations, and clothing testing, and qualitative information on health impacts, productivity loss, etc., were collected. Heat strain and associated impacts on labour productivity between the seasons were assessed using the International Standard ISO 7933:2004, which applies the Predicted Heat Strain (PHS) model.
Results and conclusions: All workplaces surveyed had very high heat exposure in the hot season (Wet Bulb Globe Temperature $\bar{x}=29.7$), often reaching the international standard safe work values (ISO 7243:1989). Most workers had moderate to high workloads (170–220 W/m^2), with some exposed to direct sun. Clothing was found to be problematic, with high insulation values in relation to the heat exposure. Females were found to be more vulnerable because of the extra insulation added from wearing a protective shirt on top of traditional clothing (0.96 clo) while working. When analysing heat strain – in terms of core temperature and dehydration – and associated productivity loss in the PHS model, the parameters showed significant impacts that affected productivity in all workplaces, apart from the laundry facility, especially during the hot season. For example, in the canteen, the core temperature limit of 38°C predicted by the model was reached in only 64 min for women. With the expected increases in temperature due to climate change, additional preventive actions have to be implemented to prevent further productivity losses and adverse health impacts. Overall, this study presented insight into using a thermo-physiological model to estimate productivity loss due to heat exposure in workplaces. This is the first time the PHS model has been used for this purpose. An exploratory approach was taken for further development of the model.

Keywords: *occupational heat stress*; *productivity*; *international standards*; *India*; *climate change*

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W hen the human core temperature reaches or exceeds 38°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, especially physically (1). A natural reaction of a working person to heat is to reduce physical activity, which reduces the body's internal heat production (2–5). An outcome of this natural preventive mechanism is reduced work capacity, which results in lower productivity (2). Occupational health is affected by climate change by increasing temperatures, among other

impacts (6, 7). The Intergovernmental Panel on Climate Change in its latest report states that hot days, hot nights, and heat waves have become and will become more frequent over most land areas (8). In addition, it has been observed that the increasing temperature of ocean surface water will create more evaporation of water resulting in higher absolute humidity of the atmosphere over most land areas (6). High humidity affects human thermal regulation because of reduced evaporation of sweat.

Heat exposure has been shown to affect outdoor workers in India (9, 10) and associations between high temperatures

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and mortality have been established (11, 12). Dunne et al. 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 (8). Without adaptation, the economic losses of reduced labour productivity relative to baseline could be significant (3) and become the most costly impact of climate change (13).

This paper explores the problem of heat stress in selected workplaces, including industrial, service, and agricultural sectors in Chennai, India. During the hottest month in Chennai, temperatures are already high enough to cause major loss of hourly work capacity and this situation will worsen for many jobs in the face of future climate change. Data were collected in the cooler and hotter seasons to estimate the current occupational heat stress situation and associated productivity impacts between the seasons. The study was conducted using the heat balance equation and the Wet Bulb Globe Temperature (WBGT, ISO 7243) index (14). Heat strain and associated reduced labour productivity between the seasons was assessed using the International Standard ISO 7933:2004, which adopts the Predicted Heat Strain (PHS) model (15). This physiological model has been used in previous studies, for example, for developing heat surveillance systems (16, 17).

Background

Climate profile of Chennai
Chennai, the capital city of Tamil Nadu, is located near the equator and experiences a hot and humid climate through-out the year. Temperature range in the hot months of May and June is between 35 and 40°C and the month of May records the highest temperatures reaching 45°C causing potential risks to local workers of developing heat-related disorders. Winter occurs from November to February, with January being the coolest month of the year (15–22°C). During the monsoons, from June to September, Chennai receives abundant rainfall and humidity is high with a relative humidity of between 80 and 96% (18). Based on this, the field work was carried out during the periods January–February and April–May to assess productivity loss between the hot and cool seasons.

Description of workplaces
Cookie factory
There are different sections and work tasks in the production line. The first section is the raw material receiving and storage area, involving such tasks as lifting of boxes, carrying, and bending. The tasks are performed in semi-outdoor conditions. In the next section, the pre-scaling area, different raw materials are received and weighed and sent to the mixing area. Mixing is done both manually and mechanically. The cookies are baked in the production area. The finished products are received in the packing area and work is performed in standing positions. Finally, in the dispatch area, the packed goods are stored and materials are loaded manually into vehicles (Fig. 1).

Canteen
The canteen has different sections that prepare western and south Indian food. In the raw material receiving and

Fig. 1. Pictures of workplaces: a) outside view of cookie factory, b) food serving area of the canteen, c) drying machines at the laundry, d) agricultural field, e) roof of construction building.

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 section, computer billing is carried out at different counters that are manned by clerks who are standing (Fig. 1).

Laundry facility
The laundry facility serves students, faculty, and the hospital. The laundry from the hospital is decontaminated before washing and hot pressing. In the hot press section, large sheets are fed into the press and the work is performed manually. In the washing section, clothes are fed into the machine and unloaded manually. After washing, the clothes are loaded onto a trolley and taken to the drying section. After drying, the clothes are manually ironed and folded (Fig. 1).

Agriculture
The agricultural area is located in a village outside Chennai where crops are cultivated according to the seasons. There are different phases in cultivation: preparation of land for cultivation, sowing, watering, clearing 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, the workers perform intense shovelling, although sometimes tractors are used. Manual work is performed in the other phases. Workers spend most of their time bending during planting and harvesting (Fig. 1).

Construction
There are different work tasks involved in construction, such as intense shovelling, carrying and disposal of debris, and cutting of iron bars. 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 work performed. Most of the workers are migrants from poorer Indian states. Besides working in the construction site, the workers are also constantly exposed to heat in their temporary housing. The houses are made of metal sheets that do not provide relief from heat exposure after work (Fig. 1).

Methods
Six parameters were measured in this study to determine the body heat balance. Four were environmental parameters: air temperature, radiant temperature, humidity, and air movement. Two were non-climatic parameters consisting of clothing and metabolic rate (4).

Environmental parameters and the WBGT index
The WBGT (ISO 7243) is a direct index simulating the response of the human body to heat stress and is widely used in the assessment of occupational heat stress (4, 14, 19). The international standard for 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 that is strongly affected by heat radiation; and T_{nw}, the natural wet bulb temperature, which is measured in the actual sun and wind exposure situation, with a wet cloth over the bulb representing the impact of evaporation (14). In this study, T_a, T_{nw}, T_g and relative humidity (RH) were collected using the 3 M™ QUESTemp°™ 32 heat stress meter (accuracy of T_a, T_{nw} and T_g: $\pm 0.5°C$; RH: $\pm 5\%$) together with personal exposure measurements using LASCAR dataloggers (EL-USB-2-LCD$^+$, accuracy of T_a: $\pm 0.3°C$; RH: $\pm 2\%$).

Clothing
The work clothing was tested for insulation and evaporative resistance on thermal manikins at Lund University, Sweden; Loughborough University, UK; and Hong Kong Polytechnic University as part of another research project (20). Five sets of work clothing from Chennai were included in the project and in this analysis based on their widespread use in many workplaces.

Metabolic heat production
Work activity was calculated according to heart rate conversion to metabolic rate (21) if possible. Heart rate was measured using POLAR pulse monitors (Käyttö 4000 RUD 11.93 STK model, with readings every 15 sec). Heart rate recordings are affected by factors such as physical fitness, environmental temperature, nutrition, health status, psychological factors, and size of active muscle mass; all of which add complexity (22). In addition, the methods of estimating the metabolic rate involve many uncertainties because the worker usually performs a combination of activities and hence, the metabolic rate fluctuates during the working day (23). Because of these aspects, and because of the limited measured data (not available for agriculture and construction), observations using the ISO 7243 reference table complemented the measured data (14).

Heat strain and labour productivity
Previous papers examining climate change, heat, and work productivity have used productivity measures such as the collection of 'bundles' (24), gross domestic product (GDP) together with climate data (8) and productivity as a function of the ISO 7243 standard guidelines (3, 8, 25) or the thermal comfort standard, the Predicted Mean Vote Index (26). In addition, the time taken to achieve production targets, company records, overtime, and the use of interviews and questionnaires about workers' perceptions of heat and

work productivity have been applied (27). Finally, thermal chamber studies have been conducted (28).

The PHS (ISO 7933) (15) is a rational physiological model based on data on physiological responses of subjects in hot conditions from laboratory studies. The model makes it possible to predict sweat rate and core temperature and calculate duration exposure limits (29–31). In this study the heat strain prediction was utilized for the thermo-physiological responses' associated productivity losses. Productivity in this paper is based on the following outputs in the PHS model: time to reach a core temperature of 38°C and maximum water loss that will indirectly affect productivity. The time to reach a core temperature of 38°C for an average worker and dehydration limits are seen as critical parameters in the model. Physiological parameters have previously been found to be indicators of productivity loss. For example, Nag et al. 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 (5). This translates into an automatic productivity loss. Internationally, the WHO 1969 guideline on the allowable limit core temperature of 38°C was developed to protect most workers (32). Dehydration affects productivity by elevating core temperature with an increase of about 0.1–0.2 degrees per percentage of dehydration (33). Dehydration also causes cardiovascular strain, resulting in elevated heart rates. Dehydration deficits of 2% of body mass can adversely impact aerobic performance, orthostatic tolerance, and cognitive function (33) and the limit used for dehydration is set at 3% of body mass for industrial workers (34). Moreover, Wasterlund et al. found that every percentage water loss in forest workers resulted in a 12% reduction in productivity (35).

In all workplaces in the PHS simulation, it was estimated that the worker was able to take three 15-min breaks (one in the morning and two in the afternoon) and one 50–75-min lunch break in between during 8 hours. Resting means the metabolic rate was set at 100 W/m². Environmental data input for resting was considered the coolest room or in the shade, as no workplace had air conditioned resting areas. An air velocity of 1 m/s, simulating a slow walk, was used in the model as body movement creates air flow over the body (19); and an air velocity of 0.3 m/s was used when resting. All workers were considered acclimatized with free access to water (however, in agriculture, the workers usually carry their personal water bottle of about 1.5 litres out to the field, consequently making them more vulnerable to risks of heat stress).

Results

The average basic environmental parameters and standard deviations for each workplace in the cooler season (January–February) and hot season (April–May) can be seen in Table 1. The results are averages of measurements in the different sections at each workplace.

A two-tailed paired students t-test proved a statistically significant difference in WBGT values between the cooler and hotter months ($p = 0.002566$). Though the productivity loss associated with following ISO 7243 guidelines (estimate value from linear regression model $\beta = 0.5924$), the increased WBGT values are not statistically significant ($p = 0.2541$), which could be partly due to the small sample size.

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

Most clothing was made of cotton and had high insulation values in relation to the heat exposures. Female clothing with shirt and head cover had higher insulation values compared to male workwear. In Chennai, it is common for female workers to wear traditional clothing – churidars and/or sarees – with a protective shirt on top and head cover while working in some workplaces, which decrease ventilation. When this was the case, the female workwear had considerably higher insulation and evaporative resistance than male workwear (20).

Metabolic heat production
The mean heart rate results and standard deviations, together with observations using the ISO 7243 reference table are presented in Table 3.

The heart rate subjects in Table 3 were only men because of cultural limitations. Most were under the age of 30; one was 52, and one was 60. Measurement time varied between 3 and 5 hours. Because of this limited data, observations using the ISO 7243 reference table complemented the heart rate data. The very high results from the heart rate data – 260 and 245 W/m² – were mainly due to very high heat exposure (33): the baker in the cookie factory and the dryer in the laundry, respectively.

Anthropometric data
The data consisted of average values measured on selected workers at the workplaces (66 males and 11 females). The average male was 167 cm (SD 7.4) and 64 kg (SD 12.6), and the average female, 150 cm (SD 4.1) and 56 kg (SD 3.9) was used as data input into the PHS model.

Heat strain and labour productivity using the PHS model (ISO 7933)
Figure 2 illustrates the output from the PHS model, which predicts the time to reach maximum water loss for the average healthy working person. The worker should rest and drink when this limit is reached, affecting productivity. The sweat rates are very high in the hot

Table 1. Environmental parameters and WBGT index measurements

Parameter	Cookie factory		Canteen		Laundry facility		Agriculture		Construction	
	Cooler	Hot	Cooler	Hot	Cooler	Hot	Cooler	Hot	Cooler	Hot
T_a	30.2 (s.d. 1.3)	35.6 (s.d. 2.4)	33.7 (s.d. 2.3)	36.8 (s.d. 1.7)	30 (s.d. 0.5)	32.7 (s.d. 0.3)	28.9 (s.d. 0.5)	32.0 (s.d. 0.3)	30 (s.d. 0.0)	34.2 (s.d. 0.8)
T_g	30.5 (s.d. 4.6)	36.0 (s.d. 4.1)	35.2 (s.d. 3.6)	38.1 (s.d. 3.0)	30 (s.d. 1.4)	32.7 (s.d. 0.2)	38.5 (s.d. 2.1)	39.5 (s.d. 0.6)	32 (s.d. 1.3)	37.6 (s.d. 5.4)
T_{nw}	22.8 (s.d. 0.9)	27.4 (s.d. 1.5)	27.1 (s.d. 1.3)	30.0 (s.d. 0.9)	21.2 (s.d. 0.3)	26.5 (s.d. 0.8)	24.4 (s.d. 0.3)	26.5 (s.d. 0.4)	23.5 (s.d. 0.4)	25.3 (s.d. 0.7)
RH	54% (s.d. 3.6)	56.4% (s.d. 3.8)	59.1% (s.d. 6.5)	55.6% (s.d. 1.1)	62.3% (s.d. 3.8)	54.3% (s.d. 7.4)	58.5% (s.d. 3.9)	50.8% (s.d. 1.9)	53.6% (s.d. 2.0)	44.4% (s.d. 2.6)
WBGT	25.0 (s.d. 1.9)	30.0 (s.d. 1.7)	29.5 (s.d. 2)	32.0 (s.d. 2.3)	24.3 (s.d. 0.3)	28.0 (s.d. 0.6)	28.0 (s.d. 0.6)	29.6 (s.d. 0.4)	25.6 (s.d. 0.3)	28.7 (s.d. 1.5)

Climate Index.

season, especially in the canteen where workers should rest half the workday to stay healthy. If water is not readily available this will translate into risks for heat disorders (4).

In Fig. 3, the predicted time in minutes (total 8 hours) to reach a core temperature of 38°C is shown. As mentioned previously, when the core temperature reaches 38°C, an automatic productivity decline has been observed in India if the worker is able to self-pace.

Limitations of the study

There are no comprehensive physiological models to estimate productivity loss in hot environments and therefore, there is a need to revise the PHS model. Validation studies are required on the relationship between PHS predictions and productivity. Although, one has to keep in mind when using a thermo-physiological model that it does not account for other aspects of the work environment that affect productivity, such as light and noise (36, 37), cognitive function (33), the psycho-social environment, long commutes, lack of sleep, and stress. In addition, the PHS model also assumes an initial core temperature of 36.6°C. However, most of the workers had travelled to work or lived in hot dwellings and had therefore been exposed to heat beforehand. As a result, performance may be affected before the indicators in the model.

In general, practical considerations had a strong influence on the field research. For example, the opportunity sampling conducted with the heart rate and anthropometric data does bias how representative the sample is of the wider population. Also, the study provides only a snapshot of the reality for these workers as each field visit lasted between 4 and 6 hours during midday and not for a full working day or over several weeks.

Discussion

All workplaces surveyed had very high heat exposure in the hotter months, often reaching WBGT values over the international standard limit values (a WBGT of around 27) (14) where, depending on the metabolic rate, acclimatization state, and clothing; actions should be taken. Most workers had moderate to high workloads, some in direct sun exposure. All workplaces studied, apart from the laundry facility, reached critical thermal conditions in the PHS model, especially in the hot season, affecting productivity. In the canteen in the hot season, the limit core temperature was reached in only 64 min for women, whereas men could work for another 95 min before reaching this limit. As mentioned previously, this is mainly due to the different clothing practices. This health impact can be significantly reduced by allowing workers to self-pace their work; providing safe drinking water and regular breaks throughout the day; and awareness of heat stress symptoms. The real danger

Table 2. Clothing description and measured insulation and evaporative resistance (20)

Ensemble	Workplaces	Permeability index (i_m) (mean of 3 measurements)	Clothing basic insulation (I_{cl}) clo (mean and s.d. of 3 laboratories)
Churidar (f)	Laundry and cookie factory	0.38	0.58 (s.d. 6.23%)
Churidar + shirt and towel on head (f)	Construction, agriculture, and canteen	0.34	0.74 (s.d. 4.86%)
Saree (f)	Laundry and cookie factory	0.34	0.74 (s.d. 7.28%)
Saree + shirt and towel on head (f)	Construction, agriculture, and canteen	0.31	0.96 (s.d. 7.80%)
Shirt and trousers, with towel on head (m)	Agriculture and construction	0.33	0.61 (s.d. 2.53%)

f = female, m = male.

is when the work is externally paced (e.g. by machinery, quotas, peer pressure), as workers will push themselves beyond the safe limit and become at risk of developing heat disorders. At most risk are workers who are poorly hydrated, unacclimatized, or physically unfit.

Clothing was found to be problematic, with high insulation values in relation to the heat exposure (although within the PHS validity range) (29). A sex difference in heat exposure was observed in the population studied because females were more vulnerable due to the traditional clothing worn under protective layers in the construction, agriculture, and the canteen workplaces. Female workers' clothing practices trap a saree's layers beneath tighter textile decreasing air, vapour permeability and

ventilation, and increasing the clothing's insulation, which generates a higher heat load for these women. On the other hand, the ventilation effect of the traditional clothing such as the saree is likely underestimated as the PHS model is based on Western clothing data. Overall, it is a local cultural practice that is hard to change and requires more research.

