How to trigger people

Weather service decision aid for everyone

Eggeling, Jakob

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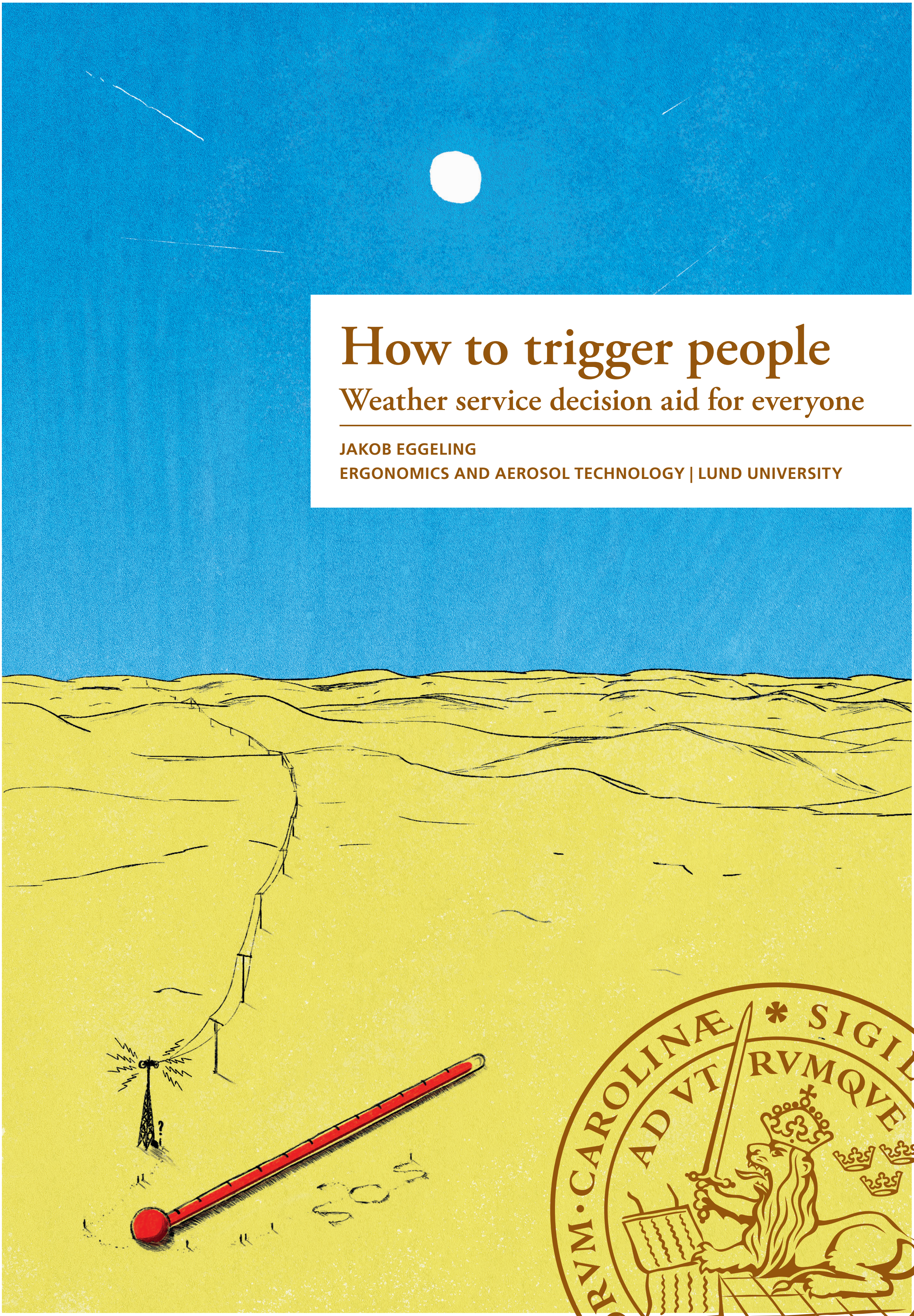

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Weather service decision aid for everyone

JAKOB EGGELING
ERGONOMICS AND AEROSOL TECHNOLOGY | LUND UNIVERSITY

JAKOB EGGELING was born in Rottne, Sweden, in the deep forests of Småland. Although the dense forests mostly provided a natural shelter against climate extremes, the obvious lack of sunny days and the aftermath of severe storms nudged him towards a degree in meteorology. Over the years as he absorbed more knowledge about the weather, his interest matured into climate research which simply put is weather over a longer time frame. This field also allows for deeper conversations than the typical comments about the daily weather. After completing his degree in applied climate strategy, he got the opportunity to extend his expertise by studying the interaction between humans and the thermal environment.

This is his thesis, a compilation of studies that brings focus to the individual in a changing climate and emphasizes the significance of every element of the exposure to the thermal environment.

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DOCTORAL DISSERTATION

Doctoral dissertation for the degree of Doctor of Philosophy (PhD) at the Faculty of Engineering at Lund University to be publicly defended on 13th of September 2024 at 09.15 in Stora Hörsalen, IKDC, Sölvegatan 26, Lund, Sweden

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Abstract: In recent years the thermal extremes have become increasingly severe, and it is expected that hot extremes will become twice as frequent if we are unable to limit global warming. The global warming will increase the available energy in certain weather systems making hurricanes more easily reach the development threshold and the increased displacement of precipitation will cause longer and more intense droughts which in turn promotes wildfires. To adapt and to mitigate the risks of these extremes, thermal health warning systems can increase the resilience of our societies.

This thesis explores the concept of integrating human thermal models which predict thermophysiological responses based on the environment into weather forecasting and early warning systems. By integrating the models, the weather forecasts may provide detailed information about the risks of exposure for individuals based on their activity and clothing. The thesis further discusses possibilities of integrating the concept on different spatial scales where both local and regional early warning systems can benefit from the integration.

Paper I evaluates the concept behind ClimApp, a smartphone app which can provide individualized thermal stress predictions based on the weather forecast and the user input of clothing and activity. The possibilities and limitations are discussed where the underlying models and indices each have their strengths and limitations.

In paper II, the developed smartphone app was tested for its usability aspects by first-time users in both a controlled laboratory setting and in a field test. The first iteration of the app was evaluated using a pre-determined set of tasks where the user actions were recorded and followed by a semi-open interview. Several improvements were made, and the second iteration was tested in the field in cold environments. A post-exposure survey and follow-up interview concluded that the ClimApp concept is viable, usable, and relevant particularly during extreme events.

In paper III, the validity of the ClimApp prediction was evaluated based on the root mean square deviation of the prediction compared to the standard deviation of the observed prediction. The evaluation concluded that the ClimApp prediction was valid for the field test. Similarly, ClimApp provides the Universal Thermal Climate Index (UTCI) alongside the ClimApp index, and it was found that UTCI overpredicted the cold stress sensation compared to users perception. The reason for overprediction was most probably due to the low activity and clothing insulation in UTCI where activity is a fixed value and clothing insulation is derived from the air temperature.

The Early Warnings For All (EW4All) action plan by the United Nations and the World Meteorological Organization aims to have every person on the globe to be covered by an early warning system by 2027. Therefore, paper IV explored the association between the El Niño Southern Oscillation (ENSO) and thermal stress for the Asia-Pacific region. By understanding the association between global weather phenomenon such as ENSO and the regional thermal stress exposure, regional early warning systems can be developed to increase preparedness and response capacity in the region.

The thesis concludes with key findings of the ClimApp concept, with feasible development possibilities to promote both individual resilience and that of vulnerable groups such as the elderly and occupational groups such as firefighters who are exposed to a multitude of risks, including heat stress.

Key words: Climate change, Early warning system, human thermal stress, extreme heat and cold

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MADE IN SWEDEN

“The sun turns black,

the earth sinks into the sea,

the bright stars

fall out of the sky.

Flames scorch

the leaves of Yggdrasil,

a great bonfire

reaches to the highest clouds.”

- Snorri Sturluson, The Prose Edda: Norse Mythology

Foreword

I chose the quote from The Prose Edda to reconnect to our ancestry and their perspective of extreme weather. I find the quote quite fitting as a changing climate is often depicted as the beginning of an apocalypse. The great apocalypse in the Norse mythology, Ragnarök, is preceeded by the extreme winter Fimbulvetr (Fimbulwinter), events and repercussions I wish we will never have to experience firsthand. In Sweden the term Fimbulwinter is still used to express very harsh winter seasons. Weather extremes has always been central to our ways of living, often referred to as the actions of Gods such as the thunder caused by Thor's hammer or when Agamemnon offended Artemis who then caused the prolonged lack of wind so that the Greeks could not set sail to Troy.

Today we live in a world full of digital information, change and uncertainty. The global security situation has been challenged several times since the research for this thesis began. As a student at the beginning of my research career, most things felt relatively safe in Sweden, my naivety lulled me into a belief that most things will work out in one way or another. Then the pandemic broke out, where covid-19 spread like wildfire across all the corners of the world. At the time and before the pandemic outbreak, actual wildfires also raged across the planet including Sweden. When people started to breathe out and look ahead, several wars erupted. In the shadows of these events, climate change was continuously affecting more and more people. The Fimbulwinter consists of three successive winters where innumerable wars follow, with a changing climate we must ensure that such events will not come to pass. We will need to make use of digital information to improve the societal resilience and well-being of the global population. At the same time, we need to find synergetic solutions to improve our planet's health while promoting our own. I find this quote by the Swedish botanist Carl von Linné quite suitable:

> "Nature itself is often the best healer of diseases"

We need to make sure that our purpose on planet Earth is greater than being a disease, cured by Earth having a fever.

Abstract

In recent years the thermal extremes have become increasingly severe, and it is expected that hot extremes will become twice as frequent if we are unable to limit global warming. The global warming will increase the available energy in certain weather systems making hurricanes more easily reach the development threshold and the increased displacement of precipitation will cause longer and more intense droughts which in turn promotes wildfires. To adapt and to mitigate the risks of these extremes, thermal health warning systems can increase the resilience of our societies.