Preventive approaches

In the questionnaire, most workers reported health problems due to heat exposure, including thirst, heavy sweating, muscle cramps, tiredness/weakness, dizziness, and headaches, and a few reported problems with nausea/ vomiting and fainting. Problems with meeting production

Table 3. Estimated average metabolic rates from heart rate data and observations at various workplaces in Chennai, India

Site, total numbers of observed workers (N) and gender	Work tasks involved (from observations)	Profession and average heart rate (b/min) measured	Average metabolic rate calculated (ISO 9886, 2004b) from heart rate (W/m²)	Average metabolic rate (W/m²) from ISO 7243 and metabolic class
Industrial: Cookie factory (N = 8; m = 7 f = 1)	Sustained hand and arm work, pushing/pulling/ lifting light weight boxes, bending, mixing, walking speed 2.4–5.5 km/h.	Mixer: 97 (s.d. 6.1)	178	**188** (130 < M < 200)
		Packer: 91 (s.d. 5.7)	144	
		Packer: 95 (s.d. 9.1)	169	**Moderate**
		Baker: 115 (s.d. 13.6)	260	
Service: Canteen (N = 9; m = 9)	Sustained hand and arm work, standing cooking, preparation, lifting/pushing/pulling light weight boxes, bending, walking speed 2.4–5.5 km/h.	Cook: 97 (s.d. 11.3)	170	**170** (130 < M < 200)
				Moderate
Service: Laundry (N = 9; m = 2 f = 7)	Sustained hand and arm work, manual loading/ unloading, ironing, folding and packing walking speed 2.4–5.5 km/h.	Dryer: 118 (s.d. 13)	245	**181** (130 < M < 200)
		Washer: 90 (s.d. 17.5)	120	
		Washer: 100 (s.d. 6)	177	**Moderate**
Agriculture (N = 4; m = 1 f = 3)	Preparation of land for cultivation, sowing, watering, weeding, pest control, fertilization, crop maintenance and harvesting, bending, walking speed 2.4–5.5 km/h.	–	–	**190** (130 < M < 200) **Moderate**
Construction (N = 16; m = 16)	Intense arm and trunk work: shovelling, carrying and disposal of debris, cutting of iron bars, pushing and pulling heavy carts, walking speed 5.5–7 km/h.	–	–	**220** (200 < M < 260) **Heavy**

f = female, m = male.
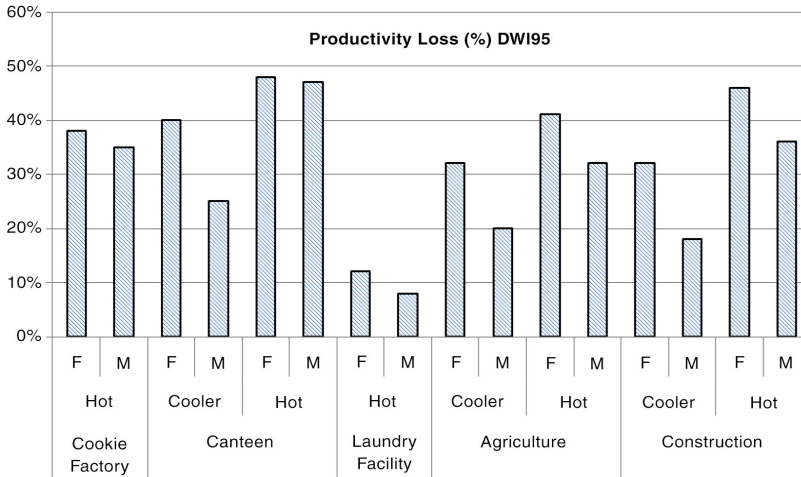Average metabolic rate for each workplace.

Fig. 2. Results from PHS simulations: predicted productivity loss estimated from Dwl95 (the maximum water loss to protect 95% of the working population). F = female, M = male.

targets in the hotter months were usually compensated for by working overtime. Locally in workplaces, there were numerous technical, behavioural, and managerial methods to reduce heat exposure. Apart from self-pacing and rest, traditional methods, including mainly drinks and diet, dominated the coping mechanisms. These were mainly drinking buttermilk (fermented yoghurt drink)

followed by fruit juice, coconut water, and fermented rice. Coconut water is a drink seen in the literature as a potential natural alternative to artificial sports drinks due to its richness in potassium, sodium, chloride, and carbohydrates (38, 39).

Other methods included ventilation, exhaust fans, and shade structures. Sustainable, low-cost and adaptable
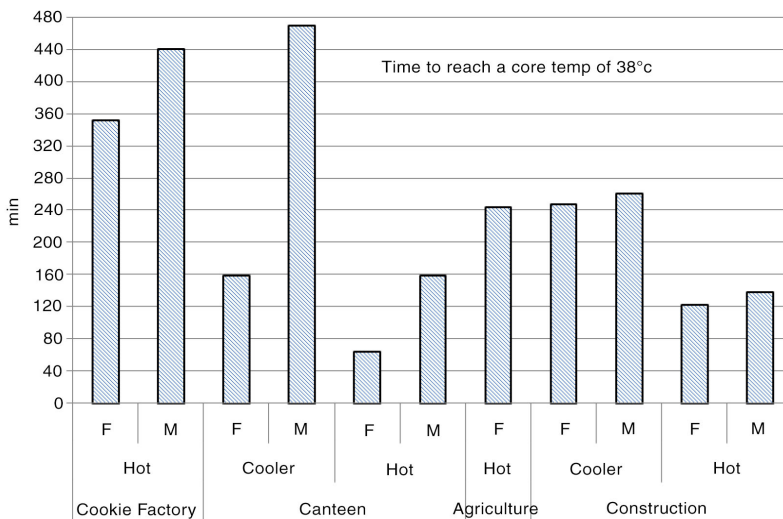
Fig. 3. Results from PHS simulation: the predicted time to reach a core temperature of 38°C. F = female, M = male.

cooling methods must be further studied and adopted together with education and awareness of heat stress.

Climate change dimensions
India is already experiencing a warming climate, and climate change risks are high and multidimensional. Warming trends and increasing temperature extremes have been observed across most of the South Asian region. The average temperature has been increasing at a rate of 0.14–0.20°C per decade since the 1960s, combined with a rising number of hot days and warm nights (40). There is a risk of an increase in mean, minimum, and maximum temperatures of 2–4°C (41). Adding these temperature projections to the current conditions at the workplaces studied, will have profound implications for the workers' health and productivity, in particular in the outdoors where cooling options are limited. Today, the thermal stress at the workplaces is already at the borderline of human tolerance and may not need to increase much to result in a drastic drop in productivity (8, 42).

Conclusion
All workplaces surveyed had very high heat exposure in the hotter months, often reaching WBGT values above the international standard limit values (measured WBGT $\bar{x}=29.7$) (ISO 7243:1989) for working safely. Most workers had moderate to high workloads (170–220 W/m²), some in direct sun exposure. Clothing was found to be problematic, with high insulation values in relation to the heat exposure. Females were more vulnerable due to work clothing practices. When analysing heat strain and associated productivity loss in the PHS model apart from the laundry facility, the parameters showed significant impact in all workplaces, especially during the hot season, affecting productivity. For example, in the canteen in the hot season, the predicted limit core temperature was reached in only 64 min for women. If self-pacing is possible and water widely available this impact can be significantly reduced. Nevertheless, with expected climate change, additional preventive actions have to be taken in these workplaces immediately to mitigate further productivity losses. Overall, this study is presented as an exploratory study into using a thermo-physiological model as the basis to estimate productivity loss due to heat exposure in workplaces. The PHS model is not designed for this, although previous studies have linked heat strain parameters with productivity loss.

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Paper III

Human responses in heat – comparison of the Predicted Heat Strain and the Fiala multi-node model for a case of intermittent work

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ABSTRACT

Two mathematical models of human thermal regulation include the rational Predicted Heat Strain (PHS) and the thermophysiological model by Fiala. The approaches of the models are different, however, they both aim at providing predictions of the thermophysiological responses to thermal environments of an average person. The aim of this study was to compare and analyze predictions of the two models against experimental data. The analysis also includes a gender comparison. The experimental data comprised of ten participants (5 males, 5 females, average anthropometric values were used as input) conducting an intermittent protocol of rotating tasks (cycling, stacking, stepping and arm crank) of moderate metabolic activities (134–291 W/m^2) with breaks in-between in a controlled environmental condition (34 °C, 60% RH). The validation consisted of the predictions' comparison against experimental data from 2.5 h of data of rectal temperature and mean skin temperature based on contact thermometry from four body locations. The PHS model over-predicted rectal temperatures during the first activity for males and the cooling effectiveness of sweat in the recovery periods, for both males and females. As a result, the PHS simulation underestimated the thermal strain in this context. The Fiala model accurately predicted the rectal temperature throughout the exposure. The fluctuation of the experimental mean skin temperature was not reflected in any of the models. However, the PHS simulation model showed better agreement than the Fiala model. As both models predicted responses more accurately for males than females, we suggest that in future development of the models it is important to take this result into account. The paper further discusses possible sources of the observed discrepancies and concludes with some suggestions for modifications.

1. Introduction

It is important to have models for heat stress prediction in order to reduce thermal risk and prevent heat induced illness in different exposure situations. The use of models to predict and quantify heat stress and strain have contributed to a reduction in morbidity and mortality in industrial, military, sports, and leisure activities (Havenith and Fiala, 2016). Mathematical modelling of the human thermal regulation goes back more than 70 years for applications in mainly occupational settings (Burton, 1937; Stolwijk, 1971; Gagge et al.,1986, 1971; Fanger, 1973; Azer and Hsu, 1977; Fiala et al., 1999, 2001, 2003; Malchaire et al., 2001; Tanabe, 2002; Malchaire, 2006). More than 100 heat stress indices and models have been developed during this time, with varying complexity and easiness to use (Havenith and Fiala, 2016). Heat stress indices and models 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 (Parsons, 2003). There are many different approaches of models to address heat stress prediction with various objectives and applications. One of the most commonly used rational indices is the Predicted Heat Strain (PHS), which is based on the heat balance equation and is also an international standard (ISO7933:2004; Malchaire et al., 2001; Malchaire, 2006). A rational physiological model representing human thermoregulation was developed by Fiala et al. (1999, 2001, 2012), Fiala and Havenith (2015), and covers to wide range of human thermal exposure and responses.

The Predicted Heat Strain (PHS, ISO 7933) index predicts changes in physiological parameters and was validated against data on physiological responses of subjects in hot conditions. The simulation model

Table 1

Metabolic rate of the activities during the exposure. Mean and standard deviation. The metabolic rate includes all types of energy use. Mechanical work was accounted for by 20% in the cycling exercise in both models.

Step	Activity	Start time	End time	Metabolic heat production [W m^{-2}]	Mechanical work [W m^{-2}]
1	Psychological test	−00:15:00	−00:00:59	80	0
2	Cycling	0:00:00	0:17:59	287 (SD 23.4)	58 (20%)
3	Rest	0:18:00	0:20:59	80	0
4	Stacking	0:21:00	0:38:59	129 (SD 14.8)	0
5	Rest	0:39:00	0:41:59	80	0
6	Stepping	0:42:00	0:59:59	220 (SD 14.2)	0
7	Psychological test	1:00:00	1:14:59	80	0
8	Arm crank	1:15:00	1:32:59	143 (SD 12.9)	0
9	Rest	1:33:00	1:35:59	80	0
10	Cycling	1:36:00	1:53:59	287 (SD 23.4)	58 (20%)
11	Rest	1:54:00	1:56:59	80	0
12	Stacking	1:57:00	2:14:59	129 (SD 14.8)	0
13	Psychological test	2:15:00	2:29:59	80	0

makes it possible to predict sweat rate, core and mean skin temperatures for an average person. However, it does not divide detailed spatial information (i.e. body segments) for sweat rate and skin temperature. An objective is to calculate duration exposure limits for use in occupational settings based on rectal temperature and sweat loss. The PHS simulation model was built on the previous required sweat rate index (SWreq) (Malchaire et al., 2001) and includes some additional aspects, such as calculation of the respiratory heat loss, distribution of heat storage in the body, exponential averaging for mean skin temperature and sweat rate, limits for non-acclimatized subjects and added mean body and rectal temperature to predicted core temperature (Malchaire et al., 2001; Malchaire, 2006). The simulation model was validated based on laboratory and field data within the European Program BIOMED II. Data from 909 experiments (672 laboratory and 237 field experiments) were gathered to a common database (Malchaire et al., 2001, 2002). One of the most innovative elements of the PHS simulation model included new algorithms for the prediction of the effects of body movements and wind on the heat exchange through clothing (Havenith et al., 1999; Parsons et al., 1999). The main limitation of the simulation model is its validity for clothing insulation in the range of 0.1–1 clo excluding highly insulating work wear (Wang et al., 2013). Furthermore, care should be taken when using available internet software with the integrated models as the algorithms of the standard model could have been modified according to the authors own interpretations and may have not been verified (d'Ambrosio Alfano et al., 2007, 2015; Ueno et al., 2009). The simulation model developed and used in the present comparison (www.eat.lth.se/fileadmin/eat/Termisk_miljoe/PHS/PHS_agenda_2.html) was based on the implementation of the model in Annex E from the international standard (ISO 7933).

The mathematical model of the human thermophysiology by Fiala (Fiala et al., 1999, 2001, 2012; Fiala and Havenith, 2015) is implemented in a commercially available software (version FPCm5.3, Ergonsim, Germany). It consists of two interacting systems: the controlled or passive system and the controlling or active system. The passive system represents the human body segmented in 20 elements and includes the physical characteristics of the human tissue and the heat and mass transfer occurring within and between the body elements as well as between the body surface and the environment. Currently, the model allows adjustment of the fitness level, acclimatization days, body size and percentage of body fat of a simulated person besides simulation of a standardized average person (Havenith, 2001; Fiala and Havenith, 2015). The active system predicts the thermoregulatory responses driven by the central and peripheral nervous system including vasomotion, shivering and sweating based on regression models. This model has been widely validated mainly for prediction of mean skin and core temperatures, showing in general an acceptable agreement in a wide range of environmental conditions, clothing and activity

level for both steady-state and transient exposures (Fiala et al., 2001; Psikuta et al., 2012; Martínez et al., 2016).

The approaches to simulate heat exchange are different in the described models, however, they both aim at providing predictions of the physiological responses to hot thermal environments of the average person. The objective of this paper was to compare and evaluate predictions of the two models against experimental human data. The experimental data was acquired from an intervention study carried out in controlled environmental conditions at Lund University, Sweden. An aim was to compare the rational simulation model PHS and the more complex rational multi-node model of Fiala against experimental human data. In addition, performance of models for simulating female and male data was analyzed as well.

2. Method

2.1. Description of the experimental study

The experimental data originates from dataset selected from a study carried out at Lund University involving ten participants (five males, five females) who performed an intermittent work protocol consisting of different occupational activities scheduled along 3 h. The experiments were carried out in the climatic chamber at a constant air temperature of 34 °C, relative humidity of 60% and air speed of 0.4 m s^{-1}. Participants were wearing a T-shirt, shorts, socks and sport shoes providing low thermal insulation. The basic thermal insulation and the evaporative resistance of the clothing ensemble considered for the simulation were 0.18 clo and 3.71 m^2 Pa W^{-1}, respectively. Thermal insulation was measured at Empa with a thermal manikin (Sweating Agile Manikin) (Psikuta, 2009) and the evaporative resistance was taken from Wang et al. (2014), for a similar clothing ensemble. Table 1 shows the duration and metabolic rate of the different activities as considered for the simulated exposure using data from 2.5 h of the work protocol as measurements started after the initial psychology test which was a part of the experimental study protocol. This period of low activity in the chamber was used as a baseline exposure for the model predictions. Each exercise bout of 18 min was followed by a three-minute break to change activity, weigh the subject and conduct other tasks according to the experimental protocol. The sweat rate was calculated from weight change between each exercise bout. Oxygen uptake was continuously measured for every activity by Metamax I (Cortex, Germany).

The activities are described below (see Table 1):

– Psychological test: assessing different aspects of cognitive performance.
– Cycling: physical activity on a cycling ergometer at 100 W at 60 revolutions per minute.

Table 2
Individual characteristics overview of participants considered in the simulations (Mean and SD).

	Age (years)	Height (m)	Weight (kg)	BMI (kg m^{-2})	VO$_2$max (ml kg^{-1} min^{-1})	Max pulse (b min^{-1})	Fat (%)
Females n = 5							
Mean	24.0	1.72	70.4	24.2	51.3	193.0	29.71
SD	4.5	0.02	2.1	0.8	5.0	5.0	1.15
Males n = 5							
Mean	27.2	1.79	77.0	24.0	57.1	192.6	19.69
SD	4.6	0.05	11.2	2.5	5.4	9.8	3.28

– Stacking: physical activity consisting of stacking 30 bricks per minute from side to side.
– Stepping: physical activity on a step bench at 30 steps per minute.
– Arm crank: physical activity in an arm ergometer at 25 W at 60 revolutions per minute.
– Break: body weight measurement and waiting for the next task to start.

Table 2 shows the average fitness level and anthropometrical data of the female and male participants, respectively. The individual characteristics data were considered in the simulated person profile in both models. The maximal oxygen consumption was determined on a treadmill with increasing inclination in a pre-test at the same laboratory using a gas analyzer for oxygen consumption measurements (Metamax I). To get an approximation of the percentage of body fat we used a calculation out of the Body Mass Index (BMI) according to Fat (%) = 1.34·BMI-12.469 for males and Fat (%) = 1.371·BMI-3.467 for females (Forrest, 1986).