This thesis explores the concept of integrating human thermal models which predict thermophysiological responses based on the environment into weather forecasting and early warning systems. By integrating the models, the weather forecasts may provide detailed information about the risks of exposure for individuals based on their activity and clothing. The thesis further discusses possibilities of integrating the concept on different spatial scales where both local and regional early warning systems can benefit from the integration.

Paper I evaluates the concept behind ClimApp, a smartphone app which can provide individualized thermal stress predictions based on the weather forecast and the user input of clothing and activity. The possibilities and limitations are discussed where the underlying models and indices each have their strengths and limitations.

In paper II, the developed smartphone app was tested for its usability aspects by first-time users in both a controlled laboratory setting and in a field test. The first iteration of the app was evaluated using a pre-determined set of tasks where the user actions were recorded and followed by a semi-open interview. Several improvements were made, and the second iteration was tested in the field in cold environments. A post-exposure survey and follow-up interview concluded that the ClimApp concept is viable, usable, and relevant particularly during extreme events.

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The Early Warnings For All (EW4All) action plan by the United Nations and the World Meteorological Organization aims to have every person on the globe to be covered by an early warning system by 2027. Therefore, paper IV explored the association between the El Niño Southern Oscillation (ENSO) and thermal stress for the Asia-Pacific region. By understanding the association between global weather phenomenon such as ENSO and the regional thermal stress exposure, regional early warning systems can be developed to increase preparedness and response capacity in the region.

The thesis concludes with key findings of the ClimApp concept, with feasible development possibilities to promote both individual resilience and that of vulnerable groups such as the elderly and occupational groups such as firefighters who are exposed to a multitude of risks, including heat stress.

Populärvetenskaplig sammanfattning

Vi lever idag i en värld full av information, förändringar och osäkerhet. Det senaste året var det varmaste kalenderåret vi upplevt enligt globala väderdata som går tillbaka till 1850. Sommarsäsongen i den tempererade klimatzonen (Juni-Augusti) var den varmaste säsongen någonsin uppmätt vilket understryker det överhängande hotet av ett förändrat klimat. De senaste åren har flera länder utsatts för intensiva värmeböljor och i Australien dör fler människor i värmeböljor än från någon annan naturkatastrof. Samtidigt härjar kylan där individuell beredskap sätts på prov då lokal och regional infrastruktur kan slås ut temporärt där kollektivtrafik och även vägar kan vara otillgängliga. I värsta fall kan man bli ståendes upp till ett dygn som de 1000 bilister på E22 i södra Sverige i början av 2024. Dessa händelser har på ett alarmerande vis förtydligat vikten av att utveckla tekniska lösningar som kan bistå individer och samhällen med varningar för att förutspå händelser som kan ha en negativ påverkan. Forskningen i denna avhandling utvärderar konceptet ClimApp som är ett varningssystem som bistår individen i beslut om vistelse i varma eller kalla miljöer.

Vår djupkroppstemperatur kräver en stabil temperatur runt 37°C för att våra organ ska fungera önskvärt och ifall vi exempelvis presterar för hårt i varmt väder utan pauser eller i olämpliga kläder kan vi snabbt nå en farligt hög djupkroppstemperatur. På samma sätt kan vi kylas ner i kalla miljöer ifall vi har otillräcklig isolering eller rör för lite på oss i kylan. Med hjälp av matematiska modeller av den mänskliga kroppen, valda kläder samt aktivitet och den rådande väderleksrapporten kan det utvecklade varningssystemet beräkna ifall individen löper risk för att bli för varm eller för kall. Traditionellt används lufttemperaturen som en indikator på det termiska klimatet men även luftfuktigheten, vinden och strålningstemperaturen är viktiga för att utvärdera miljön. Hur mycket behagligare är det inte en dag på stranden när solen värmer på jämfört med när den går i moln och vinden tar i? Därför bör framtida väderlekstjänster använda individuella faktorer som klädes- och aktivitetsnivå och beräkningar av kroppens reaktioner för att återspegla exponeringen och hälsoriskerna.

Forskningen i den här avhandlingen har utvärderat möjliga begränsningar för konceptet som kan vara viktiga att ha i beaktning vid utveckling av varningssystemet ClimApp för värme och kyla. Vidare har användningen av varningssystemet utvärderats där testpersoner fått möjlighet att testa verktyget i olika faser av varningssystemets utveckling. Genom analys av användandet samt intervjuer om testpersonernas upplevelser så kunde möjligheter samt begränsningar inom ramverket för varningssystemet förtydligas. För att ett varningssystem ska fungera optimalt kan en liknelse göras utifrån riskbedömningsteorins fyra pelare:

1. Är risken känd?
2. Observeras rätt variabel för risken?
3. Kommuniceras risken på rätt sätt? Når varningarna alla som är i riskzonen?
4. Är individen förmögen att skydda sig mot risken?

Ifall alla fyra pelare är uppfyllda så finns det goda möjligheter att varningssystemet mottas väl av individen och att individen agerar på varningarna. Det är därför av stor vikt att varningssystemet utvecklas för att ha individen i fokus, att varningar är aktuella, lätta att förstå och gör det enkelt för individen att agera utifrån sina möjligheter för att minska risken. Analys av användandet samt träffsäkerheten av ClimApps beräkningar påvisade att varningssystemet fungerade önskvärt och att det finns ett behov av systemet, främst vid extrema väderhändelser. Med den globala uppvärmningen är forskare ense om att extremväder kommer att bli vanligare och mer intensivare än det vi är vana vid idag. Varningssystem för extremväder finns utvecklade vid de flesta nationella myndigheter för väderprognos men de tar sällan människans förmåga och sårbarhet i beräkning utan är oftast baserat på lufttemperatur. Utveckling av varningssystem likt ClimApp som möjliggör att människan står mer i fokus i varningssystemet och främjar den andra punkten i riskbedömningsteorin.

Avslutningsvis så utvärderades väderfenomenets El Niño Southern Oscillation (ENSO) påverkan på det termiska klimatet i stilla havsregionen i Asien, detta för att identifiera kopplingar mellan ökad och minskad värmestress beroende på vilken fas ENSO är i. ENSO oscillerar mellan den varma El Niño-fasen och den kalla La Niña-fasen vilka har stor påverkan på klimatet i stora delar av världen, främst runt stilla havet. Genom att identifiera kopplingar mellan större väderfenomen kan varningssystem för stora områden med längre prognoslängd göra det möjligt för samhällen och myndigheter att förbereda sig inför extremväder som värmeböljor och köldknäppar.

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My co-supervisors Kalev Kuklane, Christofer Rydenfält and Karin Lundgren-Kownacki, thank you for encouraging me to explore new scientific methods and the hands-on experimental experiences. If not for Kalev I doubt I would have realized the charm of Tore, the joys of soldering joints, and the importance of a strategic and standardized approach when collecting data. To Christofer for opening new doors for me, for your valuable insights on user engagement and critical approach. To Karin, thank you for persistently making sure I consider the holistic approach and keep on track.

My wife, Johanna, thank you for keeping me grounded and motivated even though both work and life in general has proven challenging at times. Thank you for the sacrifices you made so that I have had the chance to make the most out of this journey.

My children, for constantly reminding me that there are other obligations than science alone. Thank you for motivating me to contribute to a better future where I hope you will thrive. However, if you ever read this, I hope that you will let me sleep in more often in the future!

My colleagues at EAT and Design Sciences for making each workday something to look forward to. I am grateful for all the insights I have gained from both seniors and students. What makes Design Sciences function so well is without a doubt the wonderful service group, who always makes sure to notice you and spread joy at IKDC. The administrators and technical staff make it easy to focus on my tasks and a special thank you to Robert Ohlsson for saving my hard drive and patching up a laptop for me when my laptop broke the week before submitting this thesis.

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All project members in the different research projects I have taken part in, thank you for sharing your knowledge with me and highlighting the value of multidisciplinary approaches. A special thank you to Professor Jørn Toftum for always providing me with valuable feedback and encouragement to grow as a researcher.

My friends, my family, and of course my dogs, thank you for being there and supporting me in whichever way I have required these years. I believe something good has come out of it!

Appended papers

Paper I

Petersson, J*., Kuklane, K., Gao, C. (2019). Is there a need to integrate human thermal models with weather forecasts to predict thermal stress?. *International journal of environmental research and public health*, *16*(22), 4586.

Paper II

Eggeling, J., Rydenfält, C., Kingma, B., Toftum, J., Gao, C. (2022). The usability of ClimApp: A personalized thermal stress warning tool. *Climate Services*, *27*, 100310.

Paper III

Eggeling, J., Rydenfält, C., Halder, A., Toftum, J., Nybo, L., Kingma, B., Gao, C. (2023). Validating an advanced smartphone application for thermal advising in cold environments. *International Journal of Biometeorology*, *67*(12), 1957-1964.

Paper IV

Eggeling, J., Gao, C., An, D., Cruz-Cano, R., He, H., Zhang, L., Wang, Y-C., Sapkota, A. (2024). Spatiotemporal link between El Niño Southern Oscillation (ENSO), extreme heat, and thermal stress in the Asia–Pacific region. *Scientific Reports*, *14*(1), 7448.

*The author of this thesis changed surname from Petersson to Eggeling during 2021.

The author’s contributions to the appended papers

Paper I

I defined the scope of the review with C.G. and reviewed the research field. I conducted the analysis of the joint literature with my co-supervisors and wrote the draft manuscript. My co-authoring supervisors assisted in finalizing the manuscript and revising the manuscript.

Paper II

Together with my co-supervisor CR, we settled on a relevant research question and methodology. I, CR and CG designed the study outline. I prepared the tests and survey, recruited test participants, supervised the tests, conducted the interviews, conducted the analysis, and wrote the manuscript with my co-authors assisting in improving the manuscript during submission and revision phase.

Paper III

I prepared the test with guidance of CG, I wrote the instructions and survey, recruited test participants, conducted the analysis and wrote the manuscript with revision aid of my co-authors.

Paper IV

I planned the study with assistance of CG. I downloaded the data, coded the scripts, cured, and analysed the data, and wrote the manuscript. My co-authors assisted in proofing the manuscript and improving the revised manuscript.

Other publications by the author

Peer reviewed papers

An, D., **Eggeling, J**., Zhang, L., He, H., Sapkota, A., Wang, Y. C., Gao, C. (2023). Extreme precipitation patterns in the Asia–Pacific region and its correlation with El Niño-Southern Oscillation (ENSO). *Scientific Reports*, *13*(1), 11068.

Kuklane, K., **Eggeling, J**., Kemmeren, M., Heus, R. (2023). Local effects of printed logos and reflective striping fixed to firefighter clothing material packages under low radiation exposure. *Industrial health*, *61*(5), 357-367.

Kuklane, K., **Eggeling, J**., Kemmeren, M., Heus, R. (2022). A database of static thermal insulation and evaporative resistance values of Dutch firefighter clothing items and ensembles. *Biology*, *11*(12), 1813.

Smallcombe, J. W., Hodder, S., Kuklane, K., Młynarczyk, M., Loveday, D., **Petersson, J**., Halder, A., Havenith, G. (2021). Updated Database of Clothing Thermal Insulation and Vapor Permeability Values of Western Ensembles for Use in ASHRAE Standard 55, ISO 7730, and ISO 9920. *ASHRAE transactions*, *127*(1).

Kingma, B. R. M., Steenhoff, H., Toftum, J., Daanen, H. A. M., Folkerts, M. A., Gerrett, N., Gao, C., Kuklane, K., **Petersson, J**., Halder, A., Zuurbier, M., Garland, S.W., Nybo, L. (2021). Climapp—integrating personal factors with weather forecasts for individualised warning and guidance on thermal stress. *International Journal of Environmental Research and Public Health*, *18*(21), 11317.

Conference abstracts as presenting author

Eggeling, J., Gao, C. An, D., Cruz-Cano, R., He, H., Zhang, L., Wang, Y-C., Sapkota, A. (2024). Thermal stress early warning system (EWS) utilizing El Niño Southern Oscillation (ENSO) association. International Conference of Environmental Ergonomics, Seogwipo, South Korea, June 3-7, 2024.

Eggeling, J., Gao, C. An, D., Cruz-Cano, R., He, H., Zhang, L., Wang, Y-C., Sapkota, A. (2023). UTCI trends in south-eastern Asia and its correlation with ENSO. Transdisciplinary conference on connecting health and climate change, Stockholm, Sweden, October 11-12, 2023.

Gao, C., Cruz-Cano, R., He, H., **Eggeling, J**., Kingma, B., Alce, G., Toftum, J., Brimicombe, C., Gerarda Portela, A., Wang, Y-C., Sapkota, A. (2023). Climate Change and health risk early warning systems. Transdisciplinary conference on connecting health and climate change, Stockholm, Sweden, October 11-12, 2023.

An, D., **Eggeling, J**., Zhang, L., He, H., Sapkota, A., Wang, Y. C., Gao, C. (2023, September). Extreme precipitation in the Asia Pacific Region and its relationships with El Niño–Southern Oscillation. 35th Annual Conference of the International Society for Environmental Epidemiology, Kaohsiung, Taiwan, September 17-21, 2023.

Eggeling, J., Toma, R., Kuklane, K. (2023). A new approach to estimate Ret values. Protection challenges in a changing world. Proceedings of the 10th European Conference on Protective Clothing and NOKOBETEF 15. Arnhem, The Netherlands, May 9-12, 2023.

Eggeling. J. (2023, January). Validating the personalized thermal stress application ClimApp in the cold. Arctic Frontiers Moving North, Tromsø, Norway, January 30 - February 2, 2023.

Eggeling, J. (2022, November). ClimApp – Adaptation to heat and cold. MIRAI 2.0 Research and Innovation Week 2022, Fukuoka, Japan, November 15-18, 2022.

Petersson, J., Halder, A., Kownacki, K. L., Kuklane, K., Gao, C. (2019). Required clothing insulation (IREQ-ISO 11079) and difference of thermal sensations between genders. International Conference of Environmental Ergonomics, Amsterdam, The Netherlands, July 8-12, 2019.

Table of Contents

Abbreviations

AR	Assessment Report
C	Convection
C3S	Copernicus Climate Change Service
CoWEDA	Cold Weather Ensemble Decision Aid
DJF	December, January, and February
DTR	Diurnal Temperature Range
DWD	Der Deutsche Wetterdienst
ECMWF	European Centre for Medium-Range Weather Forecasts
E	Evaporation
ENSO	El Niño Southern Oscillation
EW4All	Early Warnings For All
EWS	Early Warning System
HHWS	Heat-Health Warning System
H_{res}	Respiratory heat exchange
ILO	International Labour Organization
ID	Interaction Design
IPCC	International Panel on Climate Change
IREQ	Insulation REQuired
JJA	June, July, and August
K	Conduction
M	Metabolic rate
MAM	March, April, and May
MK	Mann-Kendall
MRT	Mean Radiant Temperature
NOAA	National Oceanic and Atmospheric Administration
NWS	National Weather Service

PADM	Protective Action Decision Model
PHS	Predicted Heat Strain
PMV	Predicted Mean Vote
PPD	Percentage Predicted Dissatisfied
PT	Perceived Temperature
R	Radiation
RH	Relative Humidity
RMSD	Root Mean Square Deviation
S	Heat Storage
S2S	Seasonal to Subseasonal
SD	Standard Deviation
SDG	Sunstainable Development Goal
SON	September, October, and November
SST	Sea Surface Temperature
Ta	Air Temperature
THWS	Thermal Health Warning System
UHI	Urban Heat Island
UN	United Nations
UTCI	Universal Thermal Climate Index
Va	Air velocity
W	Mechanical work
WBGT	Wet Bulb Globe Temperature
WCT	Wind Chill Temperature
WHO	World Health Organization
WMO	World Meteorology Organization

Definitions

Acclimatization to heat: The physiological adaptation process through which individuals develop increased tolerance to hot environmental conditions following prolonged exposure[2].

Adaptation (to climate): The dynamic process of adjusting to current or anticipated climatic conditions and their associated impacts. In human systems, the goal of adaptation is to mitigate or prevent adverse consequences while harnessing advantageous opportunities[3].

Air temperature: The dry-bulb temperature of the air surrounding[4], using material with reduced emissivity such as silver or shielding it while allowing sufficient natural ventilation[5].

Air velocity (average): The average velocity of the air, i.e. the magnitude of the air velocity vector at the measuring point over a measuring period[4].

Climate change: denotes a discernible alteration in the climate's state, characterized by shifts in its average and/or variability of properties, enduring over an extended period, often spanning decades or more[6].

Clothing insulation: The resistance of a uniform layer of insulation covering the entire body[4,7].

Cold stress: When human thermal environments result in a negative heat storage in the body due to an unfavourable combination of air temperature, radiant temperature, humidity, air velocity, clothing, and activity. This negative heat storage may lead to cold illnesses[5].

Conceptual model: An outline of what users can do with a product and which concepts are required for the user to achieve and understanding of the possible interactions[8].

Core temperature: The mean temperature of the thermal core of the body[4].

Dew point temperature: The temperature at which air becomes saturated, 100% relative humidity, with water vapor when cooled at constant pressure[4].

Diurnal Temperature Range: The difference between daily maximum and minimum temperatures[9].

Early Warning System: A system that monitors, collects, analyses, interprets and communicates data to assist decision-making regarding mitigating impact on e.g. public health[10].

Heat-Health Warning Systems: The use of climate and weather forecasts and pre-determined trigger levels of heat stress to provide advice to the public and initiate public health interventions designed to reduce health risks before, during, and after periods of extreme heat[11].

Global temperature: The average surface temperature of the Earth's atmosphere over a specific time period, typically spanning decades to centuries[6].

Globe temperature: The temperature indicated by a temperature sensor placed in the centre of a globe having standard characteristics[4].

Heart rate: The number of heartbeats observed during time based intervals, e.g. beats per minute[4].

Heat stress: When human thermal environments result in a positive heat storage in the body due to an unfavourable combination of air temperature, radiant temperature, humidity, air velocity, clothing, and activity. This positive heat storage may lead to heat health side effects[5].

Heat wave: Extended periods of unusually high air temperature that may have adverse health consequences for a population[12].

Interaction design: Designing products which assist how the user communicates and interacts during working and everyday lives[8].

Mean Radiant Temperature: The uniform temperature of an imaginary black enclosure in which a person would exchange the same amount of radiant heat as in the actual non-uniform enclosure[4].

Metabolic rate: The pace at which chemical energy undergoes conversion into both heat and mechanical work through aerobic and anaerobic metabolic processes within an organism[4].

Population: A group of individuals of the same species living within a given area[13].

Productivity: The ratio of output to input for a specific situation[14].

Relative Humidity: The ratio 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[4].

Resilience: The capacity of a social, ecological, or socio-ecological system to anticipate, reduce, accommodate or recover[3].

Skin temperature: In this thesis, the mean skin temperature is considered. The mean skin temperature is the sum of the products of the area of each regional surface element and its mean temperature divided by the total body surface area[4].

Sustainable Development Goals: The Sustainable Development Goals is a global call to action to end global poverty, inequality, and to protect the planet. The goals are designed to assist countries and organizations to improve and promote their work towards a sustainable and equal future[15].

Human thermal environment: The human thermal environment is the interplay between human and environment and can be assessed by the six parameters of air temperature, humidity, air velocity, radiant temperature, metabolic rate and clothing worn[5].

Thermal strain: The response of the human thermoregulatory system to cold or heat stress that cause strain on the body, with risks of developing cold or heat illnesses[5].