The rectal temperature (Trec) represented the core temperature and was measured with an YSI-401 sensor (Yellow Springs Instrument, USA). It was inserted by the subjects at a depth of 10 cm above the anal sphincter. Skin temperature (Tsk) sensors (YSI-402 or YSI-402AC (tip 3.0 or 3.3 in diameter)) were taped with a single layer of 3 M Blenderm™ surgical tape type 1525 on the forehead and left side of the chest, upper arm, thigh and calf. The mean skin temperature value was calculated according to the 4-points Ramanathan equation (Tsk = 0.3·T$_{chest}$ + 0.3·T$_{upperArm}$ + 0.2·T$_{thigh}$ + 0.2·T$_{calf}$) (Ramanathan, 1964).

2.2. Comparison procedure and derivation of input parameters

The experimental scenario was simulated with the web-based PHS calculation software (StandardizationOrganization(ISO), 2004 - http://www.eat.lth.se/fileadmin/eat/Termisk_miljoe/PHS/PHS_agenda_2.html) and the physiological model by Fiala (version FPCm5.3, *Ergonsim*, Germany). Simulations were carried out for the average male and the average female. The experimental data from 2.5 h of data of rectal and mean skin temperature were compared against the predicted rectal and mean skin temperature outputs in the respective models. As the Fiala model provides local skin temperatures, mean skin temperature was calculated based on the same body parts as used in the experiment, whereas in the case of the PHS model, it directly provides a steady state value based on all body segments that was used for the comparison.

Table 3 summarizes the corresponding input parameters.

The SPSS statistical (SPSS Inc., Chicago IL, USA) software was used to compare male and female data including basic statistics (mean and standard deviation) of core (*Tre*) and mean skin temperature (*Tsk*). The statistical analysis applied an analysis of variance (ANOVA) to compare the means and confidence intervals of the three datasets. A p-value of < 0.05 was considered significant.

2.3. Results

Figs. 1 and 2 present the predicted mean skin and rectal temperatures for the average female and male (a and b, respectively) according

Table 3
Overview of input parameters considered in the simulations for each model.

	PHS	Fiala model
Subjects		
Acclimatization	No	No
Adjusted anthropometry	Yes (height, weight)	Yes (height, weight & age)
Adjusted fitness level	No	Yes
Hydration	Not drinking	Not specified
Body posture	Not specified	Standing
Environment		
Air temperature [°C]	34	
Mean radiant temperature [°C]	34	
Relative humidity [%]	60	
Air speed [m s^{-1}]	0.4	
Solar radiation [W m^{-2}]	0	
Clothing		
Basic thermal insulation [clo]	0.18	
Clothing evaporative resistance [m^2 Pa W^{-1}]		3.71
i$_m$_st	0.45	
Activity		
	According to Table 1 expressed in W m^{-2}	According to Table 1 expressed in Met (1 Met = 58.2 W m^{-2})

to PHS and Fiala model compared to the corresponding experimental data.

The experimental mean skin temperature (Fig. 1) fluctuated due to changes in the activity level. Neither of the models was able to accurately reproduce such fluctuations. The PHS simulation model matched the temperature course partially and mostly kept within the standard deviation of the experimental data for males, but less so for females. Fiala model's prediction of the mean skin temperature was less sensitive to the activity level change throughout the experiment for both males and females.

The fiala model predicted the rectal temperature throughout the exposure more accurately (Fig. 2) and was closer to the experimental data than the PHS model, especially for males. The PHS simulation overestimated the rectal temperature during the first phase for males and the body's cooling effectiveness of the recovery periods, for both males and females, hence, underestimating the thermal strain. Both models underestimated the response towards the end of the exposure, for males and more so for females.

The analysis of variance (ANOVA) revealed significant differences between the simulations and the experimental data for both rectal and mean skin temperature. A confidence interval check revealed a sex discrepancy, where males were better predicted in the models against experimental data for both rectal temperature and mean skin temperature (Table 4).

3. Discussion

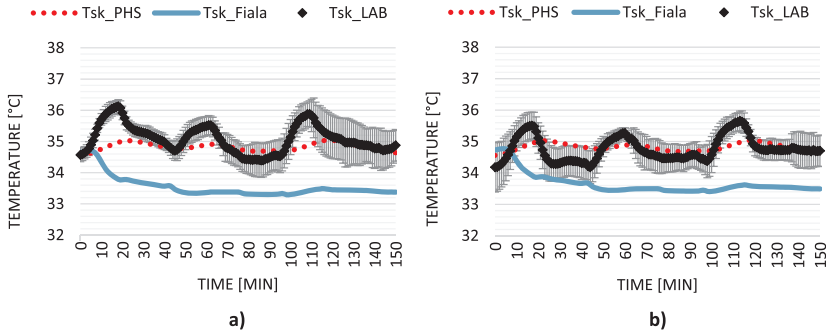The simulation models investigated in this study differ in their

Fig. 1. Comparison of experimental and predicted mean skin temperature by PHS and Fiala's models (Tsk): (a) Average female (5 females) and (b) Average male (5 males). Experimental data are represented by average and standard deviation value.

approach to predict heat stress. The Fiala model is based on passive and active heat equations and includes regression models for the thermophysiological response, represents the human physiology in anatomical detail and predicts physiological parameters for a wider range of environments; whilst the PHS simulation model is constructed around the heat balance equation with general heat exchange predictions for the whole body, based on experimental data and statistics. Furthermore, the objective of the models is differing as the Fiala model aims at prediction of the global and local thermophysiological response using detailed physical-physiological relationships whilst the PHS is primarily to be applied to set exposure limits in hot occupational settings based on core temperature and overall water loss. However, both models are validated against experimental data and aim at providing data on the physiological response of the average person to a thermal environment. The PHS simulation model over-predicted rectal temperatures in the first phase for males and the cooling effectiveness of the recovery periods, for both males and females. As a result, the PHS simulation underestimated the thermal strain in this context of intermittent work. The Fiala model accurately predicted changes in rectal temperature throughout the exposure, although, absolute values for females were lower due to the lower initial temperature predicted by the model. The experimental mean skin temperature fluctuated due to changes in the activity phases. This was not reflected in any of the models, however, the PHS simulation

Table 4

Sex statistical comparison. Basic statistics (mean and standard deviation (SD)) and analysis of variance with confidence intervals. A p-value of < 0.05 was considered significant.

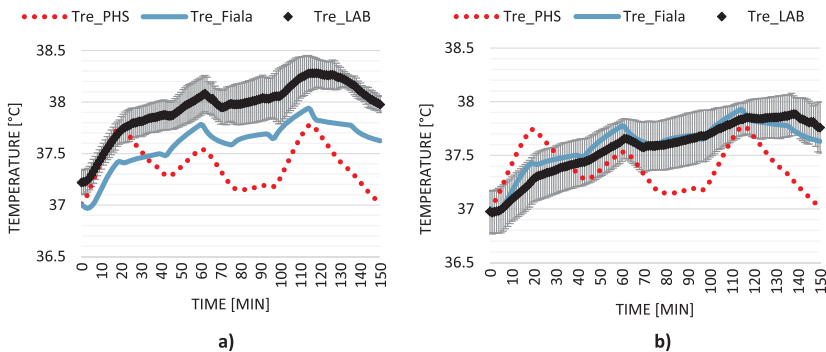|			Sig.	95% Confidence interval of the difference Lower / Upper	
Tre					
Males	Exp. data		< 0.001	37.53 / 37.61	
	PHS		< 0.001	37.35 / 37.42	
	Fiala		< 0.001	37.57 / 37.64	
Females	Exp. data		< 0.001	37.92 / 38.00	
	PHS		< 0.001	37.36 / 37.42	
	Fiala		< 0.001	37.57 / 37.64	
Tsk					
Males	Exp. data		< 0.001	34.70 / 34.83	
	PHS		< 0.001	34.80 / 34.84	
	Fiala		< 0.001	33.60 / 33.71	
Females	Exp. data		< 0.001	35.02 / 35.16	
	PHS		< 0.001	34.81 / 34.85	
	Fiala		< 0.001	33.49 / 33.61	

Fig. 2. Comparison of experimental and predicted rectal temperature by PHS and Fiala's models (Tre): (a) Average female (5 females) and (b) Average male (5 males). Experimental data are represented by average and standard deviation value.
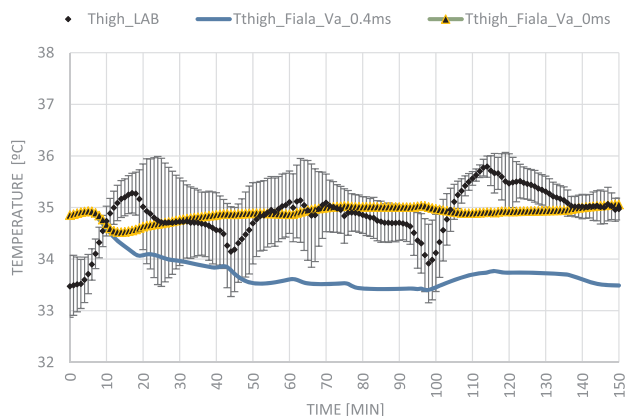
Fig. 3. Comparison of experimental and predicted local skin temperature at thigh by the Fiala model by simulations considering local air velocity of 0.4 m s^{-1} and 0 m s^{-1}.

model was closer to the temperature course than the simulation with Fiala model. Generally, both models predicted experimental data from males better than experimental data obtained from females.

3.1. Rectal temperature

The Fiala model showed higher precision in the prediction of the rectal temperature for both cases, especially for males. In case of females, Fiala model's prediction of rectal temperature showed an initial offset of 0.2 °C that seemed to be maintained throughout the rest of the exposure.

As the core temperature is a limiting factor for work in hot environments and sets the exposure limits in PHS, it is problematic that the simulation of a 2.5 h- intermittent exercise results in predicted core temperatures differing with almost a degree. The PHS simulation model is designed to predict thermal strain for 8 h of work exposure. Intermittent work exposures including regular breaks which is common in workplaces such as agriculture and construction, seem to challenge the accuracy of the PHS model. Similar conclusions were drawn by Bröde et al. (2017). In this study, the authors performed a simulation series on the influence of different heat stress assessment metrics (WBGT, PHS, UTCI-Fiala) on estimated work ability in various warm outdoor environments with varying work intensities (light, moderate, high). The authors assumed workers to be acclimatized and wearing light work clothes (0.6 clo). The authors showed that simulated rectal temperatures were higher in the PHS model than in the Fiala model, with the exception of simulating intermittent activities (Bröde et al., 2017). This could be related to the fact that the PHS model does not consider thermal inertia of the or heat distribution in the body. Considering the cumulated sweat profiles in both models, which were found to be relatively similar (see the section on sweating further down in this discussion section), it seems not to be related to sweating. Generally, there seems to be a time (exposure duration vs. rest duration) dependency in PHS, i.e. with specific selection of time intervals one could reach required rectal temperature level with PHS.

Further, PHS is poorly validated for recovery situations and thus, over-estimated the whole body cooling effect during breaks. The model is validated for a minimum of 100 W in metabolic rate. However, in this comparison we modified the model to allow lower rates to accommodate for 80 W based on the visual basics equations described in the standard. The results indicate that additional development of the PHS model is needed in order to be able to simulate breaks during a workday.

Additionally, the experimental data is only based on data from 10 relatively well-trained individuals and hence, partly acclimatized to heat. However, it was assumed that they were not acclimatized due to the experiment taking place during the winter in Sweden. Therefore, it might not be fully representative and comparable to the average individual in the physiological models per se. The PHS simulation model further allows input of the mean subject data but not fitness.

3.2. Mean skin temperature

For this specific climatic condition (t$_a$ = 34 °C and 60% RH, v$_a$ = 0.4 m/s) with no difference in mean radiant temperature and air temperature together with low clothing insulation, different factors might have contributed to the observed discrepancy in experimental mean skin temperature and the data predicted by the Fiala model. This may stem either from the methodological issues related to the data collection itself or from the models internal assumptions, including sweat evaporation efficiency. In general, the highest skin temperature discrepancies have been observed in scenarios including exercise in the heat (Martínez et al. (2016)). When measuring skin temperature of exercising persons in the heat, surface temperature sensors have to be strongly attached to skin to avoid displacement due to sweat and movement. Some studies have shown that the attaching method can locally affect the heat and moisture transfer at the measuring-site, and therefore, mislead the temperature measurement (Buono and Ulrich, 1998; Buono et al., 2007; Priego Quesada et al., 2015; Psikuta et al., 2013). Particularly, the method of skin thermistor attachment can result in significant over-estimation of weighted mean skin temperature (Tyler, 2011). One of the mechanisms is the impairment of the air movement and evaporation at the measurement location due to the tape. Fig. 3 shows the comparison of the experimental and simulated values of the local skin temperature at thigh in the aforementioned scenario described in methods section (local air speed of 0.4 m s^{-1} for every body part) and a case with absolutely no local air movement at thigh as it occurred under the tape (air speed is 0 m s^{-1}). Higher simulated local skin temperatures at thigh within the experimental range could be observed in the case of no air speed. However, setting such a simulation scenario would underestimate the global heat dissipation at the body part as no air movement only appears in a reduced area corresponding to the measurement point.

In addition, the sweat evaporation model included in the physiological model by Fiala assumes that all sweat evaporates from skin with 100% cooling efficiency, meaning that sweat evaporation takes all the
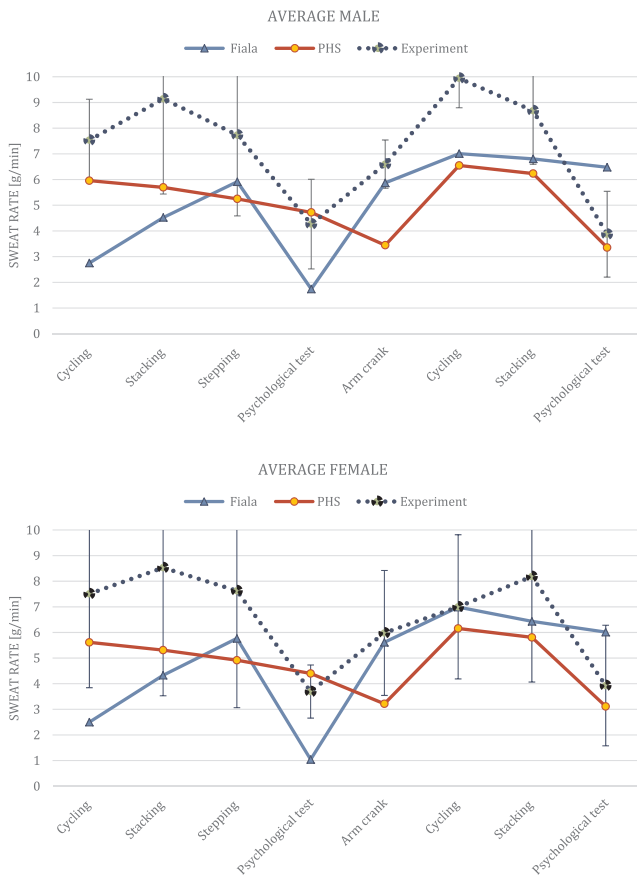
Fig. 4. Comparison of sweat rates (g/min) between models and sex.

heat from the body and no dripping occurs when the skin wettedness stays below 1 (fully-wet skin). Hence, if it is not the case in reality, the predicted skin temperature could result in lower values than experimental ones. This phenomenon of an artificially increased skin temperature could be more critical in such a hot scenario including profuse sweating.

Both models have been developed and validated based on experimental mean skin temperature measurements from a wide variety of studies using different skin sensor attachment methods. However, these methods were not generally specified and some undetermined effect of these methods could be represented in the models, yielding to some uncertainty when comparing predicted and experimental values. Moreover, specific data on local skin temperatures are not available in the PHS model as only the mean skin temperature parameter is available. Hence, no calculations based on local skin temperature were possible. Mean skin temperature in the PHS is a component of heat balance analysis. Associated equations can be found in Annex A, clauses A4 and 5, in the standard. However, it is not explained explicitly what the equations are based on. Therefore, the use of the equations in the

visual basic program has to be interpreted. The use of the visual basic program has to be further interpreted by the user.

In the current experiment, the skin temperature (Tsk) was measured with thermal contact sensors (YSI-402 or YSI-402AC (tip 3.0 or 3.3 in diameter)) taped with a single layer of 3M™ Blenderm™ surgical tape on the forehead and left side of the chest, upper arm, thigh and calf. Following up on this discussion, control measurements were carried out for comparing skin temperature measurements from thermal sensors taped on skin and complementary measurements obtained by IR thermography and non-taped sensors (< 0.3 mm thermocouples inserted into the upper skin layer). The environmental conditions were the same as in the main experimental study. This comparison showed in average 0.7 °C higher mean skin temperature data for taped sensors. After an offset correction of the experimental mean skin temperature, the predictions provided by Fiala's model would become closer and prediction of the PHS model would overestimate the experimental mean skin temperature. Start values of skin temperatures in original figures (Fig. 1) were quite close for models and the experimental data. As a result, when the experimental data is shifted lower by 0.7 °C, the

differences at the start increase. It has also to be considered that the temperature fluctuations were still present even for the sensors' set attached under the upper skin layer, i.e. when no restriction of the evaporation around the sensors was expected. These fluctuations could also be related to different body parts moving under various activities, thus, increasing ventilation around and evaporation from specific areas but also due to heat production rate in local muscles depending on the task.

3.3. Skin blood flow

The skin blood flow regulation affects skin temperature. Thus, if the represented skin blood flow regulation included in the physiological model by Fiala does not represent the specific situation of these experimental data, it might mislead the prediction of the measured skin temperature. It may be expected that the major blood flow changes occur in the extremities (hands, feet), while the central body areas (torso, thighs, upper arms and head) participate in thermoregulation in a more passive way (Taylor et al., 2014; Vanggaard et al., 2012, 2015). For the simulation of complex exposures this may become crucial for accurate estimations. In addition, the blood distribution to the different body parts might depend on the onset of the exercise itself (sympathetic reflex), and on the type and intensity of the activity. This aspect is not adjustable in the model and could cause differences if the activity produce a different blood distribution as considered. While skin blood flow is a part of Fiala model's active system, it is not utilized in the PHS model.