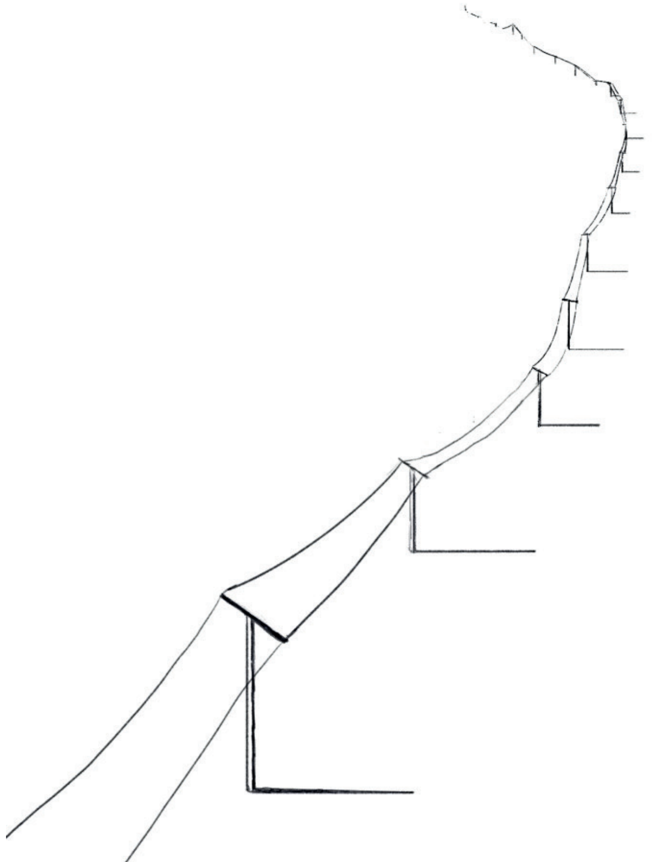
Urban Heat Island: (UHI): An urban area which is significantly warmer due to artificial infrastructure and human activities compared to its rural surroundings[16].

Usability: Usability pertains to the capacity of a system, product, or service to be utilized by designated users to accomplish predetermined objectives with effectiveness, efficiency, and satisfaction within a defined context of use[17].

Vulnerability: A variety of concepts and elements including sensitivity or susceptibility to harm and lack of capacity to cope and adapt[3].

Water vapor partial pressure: The pressure that the water vapour would exert if it alone occupied the volume occupied by the humid air at the same temperature[4].

Natural wet-bulb temperature: The temperature measured by a sensor covered with a wetted wick which is naturally ventilated[4].



Introduction

It is near impossible to start writing a scientific manuscript or document focusing on climate change without pointing out that our planet is becoming hotter or the increased intensity of extremes with each passing year compared to the pre-industrial period. The reason why it is near impossible is because the implications are dire and we as scientists with our research hope to alleviate the future risks or even find solutions to overcome this global problem. This thesis work proposes the benefits of a personalized weather decision aid and the importance of Early Warning Systems (EWS) to improve the individual well-being and societal resilience. With each Assessment Report (AR) published by the Intergovernmental Panel on Climate Change (IPCC) including the most recent AR6[3,6], our knowledge about the extent of climate change increases and the impacts on public health. The tipping points of the environment have been identified and quantified where climate change may lead to serious implications to humanity[18,19,20]. The global Sustainable Development Goals (SDG) and the identified tipping points allow us to mainstream our efforts into improving the resilience of our societies, not just on a national or regional level but also on an individual level. We are inhabitants of this planet, and we are responsible for maintaining a resilient natural environment where we can coexist. Early Warning Systems have the capacity to reduce ensuing damage by 30% according to the World Meteorological Organization (WMO) but 50% of the countries are not covered by a EWS, countries that are particularly exposed and suffer greatly from disasters[21]. In the spirit of the Early Warnings For all (EW4All) initiative by the United Nations (UN) and WMO to cover every person on the globe by an EWS[21], this thesis describes and explores the feasibility of personal and regional EWS that can be up- and down-scaled to improve the resilience on local, national, regional, and global level.

Climate change and health

Climate change is a global phenomenon, but the effects may affect populations differently. Populations with already poor capacities may be exposed to greater hazards which exacerbates the risks of climate change. One such example are the elderly whom are identified to be put at particular risk during heat waves due to their reduced behavioural and thermoregulatory capacities[22]. At the time of writing this thesis, the European Court of Human Rights (ECHR) voted in favour of a group of elderly Swiss women who claimed that their government had made inadequate efforts to reduce the impacts of climate change and ultimately putting them at risk of dying[23]. By further developing tailored EWS for certain groups such as the elderly or EWS for large populations at risk can promote good health and well-being which is the third SDG[24]. Our research and policymaking which focus on climate change will have both short-term and long-term effects and some of these will primarily benefit our children and our future legacies. Climate change is here and now, extreme weather events will continue to increase in strength and occurrences, but we already have experienced several catastrophic events where our resilience has not been sufficient. Extreme heat is a hot topic by itself which affects a majority of the global population, but the cold counterpart of the thermal environment remains as the most critical contributor to excess morbidity in temperate and cold regions such as Europe[25]. It is the belief of this author that future development of weather decision aid and tailored EWS will be detrimental in pursuing good health and well-being. Within the frame of this thesis, the weather decision aid tool ClimApp was developed to promote personal health, well-being, and their understanding of the thermal environment. The homescreen of ClimApp can be seen in Figure 1 and the technical aspects are described in detail in the technical paper by Kingma et al.[26], the ClimApp concept and functions will be further discussed throughout the thesis. ClimApp is intended to assist individuals, in particular vulnerable groups, to better understand and handle the thermal environment. Certain groups are considered vulnerable as they experience a reduced thermoregulatory capacity due to medical conditions, medical treatments, pregnancy, disability, aging, or that they experience high levels of thermal stress due to occupational requirements.

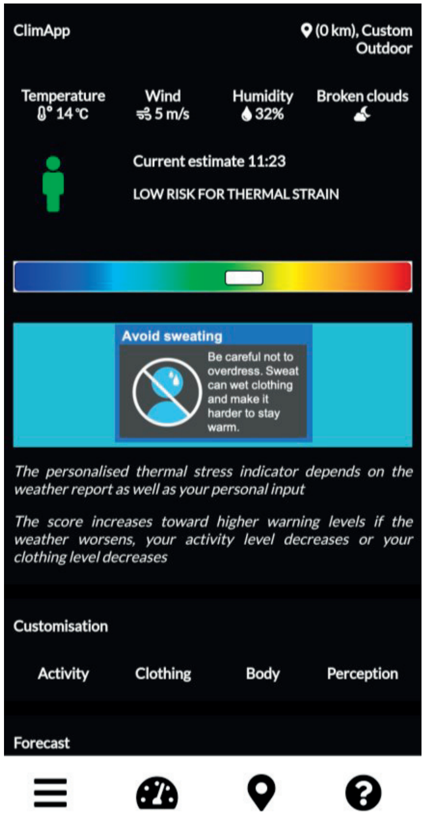


Figure 1. The home screen of ClimApp presenting the predicted thermal stress based on the weather forecast and user input.

Several parts of the world are becoming inhospitable to live in for parts of the year due to extreme heat. In some regions such as the Middle East, climate change may cause the region to become uninhabitable[27]. Mora et al. found that almost one third of the global population is already exposed to extreme heat for more than 20 days per year[28]. The International Labour Organization (ILO) identifies outdoor workers to exposed to a cocktail of hazards such as heat, UV radiation, air pollution, vector-borne diseases and agrochemicals[29]. This exposure is expected to increase and the work condition due to the heat are expected to become too severe to maintain the production targets during the warmest months[30]. Factories in these exposed areas often lack basic occupational health principles such as drinking water, enforced rest periods and training[31]. Kjellstrom et al. also predicts that there will be a greater loss of productivity in the tropical and sub-tropical areas compared to the rest of the world and southern Europe and USA are also affected[32]. In Europe, two thirds of the population could be affected by weather-related disasters at the end of this century[33]. Studies that have evaluated the intensities of future extremes agree that they will become more intense on each continent if the global warming reaches the 2°C projection compared to the 1.5°C projection[34,35,36] where hot extremes can be expected to appear twice as frequently in the former projection compared to the latter[37]. The Copernicus programme has developed a global temperature trend monitor which estimates when we will reach the 1.5°C and 2°C mean global temperature increase limit based on a 30-year average[38]. Halfway through my PhD in June 2021, the estimate to reach the 1.5°C limit was forecasted to March 2034 and as of writing this thesis in February 2024, the 1.5°C limit will be reached 6 months earlier meaning September 2033[38] which can be seen in Figure 2.

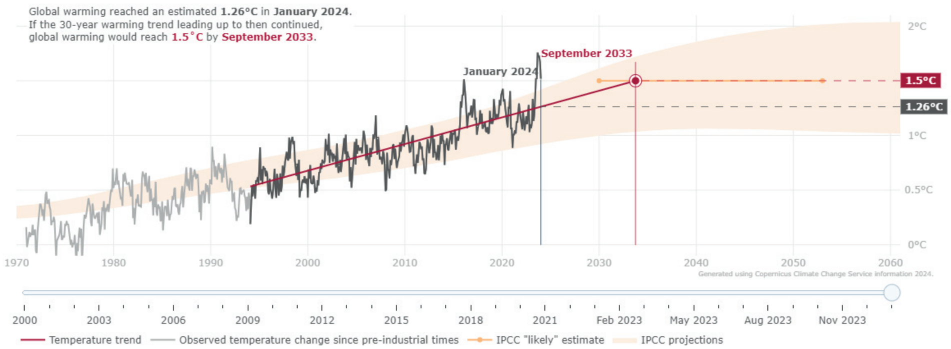


Figure 2. The global mean warming measured and compared the pre-industrial era. The tool allows to both find the forecasted global warming at a specific month and the expected month when the 1.5°C warming will be surpassed. Credit: ECMWF, Copernicus Climate Change Service (C3S).

Changes in the thermal environment may also affect the air quality as increasing air temperature will raise the kinetic energy of molecules making them more reactive[39]. By bridging our understanding of the thermal environment and air quality[40] we can further improve early warning systems to provide warnings for the risks of combined effects of both hazards to promote public health[41]. The recent Early Warnings For All (EW4All) initiative[21], the WMO climate services report on health[42] and the ILO report on worker health[29] all call for implementing early warning systems to ensure SDG 3: Good health and well-being[24].

Aim, objectives and guiding concept

This thesis work aims to put the people in focus for future warning systems where the possibility of tailored concepts are increasingly probable and more advanced tools can be applied to provide the end user with relevant information about their exposure to the thermal climate. Can thermal models and indices be integrated into weather forecasts to provide additional information of thermal exposure? Climate change is expected to increase the frequency and intensity of weather extremes and expose a larger portion of the global population to hazardous environments. Can EWS be developed that take the thermal exposure into consideration, a thermal health warning system (THWS), to promote society resilience? The objectives of this thesis are to:

1. Identify possibilities and limitations associated with the integration of human thermal models into weather forecasting warning systems (Paper I)
2. Evaluate user interactions with a personalized thermal health warning system (Paper II)
3. Validate a newly developed personalized thermal health warning model in cold environments (Paper III)
4. Explore teleconnection influence on the thermal environment for future regional thermal health warning system (Paper IV)

The objectives are achieved by applying a variety of research methodologies in the papers starting with an explorative literature review mapping out the research field. By identifying the existing knowledge and research gaps, the feasibility of advanced thermal health warning systems is assessed. The thesis revolves around putting the people in focus in the warning systems developed. This requires an understanding of the needs and capabilities of the users and highlights the importance of interaction design (ID) in EWS. In this thesis the usability of a newly developed thermal health warning system is evaluated. The thermal health warning system requires user input and provides personalized warnings and advice where the interactions between the user and the system are observed and analysed. The personalised warnings and advice promote user risk knowledge which increase response capacity. The validity of the THWS is evaluated which is an integral part as a product must deliver the intended service as well as get the trust from the user by delivering accurate and relevant information. The final objective covers the synoptics, where the teleconnection El Niño Southern Oscillation (ENSO) is evaluated regarding its influence on the thermal environment over a large region. By including teleconnections and their known oscillations, TWHS covering large regions can be cover this additional layer of thermal threat. This THWS can then be scaled down to a local level at the same time as the developed THWS can be scaled up to a regional and national level.

Early Warnings For All

This thesis work tie in the goal with the United Nations (UN) action plan EW4All that everyone on our planet should be covered by an EWS by 2027 against hazardous weather, water, or climate events[21]. The action plan is built on four Multi-Hazard Early Warning System pillars (Figure 3 and 4) which are inspired by risk assessment and shares the methodology of resilience engineering[43]. This action plan is published by the WMO and is particularly important for the small island states and the least developed countries where infrastructure is lacking, and the threat of hazards are great.

Typically, a national warning system requires an economic investment which may be difficult to manage when there are more urgent problems at hand that require solving. Therefore, the EW4All identifies that action at all spatial scales are important (local, regional, national, and global, see Figure 3) although monitoring may be primarily global and regional, and actions are categorized primarily as national and global for clarity. With AR6 at hand and the Copernicus estimate, heat hazards due to climate change will most likely be the most urgent issue making these investments effective mitigation strategies. By developing early warning systems and heat health action plans, societies are able to integrate them during the development phase of other sectors making the integrated knowledge available and adapted when the hazard occurs[44].

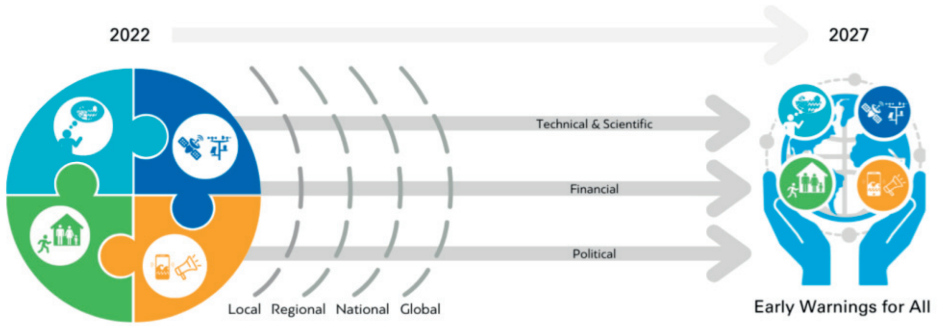


Figure 3. The EWS framework (jigsaw globe to the left) has EWS on four different spatial resolutions: Local, Regional, National, and Global. By technical, scientific, financial, and political progression it is expected to cover each individual on the planet by an EWS in 2027. Credit: WMO, Early Warnings For All[21].

A study evaluating the heat health warning system in Shanghai found that half of the deaths related to heat were below the air temperature threshold and that an unexpected number of young and middle-aged males were represented in the death toll[45]. This unexpected number was theorized to be due to males being the dominant gender in outdoor occupations which increases the exposure. These occupational group are considered vulnerable as they face elevated risks due to the outdoor thermal environment with solar radiation, physical activities, wearing protective clothing. They can benefit from strategic planning and mitigation strategies to reduce the risk of heat stress and dehydration[46,47,48,49]. A systematic review[50] assessed the effect of heat warning systems (HWS) and found one study claiming that HWS saved $468 million with the running cost of the HWS being $210,000[51]. The main conclusion by the review was that many behavioural aspects exist which aggravates research findings but the perceived threat of danger was the main factor why people heeded the warnings[50] which highlights the need of people-centred disaster risk knowledge from Figure 4.

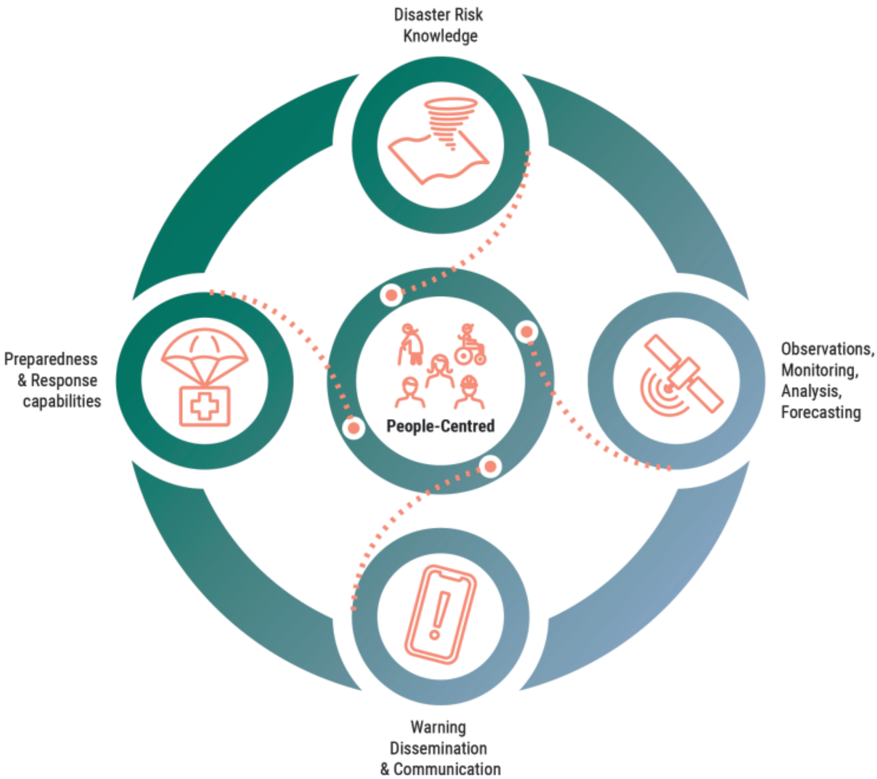


Figure 4. The EWS framework prepared by the EW4All action plan. Each part of the jigsaw from Figure 4 ties back to the people. Credit: WMO, Early Warnings For All.

In the Maldives which is one of the islands states most threatened by sea level rise, there are no words in Dhiveli that is spoken in the Maldives that captures the essence of climate change[52]. This realization sets the tone for how imminent this newfound threat is for the Maldives culture, it also emphasizes the need to provide warnings with appropriate language to reach the recipients. This is a centrepiece in ID where the product being designed needs to speak the language of the user so that layers of information are not lost or misinterpreted[53]. Hence, ID becomes an important part of EWS. The EW4All is people-centred and each step of the process is intended to focus on the people[21]:

- Are the hazards known by the people and its vulnerabilities? Are there risk maps, known trends, and data available?
- Are the variables monitored relevant to evaluate the risk of the people? Are the warnings based on sound science?
- Is the risk communicated properly to the people, can it reach those at risk?
- Are people prepared and able to respond to the warning? Has the system been tested?

Assessing the risk of thermal stress will become more and more important as extreme weather events are expected to become more frequent in the future. Risk assessment can be performed in various ways but the matrix focusing on severity of hazard and likelihood or occurrence of the hazard is a commonly applied strategy to assess the risk[54]. In Figure 5 a typical risk assessment matrix is portraying the risk of a typical hazard, for example a heat wave where the severity of the heatwave depends on the climate factors depicting the intensity, the length of the heat wave, and the vulnerability of the exposed people. In the last two decades, heat waves have become considerably more impactful in Europe[55]. Properly defining the risk levels are critical in order to define the severity of hazards which is highlighted by the study of Wu et al.[45]. Standardizing warning levels and risks is difficult as there are multiple factors that influence the vulnerability of a population. As emphasized by the EW4All action plan, the warnings should be based on sound science while the population must also be aware of the risk, be able to prepare for the hazard and trust that the warning is relevant. If too many warnings are issued that is found irrelevant by

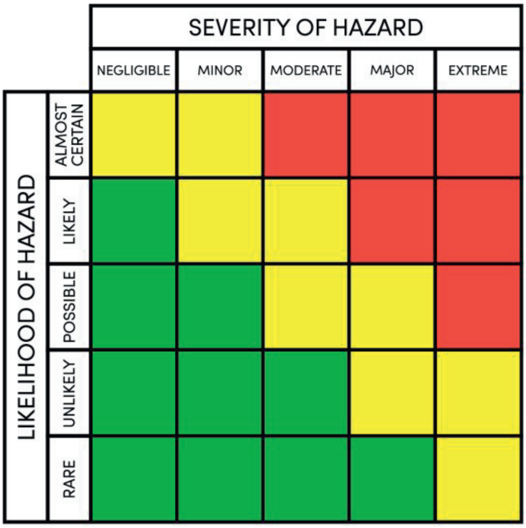


Figure 5. Severity hazard diagram, where the combination of severity and likelihood of a hazard depicts the risk using colour codes where red is a great risk, yellow a medium risk and green a low risk.

the user or if the warnings are not understood by the receiver, they will most likely disregard the warnings. The work by Lindell and Perry describes the Protective Action Decision Model (PADM) which is based on research on the response by people to environmental hazards and disasters[56]. The PADM considers the people and the typical steps taken when a hazard occurs where each step provides important aspects when developing warning systems and action plans. By involving relevant stakeholders, the needs of communities can be better understood, and warnings tailored to fit the receivers. By including important stakeholders and organizations, credibility can be gained which entice receivers to accept the warning and act upon it rather than second guessing and spending time on processing additional information before deciding how to act upon the risk[56].