3.4. The sex comparison

There is a noticeable difference in the female and male outputs in both rectal and mean skin temperature model predictions, where males are more accurately predicted in both models (see Table 4). In the experimental study, the female menstruation cycle was accounted for and subjects were tested in their early follicular phase only (days 2–10). Female subjects did not use contraceptives. One reason for the sex difference could be that thermal heat stress data are largely based on studies on young, fit males, mainly in military settings and male dominated industries (e.g. Schrier et al., 1970; USDAAF, 2003; Parsons, 2003). As both models under-predicted the thermal stress of the females in the experimental study, we suggest further development and validation of the models to take this result into account.

3.5. Comparison of sweating

In hot environments, heat dissipation relies mainly on sweat evaporation, and therefore, a relevant aspect is the sweat rate modelling. In this particular case, the sweat rates predicted by each model have been compared with the experimentally measured weight loss of the clothed participants for each separated phase in the exposure (Fig. 4). It has to be noted that the initial experimental study was designed for measuring water loss, not for a sweat rate comparison with physiological models. Therefore, this comparison is a rough estimate only.

A pre-exposure time of 15 min of low activity was modelled in both the PHS and Fiala models, following the experimental protocol. This comparison revealed that the PHS model predicted sweat rates closer to the experimental data while over-predicting its cooling effect. Fiala model predicted lower sweat rates than observed in the experiments, especially during the first phases before the exercise onset. As a result, higher modelled mean skin temperature could be expected (Figs. 1 and 4). During the experiment, the weighing was carried out under the short, 3-min rest periods. Considering that sweating during these periods was more affected by the previous exercise, then sweat loss during breaks was added to the previous exercise phase even for the models and the rates were adjusted in the experimental data.

The sweat rate comparison has a limitation in the recording of experimental data as it is calculated from weight loss. This includes sweat retained in the clothing, and therefore, does not represent fully secreted sweat amount which is predicted by the models. The sweat accumulated in clothing does have a dampening effect, i.e. collection during high sweating and extra evaporation under low workload. Sweating does develop during the first 5 min with exercise onset (the heaviest task - cycling) which made the synthetic clothing stably wet (sweating evaporation balance reached). However, moisture accumulation in clothing is neither considered in Fiala's model nor in PHS. Nevertheless, sweat accumulated in the clothing rarely reached above 50 g in the experiment and clothing worn was minimal and often synthetic sportswear.

4. Conclusion

The aim of this paper was to compare the rational simulation model Predicted Heat Strain (PHS) and the more complex rational multi-node physiological model (Fiala model) against experimental data from a climate chamber study of intermittent work in a hot environment (34 °C, 60% RH) with low clothing insulation. The analysis also included a sex comparison. The PHS model over-predicted rectal temperatures in the first phase for males and the cooling effectiveness of the recovery periods, for both males and females. As a result, the PHS simulation underestimated the thermal strain in this experimental scenario of intermittent work. As rectal temperature in PHS is used to limit work exposure then the model, based on the present results, should not be used for predicting various phases of an intermittent exposure. However, this does not say anything about the predictions for long exposures, e.g. for whole workdays, when using average values for input parameters, e.g. metabolic rate. The Fiala model accurately predicted the rectal temperature throughout the exposure. Experimental mean skin temperature fluctuated due to changes in the activity phases. This was not reflected in any of the models however, it was more so in the PHS simulation model and not at all in Fiala.

In conclusion, both models showed some limitations in different aspects. The PHS model seemed to respond quicker than the Fiala model whilst the body response was slower and over-predicted the cooling at low activity (rest) during intermittent work. An under-prediction for mean skin temperature was observed for the Fiala model in this context. As both models predicted responses more accurately for males than females we suggest that in any future validation and development of the models we should take this into account.

Declaration of interest

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Paper IV

Exploring how a traditional diluted yoghurt drink may mitigate heat strain during medium-intensity intermittent work: a multidisciplinary study of occupational heat strain

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Abstract: It is common practice in India to consume the dairy drink buttermilk as a way of mitigating occupational heat strain. This paper explores the thermoregulatory and hydration benefits of drinking buttermilk but also the impacts of work in a hot environment on the gut microbiota, renal and cognitive function. Twelve healthy participants were subjected to a 3-h period of medium load physical intermittent work in a climatic chamber (34°C, 60% RH). The subjects were given water, buttermilk (700 ml) or no rehydration at random. Mean body temperatures when no rehydration was given were significantly higher ($p \leq 0.001$). When subjects drank water or buttermilk they had a lower sweat rate than with no rehydration ($p \leq 0.05$) and the perception of feeling hot, uncomfortable, thirsty and physically exerted was significantly reduced ($p \leq 0.05$). A hormonal stress response at the end of the exposure was seen when not drinking ($p \leq 0.05$). No differences in cognitive abilities and gut microbiota were found. The exposure lowered the renal blood flow suggesting an acute impact of short term heat exposure. It was also found that buttermilk has a protective effect on this impact. Our results demonstrated that keeping hydrated by water/buttermilk consumption mitigates heat strain in well-nourished subjects.

Key words: Occupational health, Heat strain, Yoghurt/analysis, Heat stress, Hydration management, Climate change

Introduction

Heat stress is a major issue in workplaces in India and across the world. It affects worker's health and productivity, and can even threaten survival[1–3]. The situation is set to deteriorate due to climate change[2, 4–7]. Work-

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ers involved in physically demanding tasks outdoors in, for example, agriculture, construction and mining are especially vulnerable. Physiological heat strain results in a rise in both core and skin surface temperature and varies depending on physical activity, clothing worn and the environmental conditions[8–11].

In a field study looking at occupational heat stress in Chennai, India in 2013 it was found that a diluted (four times with water) dairy drink 'buttermilk' was widely consumed among workers in all studied workplaces as a traditional way of mitigating heat strain (between 67–100% of the workers in the workplaces surveyed)[2]. Consumption of fermented food, such as corn, rice, bean curd and dairy are often encountered in traditional and in societies unable to preserve food through refrigeration[12]. The current form of buttermilk being consumed by the workers in Chennai is a spiced diluted form of curd (natural yoghurt). Drinking buttermilk provides the body with liquid and nutrition in an easily digestible form as well as vitamins and minerals that are lost when sweating. Buttermilk is high in protein, riboflavin, potassium, vitamin B12 and calcium[13]. Consumption of similar diluted yoghurt drinks are seen in other hot regions such as Lassi in South-East Asia and Ayran in the Middle East.

Food that has been fermented has been studied for health benefits in terms of probiotics, such as content of live lactic acid bacteria with health benefits[13–16] and its importance in sustaining human health[12]. However, buttermilk has not been studied for its potential in mitigating heat strain, like other traditional drinks such as coconut water[17, 18]. Although, some papers mention buttermilk as a home remedy effective in dissipating heat[19].

The overall objective of the study was to study the impacts of work in hot environments from a variety of disciplines. The **primary aim** of the study was *to investigate the benefits of drinking buttermilk thermoregulation and potential hydration benefits when working physically in a hot environment, compared to drinking plain water and when no rehydration was provided.* The study also included additional aims that explore other questions and methods related to hot working conditions:

a) To explore the cognitive effects of heat strain and physical work on arousal, working memory performance, and risk-taking.

Increases in cortisol stress hormone concentrations have been previously reported under heat stress, physical exercise and dehydration[20, 21]. A large number of studies have

examined the relation between exercise and cognitive performance[22, 23]. Much of the research is based on the notion that acute exercise alters how brain systems allocate the mental resources, where various forms of cognitive tasks are supposed to be more demanding when performed in combination with physical exercise[24]. However, the findings are by no means clear-cut: the results range from a deleterious effect on cognitive performance to an enhancement. A confounding factor is the variety of methodological approaches applied, which make the results hard to justly compare. The same problem is also true for the findings on the relation between dehydration and cognitive performance[25]. Therefore, we aimed to further explore the effects on cognitive performance.

b) To examine the impact of heat strain and physical work on the human gut microbiota.

The gut microbial composition is important for human health and here, bacterial diversity has been shown to be of significant relevance[26]. To our knowledge, the gut microbial structure has not previously been investigated in relation to heat stress. However, since heat stress has physiological impact on the human body we hypothesized that latent heat stress can impact the gut microbiota such as the diversity and concentrations of e.g. *Enterobacteriaceae* and *Lactobacillus* . The study also wanted to explore whether buttermilk could have a positive impact on the gut microbial composition. No previous studies have explored these relationships.

c) To investigate effects of physical work and short term heat exposure on renal function.

Heat exposure impacts the body's fluid regulation in which the kidneys play an important role[27]. For example, acute effects of reduced renal blood flow have previously been seen when conducting hard physical labour in the heat, such as in marathon runners[28]. It is estimated that hard work can reduce renal blood flow by 50%[29]. In addition, an epidemic of chronic kidney disease (CKD) has spread among agricultural workers in many central American countries with hot and humid climates[30–33]. Here, common risk factors are not present as the vast majority of those affected are young, normotensive and lean male agricultural workers. However, they are exposed to repeated daily dehydration and hard physical labour[31, 33]. Both Garcia-Trabaino *et al.* 2015[31] and Wesseling *et al.* 2016[32] found a cross-shift increase in serum creatinine

Table 1. Overview of subjects: averages and standard deviation (SD)

	Females				Males		
Age	BMI kg/m²	VO₂max ml/kg/min	Max pulse b/min	Age	BMI kg/m²	VO₂max ml/kg/min	Max pulse b/min
24.0 (SD 3.7)	23.8 (SD 1.1)	50.2 (SD 4.8)	191.2 (SD 7.7)	27.2 (SD 2.8)	24.0 (SD 2.0)	56.8 (SD 4.4)	194.3 (SD 9.7)

N = 12

in sugarcane plantations in El Salvador and Nicaragua respectively. Dehydration and heavy work may be a major cause and it is possible that continuous exposure could cause permanent damage to the kidney[31, 32]. In this study, we wanted to investigate if the short heat exposure including physical work would affect acute kidney function.

d) A validation study of accelerometers for use in the field of hot occupational settings to estimate the metabolic rate. The findings from this aim will not be reported in this paper but further information can be found in Kuklane et al. 2015[34]).

Subjects and Methods

A cross-over study was conducted using a buttermilk recipe from Chennai, India, to assess the effectiveness of buttermilk on whole body rehydration, thermoregulation, stress and recovery during a 3-h period of medium load physical work (average 200 W/m², SD ± 74). The activities involved loading bricks, stepping, biking and arm crank at rotating intervals every 20 min in a heat chamber (34°C, 60% RH). The thermal condition is simulating the hottest measured workplace in Chennai during field work in April/May 2013[2]. The study involved three interventions; water, buttermilk (100 ml every 20 min, total 700 ml) and no rehydration. The water and buttermilk was brought inside the chamber at room temperature (~19°C) and consumed after a few minutes in the heat.

Subjects

The research was completed according to the Recommendations of the Helsinki Declaration (1983), including a written consent obtained from all subjects and an ethical approval from the regional ethical review board at Lund University (Dnr 2014/606). Twelve subjects (19–33 yr; 6 males, 6 females) were recruited. Four recruits did not complete the study due to health or other practical reasons and were replaced by new subjects. The female participants had normal menstrual cycles, did not use contraceptives, and were tested in the early follicular phase (days

2–10). All subjects were normotensive, nonsmokers, had a BMI below 27 and were not taking any medications that could alter the cardiovascular or thermoregulatory responses in the heat. Subjects performed a VO₂ max test at 20°C before the study to determine suitability. Criteria for participation for women was a maximum oxygen consumption of at least 30 ml/kg/min, and men at least 35 ml/kg/min. None of the subjects were excluded based on maximum oxygen consumption. An overview of the subjects can be seen in Table 1.

All the tests started in the morning at 8 am and were finished by noon. The subjects were requested to abstain from strenuous exercise for at least 48 h prior to the test and to consume a standard dinner the evening before each test day. They were requested not to eat in the morning of the test day but could drink a total of 500 ml of water before entering the chamber to ensure normal hydration state. At arrival in the morning, the first cortisol and urine samples were taken. However, it was not the first morning urine sample as the subjects had urinated at home before entering the lab and had consumed some water. A standardized breakfast of an egg sandwich followed. Between each test, there was at least a 5-d resting period in order to avoid heat acclimatization effects. The study was carried out during the winter season, from November until March. During the test the subject was fasting. The weight was measured before, during (including light sports wear) and after the test.

Study variables

Body core (rectal, Trec) and skin temperatures, heart rate and oxygen uptake were continuously measured together with recording of body weight change, subjective responses by the scales of thirst, thermal comfort and thermal sensation, Borg's 15-grade RPE (ratings of perceived exertion) scale[10, 35] and a final short questionnaire. The rectal temperature (Trec) represented the core temperature and was measured with an YSI-401 sensor (Yellow Springs Instrument, USA). It was inserted by the subjects at a depth of 10 cm above the anal sphincter. Skin temperature (Tsk) sensors (YSI-402 or YSI-402AC (tip 3.0 or 3.3
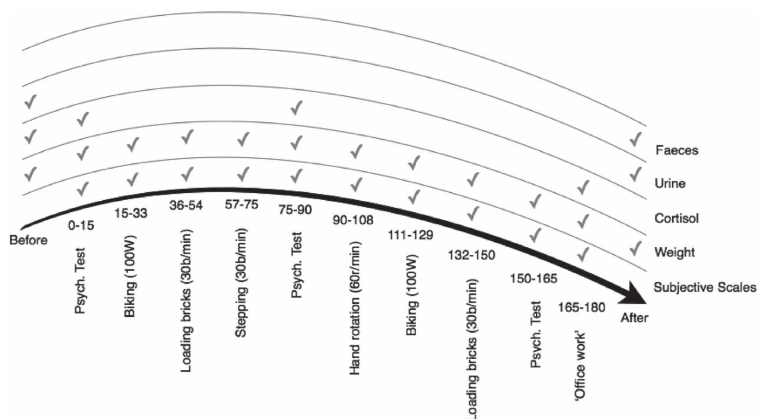
Fig. 1.   Test protocol. Heart rate, oxygen consumption and temperatures were measured continuously.

in diameter)) were taped with a single layer of 3M Blenderm^{TM} surgical tape type 1525 on the forehead and left side of the chest, upper arm, thigh and calf. Trec and Tsk were recorded at 10 s intervals by a NI data acquisition hardware and Labview program (National Instruments, USA) by a desktop computer.

Subjects rated their whole body thermal sensation, thermal comfort, thirst and perceived exertion at 20 min intervals. Further, a short final questionnaire was filled during the final test day asking questions regarding buttermilk's cooling effect, its thirst relief and refreshment potential, stomach sensations and its taste.

Oxygen uptake (VO$_2$) was measured continuously during the exercises (18 min) with MetaMax I (CORTEX Biophysik GmbH, Germany). Heart rate was recorded at 5 s intervals using Polar Heart Rate Monitors (RS400, Polar Electro, Finland). The mean skin temperature value was calculated according to the 4-points Ramanathan equation (Tsk=0.3*Chest+0.3*UpperArm+0.2*Thigh+0.2*Calf)[36]. Mean body temperature was calculated according to the formula, Tb=0.8*Trec+0.2*Tsk. Weight was measured nude before and after the test for total body weight loss calculation. During the exposure, weight was recorded every 20 min, after each activity to estimate dehydration level and evaporation rate. During analysis of weight loss, the data was corrected for the added weight of buttermilk and water. Nude weight (before and after) and clothed weight (during the exposure) was analysed separately. Urine samples were taken before and directly after each test to measure renal function biomarkers. The faeces sample was taken from the single use plastic cover of

the rectal probe, inserted into a test tube and weighed at the end of the exposure. The stress hormone cortisol was measured in saliva samples when arriving at the thermal environment laboratory, in the beginning, middle and at the end of the test, using Cortisol Salivette collection tubes (Sarstedt, Nümbrecht, Germany). The urine and cortisol samples were analysed at the laboratory of Clinical Chemistry (Skåne University Hospital, Lund, Sweden) using a standard luminiscence method. The morning sample was used as a baseline. The test protocol can be seen in Fig. 1. Description of activities:

– Psychological test: assessing different aspects of cognitive performance.
– Biking: physical activity on a cycling ergometer at 100 W at 60 revolutions per min.
– Stacking: physical activity consisting of stacking 30 bricks per min from side to side.
– Stepping: physical activity on a step bench at 30 steps per min.
– Arm crank: physical activity in an arm ergometer at 25 W at 60 revolutions per min.
– Break: body weight measurement and waiting for the next task to start.

The criteria to terminate the heat exposure were

1. 3 h of heat exposure was reached;
2. subjects felt the condition was intolerable and wished to quit;
3. rectal temperature (Trec) reached 38.5°C or;
4. the test leader decided to terminate the exposure based on observations of the subject.

After the exposure, the subject was weighed immedi-

ately inside the climatic chamber.

The SPSS statistical software was used to compare the three interventions on the rate of rectal (Trec) and skin temperature (Tsk) change for each activity (average difference between the start and end), heart rate and mean body temperature (Tb) change together with hydration variables calculated from weight loss, saliva cortisol, urine and perception scales. The statistical analysis applied an ANOVA repeated measures, a mixed model for better analysis of missing data (e.g. when subjects exceeded the limit rectal temperature and terminated the exposure), and a Freidman's test for statistics of significance ($p < 0.05$).

Psychological tests (a)

The psychological tests were chosen based on the assumption that tasks demanding immediate cognitive resources are impaired when executed under heat stress and physical exercise. However, scientific conclusions about this are not clearand several studies have not found a cognitive impairment related to heat-stress and physical activity[37]. The tests measured subjective assessment of anxiety, working memory performance, and risk taking. Tests included SAM (Self-Assessment Manikin)[38], which is a non-verbal pictorial assessment technique, where the subject's assessed their subjective feelings of arousal, control and pleasure on a scale from 1–9. The "N-back" procedure[38, 39], is a well-established way of continuously measuring the capacity of working memory. A sequence of letters is presented on a screen and the participant has to remember the letters presented earlier in the sequence. When N=1, the participant shall push a button when the same letter appear for the second time, with another letter in between. For instance, if the first screen shows an "A", the second screen a "K" and the third screen an "A", the participant shall push the button. When N=2 the participant shall push the button when the same letter appears for the second time, but with two other letter in between (that is, "A", "K", "G", "A"). Every letter is presented for 500 ms with a 1,000 ms interstimulus interval (a blank screen). The number of correct responses, misses, and "false alarms" is then calculated. In this study, a block where N=1 and a block where N=2 were used. As can be seen in Fig. 1 the participants were tested prior, during and after the exposure to the heat stress procedure. The measure prior to heat stress exposure was used as a baseline and changes between baseline and the two following measures were evaluated within subjects. The data was analysed with one way ANOVA.

Gut microbial analyses (b)
DNA extraction

Ten milliliter phosphate buffered saline (PBS, Oxoid, England) was added to the rectal samples and vortexed for 2 min. After centrifuging in 4°C at 8,000 rpm for 10 min, 500 μl PBS was added to the pellet. Twelve sterile and UV-treated glass beads (2 mm in diameter) were added into 1.5 ml tubes containing the sample. After incubating in room temperature for 10 min, the tubes with glass beads were shaken in an Eppendorf Mixer (Eppendorf, Germany) at 4°C for 45 min. Samples were centrifuged for 30 s at 3,000 rpm and 200 μl supernatant was used for DNA extraction in the EZ1 Advanced XL (tissue kit and bacteria card; Qiagen, Hilden, Germany). Finally, 22 μl sterile 10 × TE-buffer (10 mM Tris, 1 mM EDTA, pH 8.0) was added to elution tubes.

Polymerase Chain Reaction

The 16S rRNA genes were amplified from samples using FAM- ENV1 (5'-AGA GTT TGA TII TGG CTC AG-3') and ENV2 (5'-CGG ITA CCT TGT TAC GAC TT-3') primers. Each PCR reaction had a volume of 25 μl including, 2.5 μl of 10x PCR buffer, 0.2 mMol of deoxyribonucleotide triphosphate, 0.4 mM of each primer: FAM-ENV1 and ENV2, 1.25 U of Top Taq DNA polymerase (Qiagen, Germany) and DNA template. Cycling parameters in an Eppendorf Mastercycler (Hamburg, Germany) were as follows: initial denaturation at 94°C for 3 min followed by 32 cycles of denaturation at 94°C for 1 min, 50°C for 45 s, extension 72°C for 2 min and final extension 72°C for 7 min. PCR products then were pooled, purified and concentrated by MinElute PCR Purification Kit (Qiagen, Hilden, Germany) according to the manufacturer's protocol. The concentrations of purified DNA were measured using Nanodrop ND- 1000 spectrophotometer (Saveen Werner, Sweden).

Terminal Restriction Fragment Length Polymorphism (T-RFLP)

The purified DNA were digested with 10 U of restriction endonuclease *Msp*I (Thermo Scientific, Germany) for 5 h at 37°C in a total volume of 10 μl. The digested amplicons were analyzed on an ABI 3130xl Genetic analyzer (Applied Biosystems, Foster city, CA, USA) with internal size standard GeneScan LIZ 600 (range 20 -600 bases) at DNA- lab (Skåne University Hospital, Malmö, Sweden). The electropherograms were analyzed with GeneMapper software version 4.1 (Applied Biosystems). Peak detection thresholds were set to 40 flourescence units for internal standards and T-RFs.

Quantitative PCR

Enterobacteriaceae and *Lactobacillus* were quantified using separate quantitative PCR (qPCR) according to Karlsson *et al.* (2012)[40]. In brief, ten-fold dilution series of purified plasmid DNA were made in elution buffer (EB, Qiagen) and primers Eco1457-F: CAT TGA CGT TAC CCG CAG AAG AAG C, Eco1652-R: CTC TAC GAG ACT CAA GCT TGC and Lact-F: AGC AGT AGG GAA TCT TCC A, Lact-R: CAC CGC TAC ACA TGG AG (Qiagen) were used for quantification of *Enterobacteriaceae and Lactobacillus* respectively[41]. The thermal cycling was performed in Rotor-Gene Q (Qiagen) with a program of 95°C for 5 min, followed by 40 cycles with denaturation at 95°C for 5 s, annealing, and elongation at 60°C for 10 and 20 s for *Enterobacteriaceae* and *Lactobacillus* respectively. Number of bacteria was expressed as numbers of 16S rRNA gene copies /g wet weight of rectal samples with detection limits of 10^2 genes/reaction.

Statistical analyses and calculation

Shannon and Simpson diversity indices were calculated according to Karlsson *et al.* (2012)[40] with the modification that T-RFs within 40–580 base pair were considered. The differences in microbial diversity were tested by using Kruskal–Wallis rank sum test. The qPCR data were evaluated with Nemenyi-Damico-Wolfe-Dunn test for pairwise comparisons using package "coin" in the R program.

Kidney function (c)

Three biomarkers were measured and analysed: albumin, creatinine and protein HC (β1-microglobulin) and the albumin/creatinine ratio calculated. An early marker of glomerular damage is proteinuria which is measured through the concentration of albumin and the albumin/creatinine ratio. Urine creatinine concentrations were measured as an indicator of possible decreases in renal blood flow. Protein HC was measured to assess eventual tubular effects together with the protein HC/creatinine ratio to assess risk of proteinuria[42]. Albumin is a much larger molecule that would indicate a glomerular damage. The biomarkers were analysed applying a repeated measures ANOVA to compare interventions. The difference between pre- and post-exposure urinary levels were assessed using Wilcoxon's tests for paired samples.

Results

Overall, rectal temperatures reached an average of 38.0°C (SD 0.3°C) and heart rate 126 b/min (Min 63;
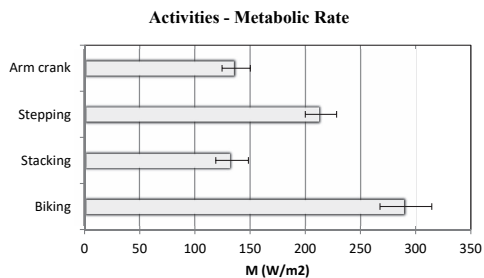

Fig. 2. Metabolic rate of the activities during the exposure for all interventions.
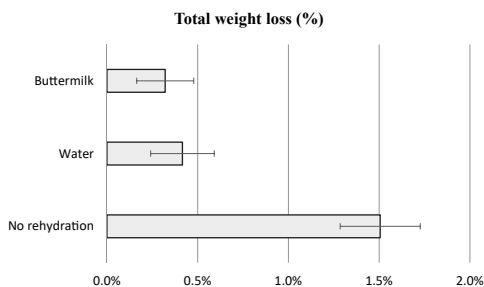Mean and SD. N=12

Fig. 3. Total weight loss – nude weight before and after the exposure (%).
Mean and SD. N=12

Max 171) during the whole exposure over the three interventions. Three subjects finished the exposure before the planned 3 h due to their core temperature exceeding 38.5°C, one for every intervention. This occurred at the end of the exposure in all three cases and was handled as missing data in the data analysis. As expected, no differences between genders were observed. In the final questionnaire, 7 out of 12 subjects reported a cooling effect and a feeling of being refreshed (10 out of 12) from buttermilk however, they preferred drinking water as it was perceived to relieve thirst better (11 out of 12).

Metabolic rates

The metabolic rate of the different activities during the exposure can be seen in Fig. 2, keeping within medium load exercise (average 200 W/m^2).

Weight loss and sweat evaporation

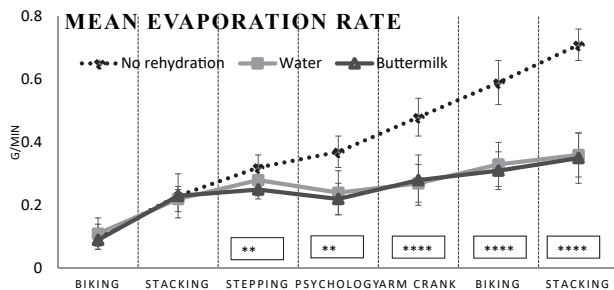When not drinking, average total body weight loss was 1.11 kg (SD 0.26 kg) corresponding to 1.51% (SD 0.22%),

Fig. 4.   Evaporation rates (g/min) based on body weight loss.
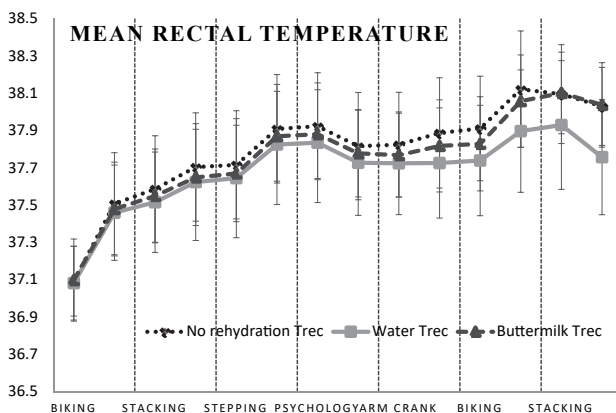Mean and SD. N=12 **$p \leq 0.01$: ****$p \leq 0.0001$.

Fig. 5.   Mean and SD of the rectal temperature (Trec) during the 3-h exposure.
N=12

when drinking water 1.01 kg (SD 0.16 kg) and buttermilk 0.95 kg (SD 0.14 kg) (Fig. 3). There was a significant effect of buttermilk in total body weight loss ($p \leq 0.05$) compared to when no rehydration was provided and when drinking water. Further, a significant difference ($p \leq 0.05$) (Fig. 3 and 4) was seen in the evaporation rate (body weight loss between tasks (g) / body weight / time (18 min) ((+0.1)) and dehydration level (% weight change between tasks) when no rehydration was provided versus when drinking water or buttermilk, suggesting a significantly lower sweat rate when hydrated (Fig. 3 and 4).

Core, skin, mean body temperature and heart rate
    The statistical analysis on the rate of change (start temperature being the baseline) showed that core (rectal) temperature (dehydrated vs water $p=0.66$ and dehydrated vs buttermilk $p=0.71$) (Fig. 5) and mean skin temperature

(dehydrated vs water $p=0.07$ and dehydrated vs buttermilk $p=0.50$) (Fig. 6) change were not statistically significant when comparing all the interventions amongst each other. The same was seen when comparing the rate of heart rate change (dehydrated vs water $p=0.75$ and dehydrated vs buttermilk $p=0.66$) (Fig. 7). However, when no rehydration was given, the mean body temperature (Tb) was significantly higher in comparison with buttermilk and water provision ($p \leq 0.001$) (Fig. 8) (Table 2).

Subjective responses
    The statistical analysis of thermal sensation, thermal comfort, thirst and physical exertion scales applied an ANOVA repeated measures and a Freidman's test for statistics of significance. The values showed significantly higher subjective responses in hydrated versus no rehydration conditions, in particular towards the end of the expo-
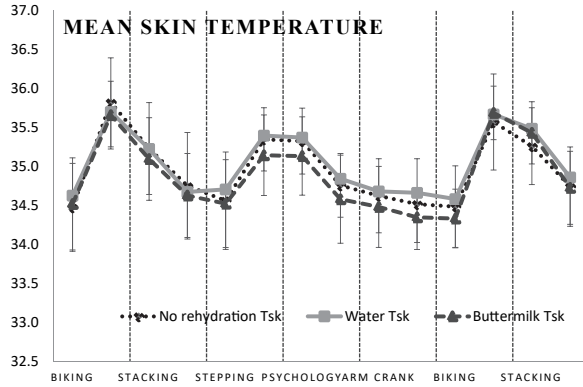
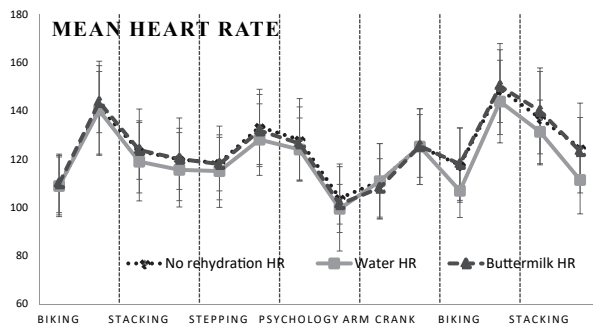**Fig. 6.   Mean and SD of the weighted mean skin temperature (Tsk) during the 3-h exposure.**
N=12

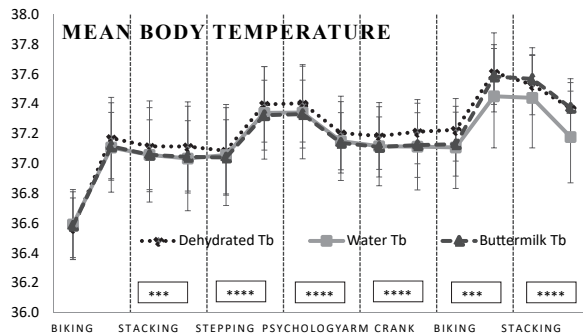**Fig. 7.   Mean and SD of the heart rate (HR) during the 3-h exposure.**
N=12

Fig. 8.   Mean and SD of the mean body temperature (Tb) during the 3-h exposure.
N=12
*statistical significance compared with no rehydration (***$p \leq 0.001$, ****$p \leq 0.0001$, see Table 3)

Table 2. Summary Table of Statistical Significance based on the rate of change for each activity – the statistical analysis applied an ANOVA repeated measures and a Freidman's test for statistics of significance ($p < 0.05$)

Activity	No rehydration – Buttermilk & Water		Water - Buttermilk
	Mixed Model	Friedman's Test	Mixed Model
Biking (15–33 min)	Tb: ****	Tb: ** HR: * Discomfort: * Thirst: ***	
Stacking (36–54 min)	Tb: *** Dehy. Level (%): *	Tb: ** Thermal: * Discomfort: *** Thirst: ** Dehy. Level (%): ***	
Stepping (57–75 min)	Tb: **** Dehy. Level (%): *** Ev. rate (g/min): ***	Tb: *** Thermal: * Thirst: ** Dehy. Level (%): *** Ev. rate (g/min): **	Ev. rate (g/min): **
Psychology Test (75–90 min)	Tb: **** Dehy. Level (%): **** Ev. rate (g/min): ****	Tb: ** Discomfort: * Thirst: ** Borg: ** Dehy. Level (%): **** Ev. rate (g/min): **	
Arm crank (90–108 min)	Tb: **** Ev. rate (g/min): ****	Tb: *** Discomfort: ** Thirst: ** Borg: *** Dehy. Level (%): * Ev. rate (g/min): ****	HR: *
Biking (111–129 min)	Tb: *** Ev. rate (g/min): ****	Tb: * Tc: * HR: * Thirst: ** Borg: * Dehy. Level (%): **** Ev. rate (g/min): ****	
Stacking (132–150 min)	Tb: **** Dehy. Level (%): ** Ev. rate (g/min): **** Cortisol (rate nmol/L): *	Tb: ** Thermal: * Discomfort: ** Thirst: *** Borg: ** Ev. rate (g/min): **** Cortisol (rate nmol/L): **	

*$p \leq 0.05$, **$p \leq 0.01$, ***$p \leq 0.001$, ****$p \leq 0.0001$. Tb: Mean body temperature. In the mixed model, gender was included as co-variate. N = 12

sure ($p \leq 0.05$) (Table 2 and Fig. 9). Consistent with expectations, keeping hydrated when working for a prolonged period in the heat did significantly affect the subjects' perceived thermal stress, workload and thirst sensation. Further, in all interventions subjects felt increasingly uncomfortable and hot following the heaviest activity, which was biking.

Cortisol results

When working in the heat a general stress response was seen in the no rehydration samples towards the end of the exposure ($p \leq 0.005$) (Table 2) relative to baseline (Δ). The no rehydration samples show a steady increase from the baseline sample, whereas both water and buttermilk samples have a decreasing trend (Fig. 10). Overall, individual influence dominated the cortisol data, with a clustering of data points and large SD. No gender difference was
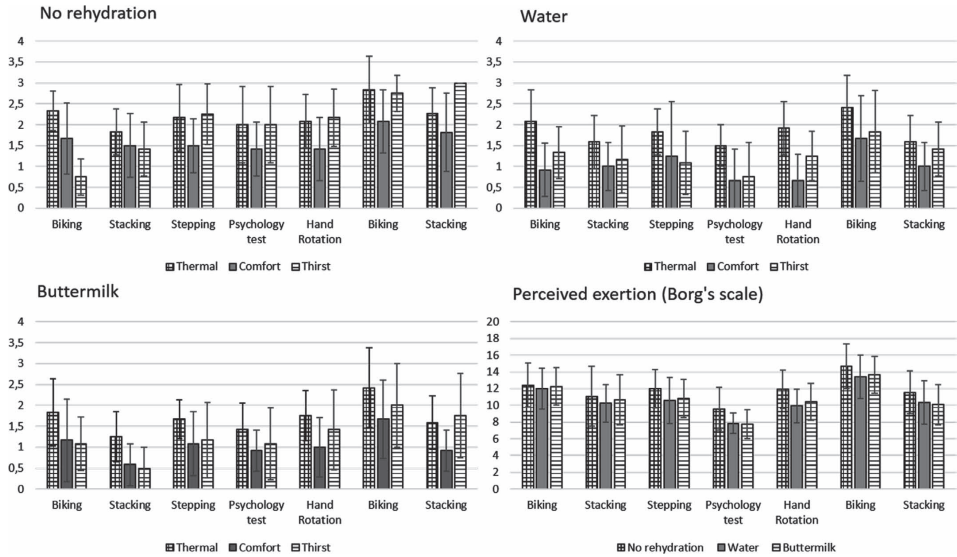
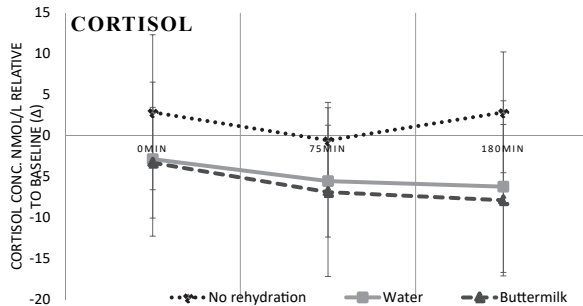Fig. 9.   **Perception scales results, mean values (SD).**
N=12

Fig. 10.   **Cortisol concentration (nmol/L) relative to baseline (Δ). Mean and SD in relation to the first sample in the morning (before entering the chamber).**
N=12

detected.