With the digitalization of society, data has become increasingly available which makes technical solutions to everyday situations more feasible. Several research projects have aimed to utilize indices to improve occupational and public health by developing tools to predict thermal stress. Xu et al. developed a decision aid tool which calculates exposure time and risks of frostbite based on the biophysical properties of the clothing worn by the user[57]. The core of this thesis is the ClimApp project which built upon the work of Liljegren et al.[58] and Lemke and Kjellström[59] where WBGT is estimated using regular weather forecast data to provide additional layers of thermal exposure information. Building on this approach is the HEAT-shield project[60], the WBGT app by Ioannou et al.[61] and the ClimApp project. Heat-Shield developed a service based on WBGT that aims to protect outdoor workers in Europe using a web-based warning system[60]. The ClimApp project developed a smartphone app, ClimApp, where the user can input their activity and clothing to receive a personalized prediction of their thermal stress[26] using WBGT, PHS, PMV, IREQ, and WCT.

Background

Human thermal environment

Human beings and other mammals strive for a steady core temperature, homeostasis, to maintain many regulatory mechanisms[5]. Even if there are multiple avenues to regulate the core temperature to maintain this steady state, external factors can have dire effects and upset this equilibrium which leads to thermal stress. Thermal stress affects individuals on multiple levels and our strongest countermeasures are behavioural. When we are exposed to heat or cold, we adapt by either changing our clothing, activity, or location. The issue with thermal stress is most obvious when people are not able to adapt to thermal stress by behavioural adaptation. One behavioural adaptation is to lower the work-pace, by self-pacing as discussed by Miller the workers can lower their thermal stress which comes at the cost of productivity if no other cooling strategy is feasible[62]. When exposed to the environment for a prolonged time, we also acclimatize to our environment by undergoing physiological changes. This has helped mankind when venturing and occupying most of the landmasses around the globe. Even though the great feats of mankind, we are now experiencing new challenges caused by man. We spend more and more time indoors[63] which reduces the time we actually experience the outdoor climate, we also rely gradually more to heating and cooling systems so that we can remain in a very narrow climatic range. Our cities and suburban areas are progressively reflecting concrete jungles with fewer natural elements which has proven to exacerbate heat stress due to the urban heat island (UHI) effect[64,65]. However, cities that focus on including nature-based solutions as well as technical solutions have shown that these can alleviate UHI[66,67,68]. Our disconnection from the prevailing weather introduces several concerns that must be put into consideration.

The interaction between humans and the thermal environment is dependent on six variables, the four climate variables air temperature (T_a), relative humidity (RH), air velocity (v_a) and mean radiant temperature (MRT), as well as the personal variables of metabolic rate and clothing properties. The activity of a person generates heat by metabolic rate (M) which may have a degree of mechanical work (W) not generating heat. If all these variables are known, the most comprehensive human thermal stress models can be used to assess human thermal stress. The conceptual heat balance equation describes the energy storage of the body (S) in different environments based on the activity of a person (M – W) and the fluxes of energy dependent on the respiratory heat exchange (H_{res}) and the climate variables evaporation (E), radiation (R), convection (C), and conduction (K)[5]. The heat balance equation is written as:

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

The heat balance is illustrated in Figure 6 and depending on the environment, certain fluxes may be primarily warming or cooling the person where the convective wind or surface temperature of an object may either be warmer or cooler than the skin temperature. If the temperature gradient between the person and the environment is great, radiative heat flux may be very high such as during winter when most surrounding natural objects are cold. These fluxes are dependent on the clothing worn which may alleviate or exacerbate the thermal stress. However, parts of the working force are required to wear protective or representative clothing that may be ill fitting from a thermal environment perspective. Such clothing can be ballistic protection for the police and army or membranes to limit biohazards for scientists and healthcare staff, or uniforms that cover most of the skin which restricts evaporation of sweat[69,70]. Firefighters is a well-known occupational group for their extreme exposure to radiant and convective heat that requires proper protection to ensure a healthy work force which otherwise could risk burns or scalding[71]. Firefighters are typically involved in solving many urgent problems and accidents other than firefighting such as car crashes, provide emergency medical care, saving trapped people and animals in the heat and cold. All the listed tasks require versatile protective clothing ranging from smoke-diving to technical rescue[72]. Depending on the environment, external heating may exacerbate the already strained conditions and a modular clothing approach may allow the firefighters to quickly adapt their uniform to suit the needs of the situation.

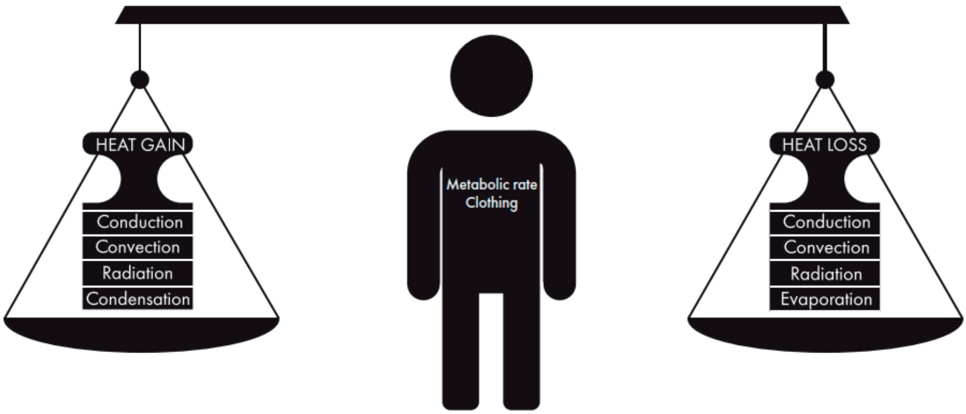


Figure 6. The heat balance is dependent on the heat fluxes between the person and the environment and is moderated by the metabolic rate and clothing. If the scale is level, a steady state is reached. The figure is published in Petersson et al.[73] and was inspired and modified from Parsons[5].

Thermal stress and health

As already mentioned, the productivity is expected to become severely impacted during the hottest month in the most exposed countries. Overall productivity will also be affected and by 2080 productivity may decrease by 11-27% by heat stress in Asia and the Caribbean[74]. Available research note that for every degree Celsius of air temperature above 25°C, productivity is expected to decrease by 2%[75,76]. Heat is also affecting mental well-being where elevated temperatures lead to increased hospital admissions for mental diseases, where the risk is further emphasized by the increased mortality for individuals with mental health conditions[77]. The vulnerability is contributed by usage of antipsychotic medications, similar vulnerability is attributed to medication to treat physiological conditions common for elderly and people with chronic diseases due to reduction or impairment of the thermoregulatory system[77]. Meanwhile, in countries in colder regions of the planet the excess mortality rate is mainly due to cold associations rather than heat associations[25,78].

When thermal stress cannot be alleviated by a change of settings, work pace, or clothing, or due to an impaired thermoregulatory capacity, thermal strain may cause short-term and long-term effects resulting in increased morbidity or mortality. In the heat, the physiological regulatory response is vasodilation to promote peripheral blood flow and to sweat which is enhanced in acclimatized and well-trained individuals. However, it requires the environmental and clothing conditions that allows evaporation and the fluid intake to match the sweat production and physical movement to promote the circulatory functions. When evaporation is hindered or sweating rate is insufficient, individuals may experience heat exhaustion, heat syncope or heat stroke[5]. If the salt intake is insufficient to keep up with the sweat rate, the risk of heat cramps increase[5]. Uncompensated heat stress resulting in elevated core temperatures above 40°C leads to heat stroke that may cause unconsciousness, kidney, and nervous system injuries, where death is a common result. Continuous exposure to heat stress and dehydration may lead to chronic kidney disease which is prevalent in hot countries with limited hydration possibilities, a malpractice that has been identified for sugarcane harvesters who perform strenuous work in the heat occurring in the peak harvesting season[79]. Salt intake may be required during excessive sweating as uncompensated salt loss leads to an imbalance in the ion system and neural stimulation of muscles will be impaired leading to cramps, dizziness, nausea, vomiting, and fatigue[5]. Properly hydrating with sports drinks[80] or pre-conditioning by ingesting cold drinks or ice slurries may mitigate the risks of heat illnesses and improve physical capacity in the heat[81,82].

When experiencing cold environments, cold stress is alleviated by increased physical activity generating heat or increased clothing insulation[5]. However, high physical load generating a lot of heat can only be maintained for several minutes at a time before the anaerobic capacity is reached and the aerobic low intensive activity which generates less heat can be utilized. If these activities are not sufficient to maintain a steady state core temperature and clothing insulation is insufficient, the body response is shivering and vasoconstriction. Vasoconstriction increases the blood pressure and puts extra strain on the heart which increase the risk of suffering from myocardial infarction (heart attack) or respiratory diseases. As mentioned, shivering is insufficient to prevent cold stress and vasoconstriction reduces the peripheral blood flow to reduce heat loss from the body core. When left uncompensated, the vasoconstriction will lead to extremity cooling and impaired physical capacity[5].

The diurnal temperature range (DTR) is a measure of climate change receiving more focus[83,84] and is the difference between the highest air temperature ($T_{a,\mathrm{max}}$) and the lowest ($T_{a,\mathrm{min}}$) air temperature measured during one day. High $T_{a,\mathrm{max}}$ in hot environments cause heat stress during daytime and high $T_{a,\mathrm{min}}$ cause a loss of recuperation during nighttime in naturally ventilated buildings while low $T_{a,\mathrm{max}}$ and $T_{a,\mathrm{min}}$ in cold environments are typically associated with outdoor exposure and occur throughout the day causing cold stress. Many studies have evaluated the mortality in relation to DTR and both extremely low and high DTR are associated with high mortality, where a consensus has found that an increase in DTR increase mortality[83,85]. The first IPCC assessment report (FAR) concluded that there was no definite evidence for a general reduction in DTR amplitude based on the increase of greenhouse gas emissions[9].

Atmospheric circulation and El Niño Southern Oscillation

The local thermal environment is the result of global circulation driven by the rotation of the earth and solar radiation. The uneven distribution of continents on the globe and the flux of radiant heat from the sun gives rise to global and regional transport of air parcels transporting heat and humidity. When air is heated it rises and leaves a deficit of molecules. This deficit is known as a low-pressure centre where the air rising will diverge and eventually cool and converge, sink, and amass at the surface increasing the number of molecules and with it, the pressure increases known as a high-pressure centre (Figure 7). The elevated pressure will cause the air to move towards the low-pressure to equalize the pressure difference.

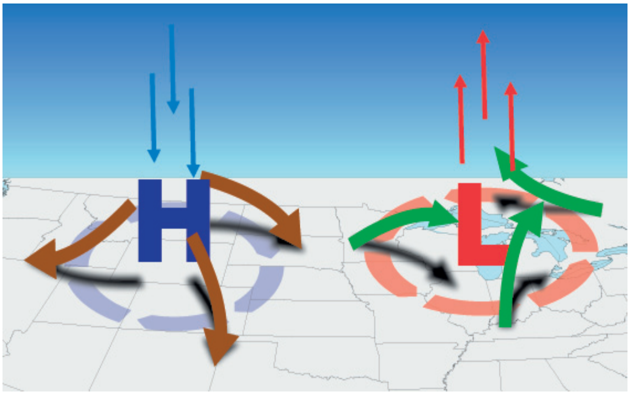


Figure 7. A graphical representation of high- (H) and low-pressure (L) centres. Credit: National Oceanic and Atmospheric Administration (NOAA), JetStream.[1]

These pressure centres are the drivers for the hydrological cycle where rising air above the ocean will bring humid air into the atmosphere and when the warm humid air cools, the water vapour condenses onto condensation nuclei and raindrops are created. As the Earth spins along its axis, a phenomenon arises known as the Coriolis effect which deflects the winds on the northern hemisphere to the right and to the left on the southern hemisphere (Figure 8a) creating cyclonic and anticyclonic wind patterns. Therefore, low-pressure cells on the Northern Hemisphere are converging counterclockwise and clockwise in the Southern Hemisphere. In the tropics, the area around the equator, the radiant heat flux from the sun is greater than the northern and southern hemisphere due to the curve of the Earth which gives rise to the atmospheric circulation cells (Figure 8b). Without the Coriolis effect, the heated air that rises around the equator would sink around the poles, but the Coriolis effect gives rise to two additional cells. The Hadley cell transports warm humid air into the atmosphere from the equator and is generally sinking around the 30th latitude where the Ferrel cell transports the air poleward. Around the 60th latitude a low-pressure belt force air upward which either circle back to the equator or to the poles where it sinks and return to the 60th latitude. The last cell is called the Polar cell, and the cells operate similarly on the northern and southern hemisphere. Similarly to the trade winds around the equator, the westerlies are winds blowing from the west to the east around the 60th latitude. These general weather patterns provide the general atmospheric conditions for the climate zones in Figure 10.

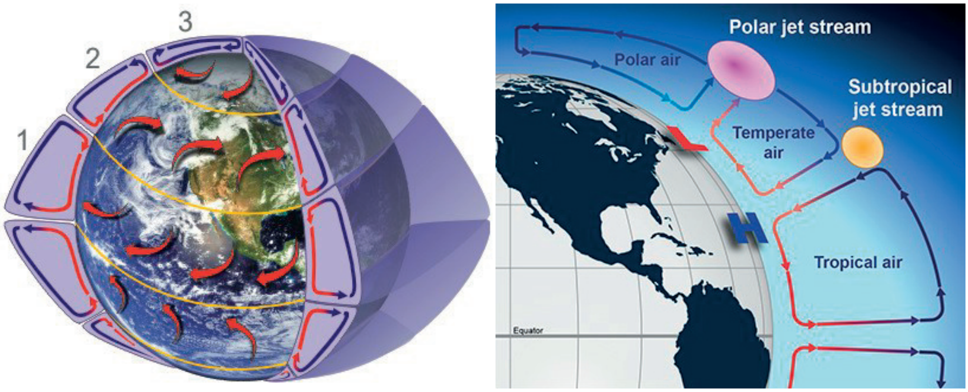


Figure 8a-b. 8a (left): A representation of the global circulation where the three cells (1. Hadley, 2. Ferrel, 3. Polar) transport air in the troposphere between the Equator and the poles on both hemispheres[86]. 8**b** (right): A graphical representation of the atmospheric cells where high- and low-pressure cells are driving the cells. At the top of the troposphere, the jet streams displace air horizontally. Credit: NOAA, JetStream[87].

The El Niño Southern Oscillation (ENSO) phenomenon is a widely studied cycle that impacts the global climate and is known to exacerbate regional weather hazards, particularly extreme precipitation[88,89,90]. The ENSO is closely monitored by measuring the Sea Surface Temperature (SST) which depicts the prevailing ENSO episode and is used for warning systems as the consequences impact different sectors which benefit from knowing the phase of ENSO, the zones used for measuring the ENSO indices are seen in Figure 9.

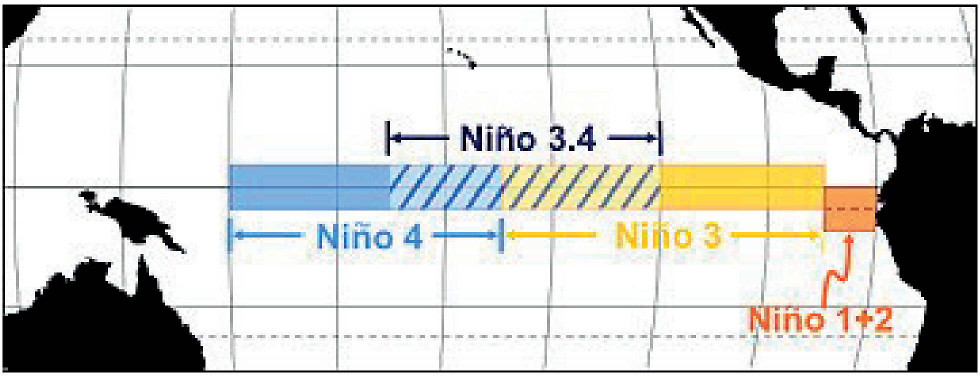


Figure 9. The zones from which the ENSO indices are calculated using the SST. The Niño 3.4 zone cover parts of Niño 3 and Niño 4 (5S-5N; 170W-120W) in the Pacific Ocean. Credit: NOAA, JetStream[91].

Under normal conditions, the normal state of ENSO, the Trade winds push the warm surface water in Pacific Ocean westward which pools at the coast of Australia. As the surface water is pushed west, an upwelling of cold water occurs in the deficit at the coast of western South America. This unequal distribution of energy will have a great impact on the regional atmospheric circulation.

The relatively high air temperature is what causes ENSO to have such a great impact on the hydrological cycle in the region, as the water holding capacity of air increases with air temperature. Therefore, the ENSO cycle is commonly leading to floods and droughts in the region that can severely impact health where infectious diseases are experience favouring conditions during the extremes[92]. Consequentially, with lacking infrastructure that are prone to flooding are exposed to waterborne diseases which severely impacts child health[93].

Climate adaptation and acclimatization

A population, Population A, located in a cold zone without dry season and having warm summer (Dfb in Figure 10, portrayed with a dark green colour) will be better adapted to their thermal environment compared to a population, Population B, living in a tropical zone with rainforests (Af in Figure 10, portrayed with a dark blue colour) who has adapted to the latter zone, the zones known as Köppen-Geiger climate classes are portrayed in Figure 10[94]. The climate classes are defined and grouped based on seasonal patterns of air temperature and precipitation, these patterns result from the rotation of our planet and the influx of solar radiation which is discussed in detail later. A person may reduce the risk of thermal stress in a new environment through short-term exposure (acclimatization) and long-term exposure (adaptation) to the local environment. Acclimatization to heat is a well-known process which takes place over 7-10 days with a minimum of two hours of daily exposure. Acclimatization to heat functions similarly to improving physical fitness where the cardiovascular system is exercised to handle higher loads of thermal stress by promoting the system to move warm blood from the core to the peripherals where the possibility of heat dissipation is the highest. Through acclimatization and exercise, sweat gland function is improved where more sweat is excreted to increase the cooling by evaporation from the skin, and the salt content is reduced to maintain the salt balance which is important for the ion communication in the body[95,96]. Lowered core temperature is not the only physiological response, but a reduced heart rate is also observed for heat acclimatized people in hot environments[97]. Acclimatization to cold is less prominent but after several weeks, the shivering response to cold stress will be replaced by recruitment of the non-shivering thermogenesis by brown adipose tissue[98,99]. Shivering is an uncomfortable response to body cooling that increase metabolic rate up to five times of resting metabolic rate, yet it is insufficient to maintain a steady core temperature during cold stress[5].