Psychology tests (a)

No significant differences were found when comparing the no rehydration intervention (prior to the heat-stress exposure) to the two following interventions (during and after the heat-stress exposure) on the N-back, or the subjective assessment of anxiety (SAM) (Table 3). Furthermore, there were no significant differences found when comparing the hydration conditions (no rehydration, water

and buttermilk) or correlations between the physiological markers and cognitive performance.

Effects on the gut microbiota (b)

In the diversity of the dominating rectal microbiota, no significant difference ($p > 0.05$) was observed when Shannon and Simpson indices were calculated and compared for the three interventions. Neither was any significant differences ($p > 0.05$) in 16S rRNA gene copies/g rectal samples found for either *Enterobacteriaceae* or *Lactobacillus*

Table 3. Means and SD of SAM(subjective assessment of anxiety) and N-back (working memory capacity). The three rehydration conditions are collapsed since no significant differences between them were found

| | SAM* | | | N-back** | | | |
| | | | | Perform | | RT | |
	Arousal	Control	Pos - Neg	N = 1	N = 2	N = 1	N = 2
First test (0 – 15 min)	6.1 (1.7)	5.2 (1.9)	3.7 (1.7)	0.95 (0.04)	0.95 (0.05)	529 (125)	613 (227)
Second test (after 75 – 90 min)	5.9 (1.7)	5.4 (1.8)	4.1 (1.6)	0.97 (0.03)	0.95 (0.03)	503 (116)	590 (210)
Third test (after 150 – 165 min)	6.1 (1.7)	5.7 (1.8)	4.0 (1.6)	0.95 (0.05)	0.95 (0.05)	489 (87)	588 (219)

*The participants assessed their degree of anxiety on the three aspects above on a scale from 1 – 9. **The tests were divided into 2 blocks. In the first block N = 1, in the second N = 2. Perform: the percentage correct answers, RT: response time in ms. N = 12

Table 4. Median and range of urine samples

| | | Albumin (mg/L) | | Creatinine (mmol/L) | |
		Pre-exposure	Post-exposure	Pre-exposure	Post-exposure
No rehydration	Median	3.5	11.9	18.4*	24.5*
	Min	3	3	4.5	14.4
	Max	66.3	117.1	32.9	46.8
Water	Median	3	3	20.7*	23.5*
	Min	3	3	1.8	10.1
	Max	20.7	29.4	43.5	73.5
Buttermilk	Median	3*	4.4*	20.1*	18.9*
	Min	3	3	4.6	14.4
	Max	21.2	58.8	43.9	59.3
Total	Median	3	4.7	19.8	22.6
	Min.	1.8	3	4.5	10.1
	Max.	66.3	117.1	43.9	73.5

N = 12. *$p \leq 0.05$ (pre- and post-exposure - Wilcoxon's test results).

among the three interventions ($p > 0.05$).

Kidney function (c)

The analysis of variance between interventions showed that buttermilk had significantly lower creatinine concentrations in comparison to both water and no rehydration interventions ($p \leq 0.05$) suggesting buttermilk could have a protective effect. In the analysis of the pre-and post-exposure data, significant results were found in creatinine ($p \leq 0.05$) secretion suggesting the exposure itself affected creatinine concentrations. The albumin/creatinine ratios were mostly below the detection limit and were therefore not analyzed further (32 quantifiable observations out of 72). Three ratios were outside the reference interval: 3.47, 6.43 and 3.47 mg/mmol respectively. In normal well-functioning kidneys, the daily normal urine protein excretion is less than 150 mg protein and urinary excretion concentrations range from 30 – 300 mg per d for albumin and 30 – 300 g for creatinine. Many of the albumin samples

were below the detection limit of 3 mg/L, corresponding to 21 samples out of 36 in the pre-exposure and 16 out of 36 in the post-exposure. Overall, individual influence dominated the analysis of the concentrations of albumin and creatinine. Most protein HC samples were below the detection limit of 5 mg/L and was therefore not analyzed further (only three samples exceeded this limit, two of them in the sample after exposure). The normal plasma concentration of protein HC is between 5 – 12 mg/L[42]. Hence, no concentrations measured indicated renal impairment in this study design. The albumin/creatinine and protein HC/creatinine ratio respectively did not exceed any limits for albuminuria nor proteinuria (30 mg/mmol). See Table 4 for median concentrations and range results.

Discussion

Summary of main results

In this study of a 3-h period of medium load physical

work in 34°C and 60% RH, we found that in the physiological parameters measured, there was significant difference in mean body temperature raise between the no rehydration intervention compared with both buttermilk and water interventions, confirming a thermoregulatory benefit of keeping hydrated. This adds to previous work highlighting the importance of hydration in hot, strenuous occupational settings[43] and the observed higher core temperature when dehydrated[43–49]. However, the rectal temperature, mean skin temperature and heart rate did not show any statistically significant change when comparing the interventions. Subjective perceptions of thermal sensation, thermal comfort, thirst and physical exertion showed significant changes between the no rehydration intervention and both buttermilk and water interventions, especially towards the end of the exposure. Staying hydrated in this study did affect the subjects' experience in a positive way.

When drinking buttermilk, the total body weight loss was significantly less in comparison to both water and no rehydration interventions, proposing a hydration benefit. A significantly lower sweat rate was also observed when keeping hydrated in the water and buttermilk intervention, suggesting a response to the lower mean body temperature or a later onset of sweating similar to previous studies[50]. This result contradicts some research suggests a lowering of the sweat rate when hypohydrated[49]. However, the subjects in the present study did not reach such a status of dehydration, with an average of 1.5% body weight loss. It is also important to note that sweat rates may vary greatly between individuals, influencing the results for this research design with a low sample size[50].

a) The cognitive effects of heat strain and physical work on arousal, working memory performance.

An increase in cortisol concentrations was seen in the no rehydration intervention whereas a decrease in the rate of change in saliva cortisol concentration was found in both water and buttermilk interventions. The circadian rhythm was theorized to be accounted for due to the standard protocol used[51, 52]; the test always started at the same time of the day about two hours after awakening (~09:00), suggesting the morning peak of cortisol had passed[53, 54]). In addition, methodological issues were accounted for[55–58], for example, no exercise the day before together with a standardized breakfast and similar dinner the night before each of the three tests. The focus of analysis was on the response when spending 3 h in the climatic chamber. However, factors such as the morning commute and nervous-

ness about the test ahead could have had a differing impact for each test day[59, 60].

No heat stress or exercise dependent impairment was found in the cognitive tests. On the one hand, the result is in line with, for example Caldwell *et al.*, (2012)[37] who likewise found no changes in the cognitive capacity when testing the effect of auxiliary cooling and protective clothing in heat compared to control conditions. On the other hand, the results are not in line with several of the studies reviewed by Chang *et al.*, (2012)[23] who found a slight improvement of cognitive performance related to increased heat stress and exercise. The assessment of the experienced anxiety level (SAM) did not change during the experiment, possibly indicating that the participants felt able to control the situation, even though the physiological markers showed increased strain. Since the level of cognitive performance was retained, this could also be interpreted as the ability to control the situation was keep intact. However, as the result of the working memory test showed the performance was relatively close to perfect, it is possible that the cognitive load the test imposed might have been insufficient to detect a possible decrease at the studied heat stress level (Trec < 38.5°C).

b) The impact of heat strain and physical work on the human gut microbiota.

We found no significant difference in the diversity of the dominating rectal microbial flora or the amount of *Enterobacteriaceae* and *Lactobacillus* when comparing interventions in this study. The analysis indicated that the microbiota differed widely between the study subjects. Inheritance and diet are two important factors influencing the composition of the gut microbiota of an individual confirming each person having an individual microbiota[61]. Further, diet is reported to be the key spark for the development of the intestinal microbiota structure[62] and long-term dietary patterns largely determine the main phyla of the gut microbial profile[63]. Thus, for the short exposure in this study (3 h), dietary pattern may have been an important factor that may affect the gut bacterial flora. It also should be stressed that, the order of the three interventions were randomly decided and the time in between the interventions differed randomly depending on availability. Thus, it might be difficult to observe differences in the microbiota, as well as the cortisol level differences for this study design.

c) The effects of physical work and short term heat exposure on renal function.

The analysis of renal function between interventions suggested a protective effect of drinking buttermilk. When analyzing all pre-and post-exposure data, a significant urine concentration impact was found for this study design of short-term heat exposure combined with physical work. Loss of water by sweating and the decrease in renal blood flow due to physical work (blood flow is redistributed to the extremities) causes an increase in tubular reabsorption of water, sodium and urea which affects urine creatinine concentrations and reduces the glomerular filtration rate (GFR). Increased breakdown of muscle creatinine and purine could also contribute to this however, it is unlikely in this study[30]. These preliminary results do suggest an acute impact of short-term heat exposure combined with physical work on renal function and that buttermilk may have a protective effect on this impact. As a result, buttermilk consumption could have a protective effect for poor agricultural workers prone to chronic kidney disease (CKD)[30-33]. A limitation in this analysis is that it was performed on frozen samples, and long-term storage can decrease concentrations[32]. However, no concentrations measured indicated renal impairment and hence, suggested a concentration effect of short term heat exposure and physical work due to the body's fluid regulation[27].

Workers participating in the field study[2] drank buttermilk as a way of getting the extra energy and nutrition to work for longer without eating a solid meal, which could add to the heat strain. Buttermilk is often a major source of nutrition for the working day, which is the primary benefit in combination with the thermoregulatory effect described. A suggestion from the study is therefore to combine drinking buttermilk with water when working in the heat particularly for undernourished poor workers in India.

Wider implications

As the occupational heat stress situation is bound to worsen due to climate change[1-7], additional preventive actions have to be implemented to prevent adverse health impacts for workers in hot strenuous occupational settings. Whilst the global community face increasing heat extremes, little has been studied on the effects of diets affecting thermal regulation, e.g. by increasing sweating, in the climate change research community and more focus has been on the mitigation potential of changing diets[64] and its co-benefits to health[65]. Traditional low cost methods of coping with heat stress through diet,, such as drinking buttermilk could have an important role to play for managing future high heat levels.

Limitations and suggestions of improvement

An aspect to consider is that the subjects were not from India, but rather of European origin. This affects the experience of drinking buttermilk, as for some, it was the first time. Field studies are therefore necessary, involving poor under-nourished workers in order to further investigate the benefits of drinking buttermilk as the workers in the field described its cooling potential.

Suggestions of improvements from this study design include laboratory tests with longer duration to improve ecological validity combined with a lighter breakfast (to tease out hunger mechanisms), reduction of the initial water intake of 500 ml and introduce heavier work tasks, in order to make subjects more dehydrated.

Furthermore, one could speculate that the water intervention could prove to have a significant thermoregulatory effect if the study had been prolonged as the last activity had a *p*-value of 0.06 compared with no rehydration.

Conclusion

The study investigated the benefits of drinking a traditional Indian diluted yoghurt drink, buttermilk. The research was innovative in its multi-disciplinary study design, combining research questions linked to physical labour in a hot climate from different disciplines. It also links findings from a field study to further analysis in an experimental study design. Parameters included thermoregulation and hydration benefits and the impacts of work in a hot environment on gut microbiota, cognitive and renal function. Both water and buttermilk performed well in terms of whole body cooling, to lower the sweat rate, improved hydration and reduced hormonal stress. When subjects drank water or buttermilk they also reported that they felt significantly less hot, more comfortable, and less thirsty and that they were less physically exerted than in the no rehydration intervention. The saliva cortisol concentrations in the no rehydration intervention showed a stress response at the end of the exposure. With this study design, no differences in cognitive abilities or short term impacts on the gut microbiota were found between the groups. Effects were seen on the urine creatinine concentrations in the water and no rehydration interventions suggesting a protective effect of drinking buttermilk. Further, the exposure itself affected creatinine concentrations, suggesting a urine concentration impact of short-term heat exposure combined with physical work.

Our results are in line with other literature that indicates keeping hydrated reduces body temperature, sweat

rate and hormonal stress and results in a reduction in the perception of feeling hot, uncomfortable, thirsty and physically exerted. Buttermilk was as good as water to mitigate heat strain in well-nourished subjects. However, further research is needed to study the advantages of buttermilk for undernourished workers. As the occupational heat stress situation is bound to worsen due to climate change, traditional low cost methods of coping with heat stress through diet, including consuming buttermilk, have a potential to be a part of managing heat exposure in the future.

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Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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Paper V

SPECIAL ISSUE ON TRANS-DISCIPLINARY APPROACHES TO CLIMATE CHANGE

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Climate change-induced heat risks for migrant populations working at brick kilns in India: a transdisciplinary approach

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Abstract

During the summer of 2015, India was hit by a scorching heat wave that melted pavements in Delhi and caused thousands of deaths, mainly among the most marginalized populations. One such group facing growing heat risks from both occupational and meteorological causes are migrant brick kiln workers. This study evaluates both current heat risks and the potential future impacts of heat caused by climate change, for the people working at brick kilns in India. A case study of heat stress faced by people working at brick kilns near Chennai, India, is the anchor point around which a transdisciplinary approach was applied. Around Chennai, the situation is alarming since occupational heat exposure in the hot season from March to July is already at the upper limits of what humans can tolerate before risking serious impairment. The aim of the study was to identify new pathways for change and soft solutions by both reframing the problem and expanding the solution space being considered in order to improve the quality of life for the migrant populations at the brick kilns. Technical solutions evaluated include the use of sun-dried mud bricks and other locally "appropriate technologies" that could mitigate the worsening of climate change-induced heat. Socio-cultural solutions discussed for empowering the people who work at the brick kilns include participatory approaches such as open re-localization, and rights-based approaches including the environmental sustainability and the human rights-based approach framework. Our analysis suggests that an integrative, transdisciplinary approach could incorporate a more holistic range of technical and socio-culturally informed solutions in order to protect the health of people threatened by India's brick kiln industry.

Keywords Brick kilns · Climate change · Heat stress · India · Migrant work · Technical and socio-cultural solutions · Transdisciplinary approach

Introduction

India is experiencing increasing heat both in the economy and in rising temperatures (IPCC 2013). The people suffering the most from actual heat, such as rural populations and migrant daily wage laborers, are to a large degree left out of by globalization and neoliberal capitalism while still bearing the brunt of its negative consequences (Klein 2009; O'Brien et al. 2004). The structural adjustment programmes (SAPs) launched in the early 1990s led India into a new economic era and transnational corporation export-oriented growth that has mainly manifested in its cities, widening the inequality gap between rural and urban populations. One consequence of this is a booming building industry that drives demand for clay bricks from brick kilns that employ rural migrant labor (Kumbhar et al. 2014). Here, we find two sides of India emerging as the paradox of a building technology shaping the new while still based on ancient techniques of fired soil and human labor (SDC 2008). Hence, at one extreme, new high-rise buildings are hosting busy modern life of people from India's growing middle class, working for global companies and cooled down by air conditioning. At the same time, India's local economy long nurtured by rural village farming

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populations found themselves falling into increasingly precarious circumstances, forced off the land, often due to mounting debts, and into the migrant working force with many ending up at brick kilns. Generally, the most vulnerable populations, such as migrant workers and the elderly, have borne the unjust burden of climate change consequences (Klein 2009; NDMA Government of India 2016; UNDP 2016).

The negative impact of the SAPs on agricultural policies for rural labor, combined with climate change-driven factors that have worsened the dry season, has forced rural populations and landless migrant workers to travel from the poorest of Indian states, such as Bihar, Orissa, Uttar Pradesh, and West Bengal, into low-tech jobs, such as brick making. The brick kiln sector in India employs millions of migrant workers (SDC 2008). Though now illegal in India, various forms of bonded labor that amount to essentially forms of slavery, including child labor, continue to be common practice throughout India's brick industry due to weak law enforcement (Guérin et al. 2012). Families, including young children, work in harsh, low-paying conditions, commonly compensated piece by piece (Khandelwal 2012). There is typically a lack of basic facilities, such as access to clean drinking water and sanitation (Inbaraj et al. 2013). Risks to health are many and the sector has high death rates. Health impacts mainly originate from breathing in smoke and physically demanding work outdoors combined with extreme weather causing heat strain and other illnesses such as pneumonia and respiratory infections (Nizami 2011; Pingle 2012). Long-term brick kiln workers, who adopt a specific posture for prolonged working periods, commonly develop severe musculoskeletal problems (Inbaraj et al. 2013).

The aim of the study was to identify new pathways for change and soft solutions by both reframing the problem and expanding the solution space. The objective was to look at the problems faced at brick kilns from different angles, using a transdisciplinary approach to identify soft solutions for migrant brick kiln workers in Chennai. This approach is novel in the current brick kiln literature that has otherwise predominantly looked at technical aspects. The intended audience for this paper includes field workers within development organizations and activists working with human rights and health issues at brick kilns, as well as government policy makers wanting to influence the lives of workers at brick kilns now and in the future.

Methodology

The research team used a "mixed methods" transdisciplinary approach that applied both quantitative and qualitative methods. Climate forecast data was generated from climate modeling tools, specifically the Climate CHIP/HOTHAPS Soft toolset (Climate CHIP 2016). A qualitative analysis was conducted using a transdisciplinary literature review in order to provide the national context. Local case study data was collected around Chennai, India. This included occupational heat stress measurements and observations from brick kilns. A case study research methodology is suitable given the multifaceted ecological and human rights marginalization experienced by people working at brick kilns in India (Flyvberg 2001; Yin 1994). Case study research is concerned with the complexity and particular nature of the case and location in question (Bryman 2008). Chennai was selected as a representative case site where the research question could be applied to both field observations and climate projections so that a transdisciplinary approach could be used to identify potential solutions. The primary field data for the Chennai case study was collected at brick kilns using quantitative methods focused on evaluating occupational health indicators (Venugopal et al. 2016). The case study source materials for qualitative observations were based on a transdisciplinary literature review (Hakim 1987; Kiecolt and Nathan 1985). Transdisciplinarity generally refers to the appropriate combination and integration of knowledge from many different specialties, especially as a mean to shed new light on a problem. The combination of disciplines adds value—the total is more interesting than the sum of the individual contributions or parts (Brewer 1999; Jantsch 1970/72). This requires academic researchers to collaborate across disciplinary, epistemic, and methodological boundaries.

To mobilize the transdisciplinary approach in identifying potential *future pathways*, existing literature was reviewed through a critical discourse analysis lens taking into account the health and environmental risks faced by the people working at the brick kilns. The critical discourse analysis was then directed into a form of framing analysis approach (Fletcher 2009; Jerneck and Olsson 2011; Wise et al. 2014). Framing analysis is a form of discourse analysis. By *discourse*, we apply what social theorist Michel Foucault would describe as "a way of talking about or dealing with a phenomenon" (Ingstad and Whyte 1995). Thus, the Foucauldian notion of discourse is a culturally constructed representation of reality that is used to construct knowledge and thus governs, through the production of categories of knowledge (including disciplinarily categories) and assemblages of texts, what it is possible to talk about and what is not (Foucault 1972/1995; Foucault 1991).

Framing analysis exposes the role of "political language and worldviews in the construction of plausible, meaningful and socially relevant pathways that can enroll a majority of stakeholders and citizens in collective action" (Fletcher 2009). Taking a solutions-oriented approach to framing analysis, we applied discourse analysis as a way of showing "how problems are embedded in particular narratives." Further, an applied approach was taken to illustrate how "reframing stimulates alternative understandings and problem solutions" by applying the capacity of reframing to associate ideas across theoretical, empirical, and disciplinary divides as a way to

break through "disciplinary compartmentalization" traps that ignore the complexity of cross-cutting sustainability challenges (Jerneck and Olsson 2011).

Identifying new solution pathways is critical for saving lives as the risks posed by climate change grows. Studies have pointed out that "the nature and effectiveness of responses" to climate change are strongly influenced by framing (Wise et al. 2014).To realize the solutions-driven focus of this study, potential future pathways were uncovered discursively in a stepwise approach that applied *framing analysis as method*. The first step was the transdisciplinary literature review. Migrant brick kiln workers in India face heat risks from multiple causes that require a holistic analysis. Due to this, the authors found it a critical workplace to study and conduct a transdisciplinary analysis. The literature review was transdisciplinary because the researchers intermixed a diverse range of disciplines, including environmental science and engineering, architecture, human ecology, social anthropology, and occupational health. The analysis could have included more disciplinary perspectives; however, this was not possible due to time and other structural restrictions. The disciplinary frame brought into the study by each researcher was leveraged to evaluate the discourse uncovered in the literature review. The second step was to engage in an initial deep interactive discussion about the literature as a way to identify both synergies and incongruences based on disciplinary perspectives and empirical data. The third step was a final reframing discussion during which the discourse uncovered in the literature review was analyzed together with the case study results combined with challenges imposed by climate change-induced heat. Additionally, the overall challenge in the reframing analysis was to uncover ways of providing low-cost, soft solutions accessible and attainable at low cost for local people whenever possible.

Research findings: current state

Transdisciplinary literature review: climate change reinforcing heat feedback loops

Brick kilns in India produce between 150 and 200 billion bricks annually (CATF 2012), a building material that has been predominantly used during India's construction boom. The brick kilns only stop operating during the rainy season, so the brick industry relies on largely manual labor throughout the dry season and is generally confined to rural and peri-urban areas.

The Central Pollution Control Board has identified brick making as one of the most polluting industries in the small-scale sector (Development for Alternatives 2012).Bricks are commonly fired to a temperature of 700–1100 °C, requiring an enormous amount of energy for the firing operation, resulting in brick kiln owners sourcing fuel from many supply streams. The pollution generated as by-products of the combustion process can generate significant negative local health impacts from particulate matter, black carbon, sulfur dioxide, oxides of nitrogen, carbon monoxide (CO), and black carbon/soot that contribute to worsening of climate change globally (Menon et al. 2002). Black carbon by itself is a major health hazard (Löndahl et al. 2010), so even mitigating soot production alone could significantly reduce the rate of warming over the next decades (UNEP/WMO 2011). Brick kilns are estimated to consume roughly 25 million tons of coal per year, thus making them among the highest industrial consumers of coal in the country, which contributes to both climate change globally and local health risks arising from respiratory ailments (CATF 2012; UNEP/WMO 2011). In addition to the brick industry in India consuming an estimated 8% of the total coal consumption in the country, it also consumes a large amount of other fuels, mainly wood and agricultural waste. The industry also uses other available cheap and polluting waste such as rubber tires (Development for Alternatives 2012).

While the technical side of brick manufacturing in India has been covered widely in scientific literature, this has not been the case to a similar extent as regards the human part of the industry. The situation for India's brick kiln workers, however, gained international media coverage starting in 2014 through a number of spectacular articles and TV presentations. Headlines included "More than two million people work in the *brick kilns* that supply the India's booming construction sector, and many are held in conditions little better than slavery" (BBC 2014); "Blood Bricks: How Indian urban boom is built on slave labour" (The Guardian 2014); and "India's booming cities built from 'blood bricks' of bonded laborers" (Reuters 2016). Media thus directly combined what they saw as slave-like conditions of brick laborers and their families with India's growing economy and booming urban construction sector. Here we see a strong image combining the "new" and "old," the hard and the soft India through the figure of the brick and the person producing it. They were, thus, put into new frames and while the industry is seen to look for hard solutions, the human side, as we argue in this article, needs soft solutions and structural change.

Traditionally, India is a country where people have predominantly lived from agriculture with the local village as the center of existence, providing livelihood directly from the land. The traditional agricultural system was based on farmers' own-resource-based subsistence farming. With the green revolution, initiated already in the 1960s, this has increasingly moved to purchased input-based intensive commercial farming based on cash crops. After structural adjustment in the early 1990s, and the neoliberal reforms, there has been an increasing marginalization of land holdings together with loss of subsistence farming practices. It is further found that opportunities for non-farm local work in rural areas have declined after the economic reforms

with the consequence that employment for rural labor now has a tendency towards relatively more insecure and casual work while secure jobs or self-employment has declined (Reddy and Srijit 2012). This has also created a decline in livelihood opportunities for landless agricultural laborers, thus forcing former peasants into the semi-urban brick kilns (The New York Times 2007).

The main raw materials used for brick kiln production are soil and coal. A study from Bihar (Development for Alternatives 2012) showed that as much as 90% of the soil used for brick production in the state was procured from agricultural land, and if kept in agricultural production, this land could have produced 7000 t of rice, enough to keep 110,000 people with food grain. Given that a large portion of the brick kiln workers in large cities, such as Chennai, migrate from Bihar, one of the poorest states, it indicates another one of the tragic loops that drives the system. Black carbon/soot still furthers the negative loops and necessitating migration as it heats up the atmosphere and thus accelerates the melting of Himalayan glaciers that feed India's large rivers (Menon et al. 2002; Xu 2009).

To this comes climate change, creating an added environmental crisis of agriculture with rising temperatures, resulting in weather extremes with water scarcity and severe drought in many areas. Further extremes are increasing precipitation with tropical cyclones. This results in greater instability in food production (Aggarwal 2008; Reddy and Srijit 2012). The extension of the technology of the Green Revolution to regions where it was not suitable, such as dry and rain-fed parts of the country, further aggravates the water crisis. Seasonal migration thus becomes a survival strategy for rural people now completely dependent on diminishing land holdings, under increasing environmental stress, as a main source of livelihood for continued life in the village when other opportunities for rural work are disappearing.

Most brick kiln workers do, however, maintain their linkage to their original place of residence, engaging in a form of circular migration where farm work and unorganized work at the brick kiln supplement each other as sources of livelihood for rural poor such as landless laborers and marginal farmers. They migrate for the brick kilns during the dry season when there is not much work in agriculture and return to their villages at the start of the monsoon. They are contracted to the kiln industry in their villages by a local contractor who will know which people are in need of loans and extra livelihood and thus willing to migrate. The contractor gets a commission from the number of bricks made by the worker supplied by him (Molankal 2008). The lure is the lump sum the worker gets in advance and which the family can use for paying back debts and buying foodstuff during an otherwise lean period (Molankal 2008). He and any accompanying family are then bonded to work in order to pay back the advance.

Local case study field observation: occupational heat stress data from brick kilns near Chennai, India

The quantitative data collection for the case study took place at brick kilns in the local area near Chennai, India. Chennai, the capital city of Tamil Nadu, is located on the Coromandel Coast of the Bay of Bengal and has a hot and humid climate. Chennai is a major administrative and cultural center and has also become one of the major outsourcing destinations within India (Kobayashi-Hillary 2005). Large-scale brick production on the outskirts of Chennai dates back to the mid 1970s and the state is one of India's most important brick-making states due to strong growth in the construction sector (Prakash 2009). Further, it has been backed by a vast housing scheme from the Tamil Nadu Government that was unaffected by the global economic crisis of 2008 (Guérin et al. 2012).

The field study focused on gathering occupational heat exposure in order to understand the health risks faced by people working at brick kilns. It confirmed that brick kilns are work sites where people are exposed to both extreme outdoor temperatures (maximum ranges between 40 and 45 °C in the hot months) and high radiant heat from brick kiln furnaces over many hours (globe temperatures of between 19 and 52 °C year-around). Additionally, high levels of heat stress are experienced by people working at the brick kilns due to the limited or non-existent cooling options provided on-site by brick kiln owners.

Environmental heat measurements

An assessment of the thermal environment was conducted in accordance with occupational health and safety guidelines issued by the International Labour Office (ILO) and the International Organization for Standardization (ISO). The ILO guidelines state that "measurements of thermal conditions should take account of: (a) all stages of work cycles and the range of temperature and humidity under which the tasks are performed; (b) the range of clothing worn during the tasks; (c) major changes in physical activity level (metabolic heat production)" (ISO 1989; ILO 2001). Measurement techniques include the use of the Wet Bulb Globe Temperature (WBGT) index (ILO 2001). The WBGT index is a common occupational health-screening tool used for setting limit values for work in both indoor and outdoor environments (Bernard et al. 2005; Gao et al. 2017 this issue; Parsons 2014).

The ISO 7243 standard incorporates environmental temperature, humidity, and solar radiation (ISO 1989). 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; $\pm 5\%$) during the colder

(January–February) and warmer (March–July) months. The QUESTemp uses a 5-cm diameter globe for a faster response time while the WBGT index is based on the response of a 15-cm diameter globe. As a result, the instrument correlates it to match that of a 15-cm globe. Average WBGT values and minimum and maximum values (Table 1) were measured at five brick kilns: one from Salem, Trichy, Chengalpattu, and two from Thiruvallur district. Due to access constraints 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 and 6 h.

The brick kilns have high heat exposure in the hot months (see maximum values in Table 1 and the month of May in Table 2), with WBGT sometimes exceeding the international standard limit value of 28 °C for acclimatized workers under moderate workload (ISO 1989).

Internal heat production

Most workers in the Chennai brick kiln had moderate workloads (130–200 W/m^2; ISO8996 2004), all in direct sun exposure (Lundgren et al. 2014). From brickwork simulations with 1.7-kg bricks carried out by the authors in a climate-controlled chamber measuring oxygen consumption, the average metabolic rate was 133 W/m^2 (SD 15 W/m^2). From measurements from 114 brick kiln workers in the field of between 3 and 6 h, heart rate averaged 87 bpm in the cool season and 88 bpm in the warm season with a maximum of 116 bpm and a minimum of 60 bpm. Sweat rates averaged 0.4 l/h in the cool season and 0.8 l/h in the warm season with a maximum of 1.2 l/h.

From field observations, the main work tasks have varied workloads following these steps:

1. *Material Procurement*: The clay is mined and stored in the open.
2. *Tempering*: Clay is mixed with water to get the right consistency for molding. Mixing is done manually with hands and feet.
3. *Molding*: A lump of mix is taken, rolled in sand, and slapped into the metal mold.
4. *Drying*: The bricks are emptied onto the drying area, where they are dried in the sun. Every 2 days, they are turned over to facilitate uniform drying.

5. *Firing*: The bricks are arranged in a kiln and insulation is provided with a mud-pack. Fire holes are ignited and the kiln is later sealed to keep the heat inside.
6. *Sorting*: After the kiln is disassembled, the bricks are sorted according to color. Color is an indication of the level of burning.

Work clothing trapping heat

Clothing also affects the level of heat exposure for each person (ILO 2001). Traditional clothing such as churidars and saris are commonly worn at the kilns by women, with an average clothing basic insulation range of 0.58 clo for the churidar to 0.96 clo for a sari with a protective shirt and towel on the head. Men usually wear a shirt and trousers with an average clothing insulation of 0.61 clo (Lundgren et al. 2014; Havenith et al. 2015). The sari has also proven to be a very effective garment to protect workers from heat (Indraganti et al. 2015); however, its effectiveness is hampered by the protective shirt (Lundgren et al. 2014). Indirectly accounting for moderate metabolic rate, a work limit value for WBGT would be around 28 degrees for the acclimatized worker (ISO 7243 1989). Further, in the present study, clothing adds further heat stress in particular for females.

Self-reported heat stress

Questionnaire data with simple yes and no questions regarding health and productivity was also collected at the brick kilns in Chennai and the results are presented in Table 3.

These results are consistent with concerns raised about the harsh working conditions found at brick kilns. Most workers report symptoms of heat strain, reduced productivity, and impacts on daily life during the hot season, which lasts for over 6–8 months. However, a bias could have been introduced in the collected data as the employer was always present during the questionnaire.

Analytical discussion: reframing potential future pathways

This analytical section uses framing analysis as a way forward to identify "pathways" for change. This qualitative way of framing

Table 1 Seasonal comparative table—WBGT summary measurements from five brick kilns in the Chennai area (2013–2015)

		WBGT min	WBGT max	WBGT average
Hot season	June–July 2013	25.8	28.6	27.0
	March–April 2014	24.8	35.0	29.0
Cool season	February 2013	18.8	25.2	22.2
	January–February 2015	22.9	28.3	25.6

Table 2 Example brick kiln from Chennai in 2013—seasonal comparative table with data from different work stations

Work location	May			January		
	Temperature (°C)	Humidity RH (%)	WBGT (°C)	Temperature (°C)	Humidity RH (%)	WBGT (°C)
Brick production from clay	29.3	57	25.9	20.0	88	18.8
Brickmaking area	30.5	33.0	27.8	22.0	79	25.2
Furnace area 1	27.0	28.9	25.8	20.0	88	20.5
Furnace area near chimney	27.0	28.9	26.2	20.5	88	20.7
Furnace area 2	27.0	28.9	26.6	20.0	88	21.0
Furnace area 3	27.5	29.5	26.6	20.0	88	21.4
Furnace area 4	30.5	33.0	28.6	22.0	79	24.9
Working place 1	30.0	48.5	25.6	20.5	88	22.4
Brick loading area	28.0	30.2	26.0	22.0	79	24.7
Average WBGT	26.7			22.2		
	(SD: 1.0)			(SD: 2.1)		

solutions borrows the "pathways thinking" metaphor used in the sustainable development discourse (Wise et al. 2014).

The climate connection: forecasted climate change-related heat impacts

India is already at high risk of excessive heat. In many places, the maximum temperatures during some parts of the year already exceed 40 °C. An additional 3–5 °C will make outdoor physical work very difficult during the hottest periods (Kjellstrom 2009; Venugopal et al. 2016). Figure 1 shows the average heat stress index WBGT (ISO 1989) during the month of May in Chennai over time and future modeling based on the IPCC's representative concentration pathway of 8.5 (Climate CHIP 2016; IPCC 2013). The WBGT is calculated from airport weather station data and modeling data from the University of East Anglia, UK, produced by HOTHAPS Soft (Kjellström et al. 2013; Lemke and Kjellström 2012). Hence, solar radiation is not accounted for in this data set. WBGT levels are already close to or even above the limit values identified for brick kiln work in Chennai (specifically a WBGT of 28 °C), and that is without even accounting for solar radiation and the contribution of the urban heat island effect (Kleerekoper et al. 2012). Temperatures are projected to climb above the limit values of 33 °C for a resting acclimatized worker by the end of the century (Fig. 1), thus worsening conditions in Chennai.

Given these potential thermal futures, the need for radical interventions becomes even more apparent. Our analysis now turns to ways of redefining the problems and finding new soft solutions to overcome the complex challenges faced by people working at brick kilns.

Reframing the role of technology: from high tech to "appropriate technology"

It became apparent during the literature review that experts have tended to focus primarily on technical solutions whether using infrastructure changes such as improved smoke stacks, or fuel mix modifications at the kiln furnace. Furthermore, the solutions suggested tend to focus on mitigating problems affecting populations living far away from the brick kilns, but not specifically on health challenges facing the local migrant populations working at the brick kilns to frequently live either on-site or nearby the facility. For example, in the Clean Air Task Force's 2012 report on brick kilns, the final roadmap includes many technical solutions, but only in the final sentence of its recommendations do they suggest their technical solutions may lead to an "improvement of working conditions for millions of workers employed in brick kilns" (CATF 2012: XXIV).

In this next section, "appropriate technologies" are suggested that may actually be better suited to resolving some of the heat-related social and environmental issues affecting people working at brick kilns.

Locally "appropriate technology" approaches

Alternative choices in building materials could minimize environmental hazards and reduce the health impacts of brick production. One alternative is to use sun-dried mud bricks as a more locally appropriate technology. In Chennai today during the working season, the sun provides a free and abundant source of heat. Thus, the sun can be used as a natural fuel for drying the bricks. Experiments with using sun-dried earth bricks (Fathy 1973; Kennedy 2004) show that using local and natural earth materials in buildings is energy efficient, low in

Table 3 Comparative table depicting self-reported impacts of heat stress on health and productivity from a questionnaire (N = reported cases)

Variable	Impacts	Summer (N = 87) June–July 2013 and March–April 2014		Winter (N = 61) February 2013 and January-February 2015	
		N	Percent (%)	N	Percent (%)
Impacts on health	Excessive sweating	82	94	40	66
	Muscle cramps	32	37	28	46
	Tiredness/weakness/dizziness	75	86	44	72
	Headache	55	67	19	31
	Nausea/vomiting	7	8	3	5
	Fainting	13	15	6	10
	Prickly heat	21	24	7	11
Production target and issues	Have production target	2	2	10	16
	Able to complete production target	2	2	9	15
	Not able to complete production	–	–	1	2
Impacts on productivity	Absenteeism/taken sick leave due to heat	14	16	10	16
	Less productivity/more time to complete task/work extra hours	42	48	10	16
	Irritation/interpersonal issues	16	18	1	2
	Wages lost	–	–	5	8
Coping mechanisms	Take rest	65	75	60	98
	Drink water	87	100	61	100
	Cool shower, bath, or sponge bath	24	28	1	2
	Traditional methods (e.g., drinks and diet, self-pacing)	49	56	14	23
Impact of clothing on comfort	No impact	72	83	60	98
Impact of clothing on productivity	Moderate impact	24	28	12	14
	High impact	4	5	1	1

toxicity, safe, and durable, especially if obtained from the local environment. Other research shows that using low energy-intensive earth building materials could be an asset in reducing CO_2 emissions as well (May 2010; Rael 2009). The use of locally sourced materials can provide social and economic benefits locally while also reducing production costs compared to using both imported and industrialized building methods and materials (Morela et al. 2001). In countries
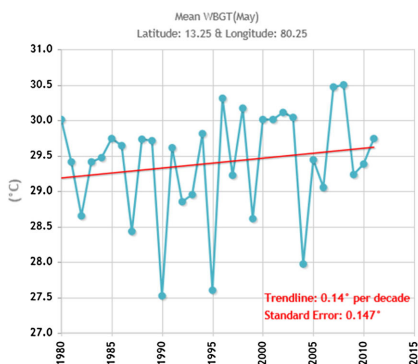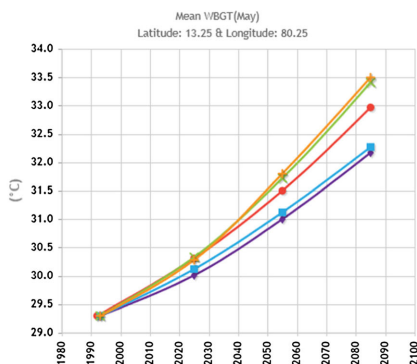

Fig. 1 Historical and future heat stress during the month of May in Chennai, without taking solar radiation into account, according to measurements and simulations. Produced by HOTHAPS soft (Kjellström et al. 2013; Lemke and Kjellström 2012; Climate CHIP 2016). The different colors represent different models datasets of RCP 8.5 (**HadGem**, **NORES**, **GFDL**, **IPCM**, and **MIROC+**)

where labor is abundant and labor costs are low, using the existing workforce of craftsmen and skilled locals opens up more job opportunities for local people (Dabaieh 2011) while strengthening the local community and reducing the dependency on energy-consuming construction techniques.

Another benefit of using mud brick and other locally produced natural building materials is the ability to ensure building materials are locally produced, recycled, and re-used, as well as being simply able to return to Earth as soil for vegetation (Morela et al. 2001). The sun-dried bricks can be promoted in the local market as an environmentally friendly building material, and help local consumers to gradually become aware of "green" issues. Legislation can help introduce sun-dried bricks into the marketplace and put into effect environmentally friendly building practices. The bricks also have significant implications for long-term costs, building performance, and energy consumption due to their thermal properties. Using sun-dried clay brick can help in producing so-called zero carbon buildings for two reasons. Firstly, the embodied carbon from energy usage during brick production is minimal thanks to using sunlight instead of coal or firewood in the drying process. Secondly, the sun-dried bricks can become CO_2 storage sinks if lime is added to the clay mixture of the bricks during production to help the bricks take CO_2 out of the air. Basically, the lime acts to provide this CO_2-absorbing capability by changing the physical properties of the clay to improve the water resistivity properties of the bricks (Jones 2005). Plastering sun-dried brick walls with lime plaster then rendered with casein protects the external brick surface from water erosion during rainy seasons. However, one caveat is that the weather in Chennai can be quite humid. Even though the lime needs humidity for the complete chemical process in the clay mix to take place, the humidity may impair the sun-drying process.

Local initiatives have already begun trying to pilot projects using cast mud bricks in building construction (Auroville Earth Institute 2016). The know-how is there, as is the tremendous potential to gradually transform brick manufacturing into a cleaner industry. If sun-dried mud bricks are cast manually, one person can cast up to 700 bricks ($25 \times 13 \times 12$ cm) in 8 working hours. If compared economically with fuel prices, sun-dried mud brick production could be far more economical, thus making the final brick price more competitive in the market. Further, the burning process takes almost the same time as it takes for the sun-dried bricks to dry in the sun. From a life-cycle analysis and cradle-to-cradle perspective, the embodied energy in creating the sun-dried mud bricks, from manufacturing to demolition and reuse, is minimal. Thus, sun-dried bricks have the potential to address more challenges overall compared to the other existing brick-manufacturing options available today, such as fly ash bricks, perforated bricks, and hollow cement bricks. Retrofitting the existing brick factories could take advantage of their mixing and casting infrastructure, while removing the energy intensive, heavily polluting firing process found in India's current brick kiln factories.

Reframing the role of people: from global human capital to local human rights

A recent UN report on the connection between labor and climate change argues for incremental interventions that focus on policy recommendations that emphasize the use of direct occupational health approaches that look to ILO guidelines (UNDP 2016), but only under business-as-usual structural regimes. The report mentions "productivity" 107 times, while never once recommending a rights-based approach for protecting people and the environment from a changing climate. The report does not evaluate the risks of coercive bonded labor practices, inequality, and oppression increasing among vulnerable populations who are forced to work at sites where heat exposure is already high and will worsen under climate change, as could happen with people working at brick kilns. However, the ILO stated as early as 2005 that brick kiln work "is a particularly prominent feature of contemporary forced labour situations" (Srivastava 2005). This has been corroborated by other reports that have pointed out that industrial brick production sites have been found to be sites of neo-bondage, mediated by middlemen posing as recruitment agencies (Breman 1996, 2007; Molankal 2008).This underscores the need to reframe the discussion from being about how to maximize the productivity of global human capital to being about a rights-based approach to protecting people and the environment. In this next section, we present framings that incorporate localization strategies, and an approach for protecting environmental sustainability along with local human rights.

Participatory socio-culturally informed localization approaches

Loss of local decision-making influence can be a side effect of globalization. Localization helps local people bridge the growing democratic influence gap by regaining influence within their communities. Localization of decision-making could provide a way to regain self-sufficiency for India's village communities. Using an open participatory process could also engage a wider range of local actors, including vulnerable groups such as migrant workers. Re-localization could be described as a process in which "people are reaffirming control of their lives" (by) putting culture and dialog back at the heart of their efforts to liberate society (Liegey et al. 2015). It is not too late to reach for what Metcalfe (1833) recommended, which was to cultivate India's local village economies, which were later called village republics and village *swaraj* by M. K. Gandhi (Mandelbaum 1970).The Delhi-based Centre for

Science and Environment similarly argued for decentralized governance and sustainable village ecology as an answer to rural India's threatened ecological existence. In their 1995 video *The Village Republic*, which followed up on their 1989 landmark publication, *Towards Green Villages: A Strategy for Environmentally-Sound and Participatory Rural Development*, they reported on "pioneering community-based rural natural resource regeneration efforts in India carried out in the 1970s and 1980s" as practical examples of the Gandhian "Village Republics" concept (CSE 2017).

Then there is the open re-localization approach, which emphasizes "openness" in order to underscore the collaborative and dialog-based dimensions of the localization process beyond nationality or religion, so as to instead celebrate diversity and provide "democratic tools that facilitate dialogue-driven, power sharing community arrangement[s] that pave the way towards non-violent outcomes that protect human rights and ecological sustainability" (Liegey et al. 2015). This shift to local economic decision-making would help local communities to regain control of what they produce and exchange through Social and Solidarity Economy (SSE) practices. SSE is used by organizations that are actively pursuing "social aims and fostering solidarity" (ILO 2014), and provides a way for local individuals and organizations to benefit from economies of scale and reduce costs, and achieve a common goal that would otherwise be unreachable individually (ILO 2002).

SSE also builds on ideas Peter Kropotkin described as "mutual support" in his book *Mutual Aid: A Factor of Evolution*, originally published in 1902, in which he declared that "mutual support – not mutual struggle – has had the leading part" in shaping what could be called "progress" in human communities as a counterpoint to the social Darwinism rooted in competition (Kropotkin 2014). Bringing local people into a participatory process to define both the problem and solution spaces would be key anchors in a process of "rehabilitating the political realm [by putting] culture and dialogue back at the heart of our efforts to liberate society [and] actively calling into question [...] the primacy of the economy and of work as society's central values" (Liegey et al. 2015) so that socio-culturally informed ideas from the people themselves could enter the deliberative decision-making process. This would help migrants to begin to gain power over their own lives and to escape the neo-bondage.

The environmental sustainability and human rights-based approach framework

The most fundamental issue facing the people working at brick kilns is the system that perpetuates brick kilns as sites of coercive bondage and neo-bondage, which constitutes nothing less than institutionalized slavery. Addressing heat and climate change without considering human rights and ecological injustices ignores the obvious "elephant in the room" when it comes to addressing brick kilns in a broader, socio-culturally informed fashion. Based on the evidence found at the Chennai field site and the climate change projections from the climate model, the hazards facing the migrant labor population are undeniable. The technical solutions presented in the previous section provide one pathway towards reconciling the human health threats facing the local people. Thus, this section details a socially inclusive pathway towards change. This socially inclusive perspective is used to reframe the solution space in which inclusive solutions are formed. Rather than formulating a top-down strategy, this section suggests a way in which solutions could be co-created alongside local populations as part of inclusive, iterative participatory processes. This more inclusive bottom-up approach provides a way for local people, including migrant populations, to become involved in work with local development agents to reframe the issue in a way that integrates considerations that reveal linkages between human rights violations and ecological injustice. Taking this approach provides a venue for raising climate change mitigation and adaptation strategies, while also providing an approach through which a new pathway can be formulated to reveal the true benefits of "what development is [meant] to achieve" (GI-ESCR 2014).

The Global Initiative for Economic, Social and Cultural Rights (GI-ESCR) has published training materials for international development projects, advising an approach to rolling out development projects in order to secure "human rights for the current generation within a sustainable amount of ecological space that does not compromise the human rights of future generations" (GI-ESCR 2014). By emphasizing the need to integrate human rights and environmental sustainability as the core success criteria for sustainable development, the GI-ESCR has created what could be called the environmental sustainability and human rights-based approach (ES-HRbA) framework. The framework described in the guide is intended for application at the local level (GI-ESCR 2014), which also gives it the potential to be a critical tool when evaluating pathways for change. It provides a powerful framework of analysis and a basis for action, while helping to understand and guide development at the local level (GI-ESCR 2014).

The first stage of the ES-HRbA is to analyze the underlying causes of social injustice. Using environmental justice theory as the underlying framing in ES-HRbA provides a tool to "examine how *social injustice* is inextricably bound up in *ecological injustice*" by examining how discrimination and marginalization of vulnerable groups manifests. In the case of this study, the vulnerable groups we are referring to are workers at brick kilns' sites (Breman 1996, 2007; Molankal 2008). Particularly from an environmental justice perspective, brick kiln workers also become vulnerable by virtue of living and working where pollution and hazard intersect with poverty and exclusion, coining the terms "environmental discrimination" (GI-ESCR 2014). Interventions can then be

designed that focus on local sustainable development strategies for addressing "all humans" needs and capabilities, rather than (focusing on) the accumulation of wealth. Instead, human rights and respect for ecological boundaries become the focus (GI-ESCR 2014).

The next stage of the ES-HRbA combines the fight for human rights with the need for subsistence rights through resource conservation. This would help marginalized rural populations to escape or avoid farm debts by securing subsistence rights to control natural resources. Protecting subsistence rights as "a central plank of natural and environmental conservation [helps ensure that] resources of the poor will not be easily diverted to the rich" (Sachs 2003).

By focusing on human rights at the brick kilns in India, they cease to be just another kind of workplace with a voluntary workforce. The human rights focus would demand the immediate abolition of all forms of slavery, including bondage and neo-bondage, in accordance with both international laws against human trafficking, as well as the federal laws in India, which are criticized for being seldom enforced. Finally, there would be a clear mechanism for national and state authorities to enforce existing international laws from the UN and the ILO, in addition to existing national laws already ratified in India prohibiting child labor, bonded labor, and neo-bondage. This step alone could protect people from extreme heat exposure by addressing the enslavement of thousands of rural people, including migrant adults and their children in forced labor conditions, within India's brick kiln factories.

Limitations to our analysis

Limitations to our analysis include a lack of time and resources to pilot solutions through actual interventions in the field. This is something that creates a future opportunity for new research, and practical interventions, whether through local engagement using action research or through federal level interventions. While differences in responsibility and impacts were reviewed between countries, as well as within India between the rural-urban population, this study did not investigate solutions to curtail the contribution of India's affluent population to climate change. India's growing affluent population shoulders some of the responsibility for climate change-inducing emissions, whether as brick kiln business owners or as consumers of energy-intensive products and services coming from the fossil fuel intensive economy. Thomas Piketty and Lucas Chancel describe the inequality of energy intensity usage measured as carbon dioxide equivalent (CO_2eq) emissions within every country in their 2015 report. Their report stated that "within-country inequality in CO_2eq emissions matters more and more to explain the global dispersion of CO_2eq emissions [so] it is then crucial to focus on high individual emitters rather than high emitting countries [since] within-country inequality [now] makes up 50% of the global dispersion of CO_2eq emissions" compared to the one third it accounted for in 1998 (Chancel and Piketty 2015). Thus, the rapid growth of emissions from India's affluent should be examined critically.

Conclusion

Climate change-induced heat drives feedback loops that increase hardships for workers at brick kilns in Chennai on multiple fronts. The increasing heat at already hot brick kilns in Chennai brings forward a multi-dimensional issue that demands first and foremost a pathway towards addressing the egregious human rights violations at the brick kilns, while at the same time also ensuring the reduction of pollution through locally appropriate technical solutions. Brick kilns around Chennai are already reaching the limits for occupational heat exposure and are also sites of institutionalized slavery. We argue that it is necessary to take a holistic approach in order to ensure that solutions for people living in and around brick kilns will help them to make a transition that includes a mix of locally appropriate technologies and human rights-based approaches. This could lead to regulatory interventions that are based on locally defined socio-cultural priorities that speed structural shifts towards environmentally sustainable, human rights-based outcomes.

The federal government can create structural conditions that either further privilege the affluent urban populations in accumulating more wealth through more globalization as was done with the SAPs, or assist the rural populations to regain their former resilience through more localization. We focused on the possibility for more domestic, local interventions, since it is on the local level that populations will need to face the looming climate crisis.

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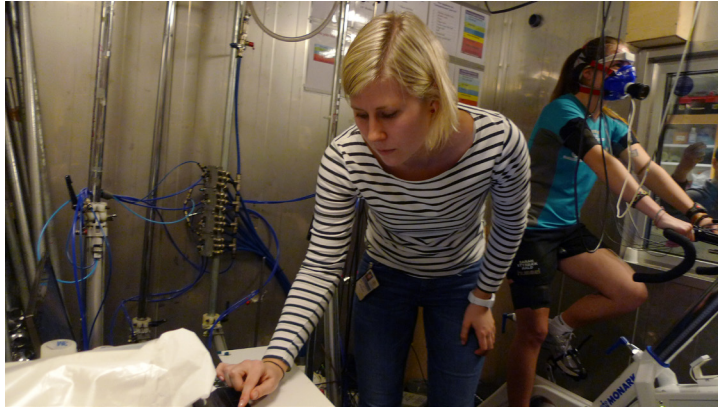
Karin Lundgren Kownacki was born in Umeå, Sweden and has been concerned about the state of our planet since childhood. She has a background in Environmental Science from the University of Plymouth, England and continued to study a master's programme in Environment and Sustainability Science at Lund University. She quickly learnt during her studies that environmental problems cannot be dealt with exclusively by the natural sciences as they originate from within society.

This is her thesis. It deals with the serious consequences of increasing heat exposure because of climate change on worker's health and productivity. Increasing heat is one of our greatest societal and scientific challenges and is already affecting people's livelihoods and health. This thesis is her contribution to this challenge.

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