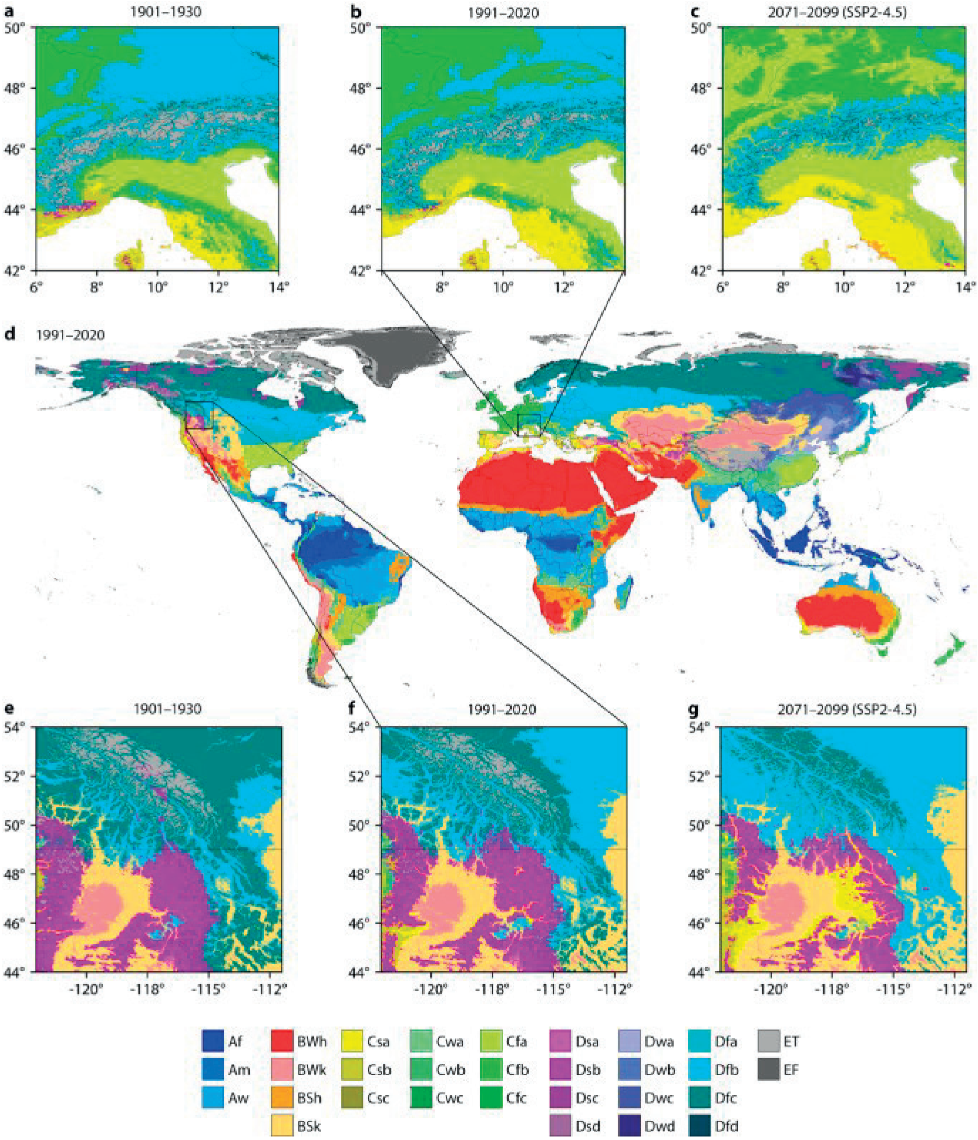


Figure 10. The Köppen-Geiger classification of climate classes updated by Beck et al in 2018 where classes are defined by their season patters of air temperature and precipitation and portrayed by different colours such as BWh is bright red and represent an arid (B) desert (W) that is hot (h). The overarching classes listed by Beck are A: Tropical, B: Arid, C: Temperate, D: Cold and E: Polar. See the second table in Beck et all for all classifications and definitions[94].

Early warning systems

Since my PhD journey started, there has been an increasing amount of focus on heat health warning systems to provide larger populations with warnings about upcoming heat events[60,100,101]. The overview of existing Heat-Health Warning Systems (HHWS) by Casanueva et al. found 16 existing systems in Europe where warning systems are provided by the national meteorological institutes based on simple indices or air temperature[100]. Most warning systems focus on heat but on the northern hemisphere, in countries around the latitudes close to the polar circle, cold is still and will continue to be, the major cause of death where climate factors are co-factors[78,102,103,104]. The cold alerts in countries such as Canada, Finland, Norway and Sweden are based on air temperature and the Wind Chill Temperature (WCT) where warnings are most commonly focused on snow and ice.

Most commonly, air temperature is used as a proxy to predict heat stress, often the highest daily air temperature ($T_{a,\mathrm{max}}$) is of interest but also the lowest daily temperature ($T_{a,\mathrm{min}}$) can provide information of recuperation from the heat. As identified by Casanueva et al.[100], several weather services that incorporate indices into their weather warning systems. The Heat Index combines the effect of air temperature and humidity and is applied by the National Weather Service (NWS) in the United States. Similarly, the Humidex used by Environment and Climate Change Canada functions like the Heat Index but has set the base dew point temperature to 7°C while the Heat Index base is set to 14°C. Japan Meteorological Agency applies Wet Bulb Globe Temperature (WBGT) to issue a heat stroke alert to raise awareness of heat and promote public preparedness. WBGT is also applied by the Australian Bureau of Meteorology and is currently being prototyped by the NWS. The German meteorology bureau, Der Deutsche Wetterdienst (DWD), has adapted the Perceived Temperature (PT) which is an output of the Klima-Michel model developed by Jendritzky et al.[105,106] building on the work by Fanger[107] to issue warnings of heat stress. The PT follows similar calculations to UTCI but there are observed differences particularly in colder environments[108]. The European Centre for Medium-Range Weather Forecasts (ECMWF) are developing a forecast model to predict a heat health hazard index based on the Universal Thermal Climate Index (UTCI) which will be operational on the second half of the 2020-ies[109]. The Cold Weather Ensemble Decision Aid (CoWEDA) tool by Xu et al. predicts cold stress and risks of cold injuries applying a six-cylinder thermoregulatory model to describe human physiology and biophysical properties of clothing[110]. Several research projects have recently developed tools integrating thermal indices to assess thermal stress. Ioannou et al. developed a smartphone app based on WBGT to provide personalized heat-health guidance[61]. The EU project hackAIR developed a platform to assess air quality and thermal comfort conditions using low-cost sensors to promote public health[111,112]. The recently developed web tool HeatWatch in Australia aims to reduce adverse health effects due to heat stress[113].

The role of human thermal models and indices

Extensive research has generated an upheaval of thermal indices and their underlying models that can be used to quantify the environment, or the physiological response based on the exposure to the thermal environment. These models and indices provide a comprehensive assessment of the thermal exposure which the four climatic variables on their own may not. Grand efforts have been undertaken by Ioannou et al.[114] and De Freitas and Grigorieva[115] to catalogue the available models and indices depicting the thermal environment, each with their strengths and limitations. Thermal indices can be grouped depending on the theory of assessment into either rational indices, empirical indices, or direct indices. Rational indices predict the physiological response based on heat transfer equations and can provide detailed feedback for the exposure such as Predicted Heat Strain (PHS)[116] in the heat and Insulation REQuired (IREQ) in the cold[117]. PHS predicts the core temperature and sweat loss in a known hot environment to estimate exposure limits while IREQ estimates clothing insulation needed based on heat loss in a cold environment. A comprehensive index to cover both hot and cold outdoor environments, UTCI was developed in 2009 to be a versatile index usable on each continent on our globe[118]. However, exposure is not limited to outdoors and the Predicted Mean Vote (PMV)[119] is a rational index derived for indoor assessment of thermal comfort based on clothing, activity and environmental parameters developed by Fanger[107]. PMV is coupled with the Predicted Percentage Dissatisfied (PPD) index to complement PMV with an indication of how many of the population find the environment uncomfortable. Empirical indices are fitted equations based on data collected from exposure studies such as the WCT that predicts the time of exposure before frost bite occurs on exposed skin based on air temperature and wind speed[120]. Direct indices are indices that are given directly from an instrument to quantify the exposure based on the readings, where WBGT is the most commonly applied index developed by Minard and Yaglou that combines the effect of a black globe thermometer for radiant temperature, a shielded dry bulb thermometer for air temperature and the natural wet-bulb temperature measured by a bulb thermometer covered by a wet sock to quantify the effects of evaporation[121]. As catalogued by De Freitas and Grigorieva, more than a hundred models and indices have been developed[115] but only those applied in the appended papers of this thesis are being mentioned and discussed in this work (IREQ, PHS, PMV-PPD, UTCI, WBGT and WCT) with the exception of ET which serves as a schoolbook example.

The role of human factors and interaction design in climate and health early warning systems

The relevance of human factors and ID has been touched upon earlier in this introduction, but several concepts are relevant to understand when developing a successful tool. When developing a service or a tool, the developer must consider the capabilities and motivations of the end-user or recipient. In terms of a climate and health warning system, the service must provide information in a fashion that is relevant to the targeted audience. If the information provided is too cumbersome, the user will not bother to utilize the tool because the burden is perceived as greater than the gain. But if the information is too simplified and thin, the user may not receive any new useful information by using the tool which means the time spent has been in vain. Research has shown that users are more inclined to use a tool which offers good function compared to the ease of use[122]. It is however important to consider both the product's usability and ease of use[8]. The human computer-interaction (HCI) has traditionally been focusing on how digital artifacts should be designed with emphasis on the cognitive capacity of the users[123,124]. It is also relevant to take into account that context plays an important role when interaction with digital artifacts[125], and the intention or motivation of the user which gives the interaction some deeper meaning[126,127]. The social context must be taken into consideration where population A and population B was discussed earlier in terms of adaptation, where language, culture, education, and infrastructure most certainly provide each population with different capacities for preparedness.

The concept of usability is a combination of whether a product is easy to use, if it is effective and enjoyable to use and is in line with the user's goal of the interaction from a user's perspective[8,17]. In order for a product to be deemed usable, there must exist a user who finds meaning in using the product in order to achieve the goals of the user. Therefore, a product must be tested using test persons and in setting that offers the user to utilize the product. Nielsen's 10 general principles are known as the heuristics in ID as they provide a framework for a well thought-through product[53]. The heuristics were developed by Jakob Nielsen and Rolf Molich in the 90's but the robustness have proven to be powerful guidelines. As seen in Figure 11, the heuristics highlight the need of clarity, ease of use, and assistance through different means.

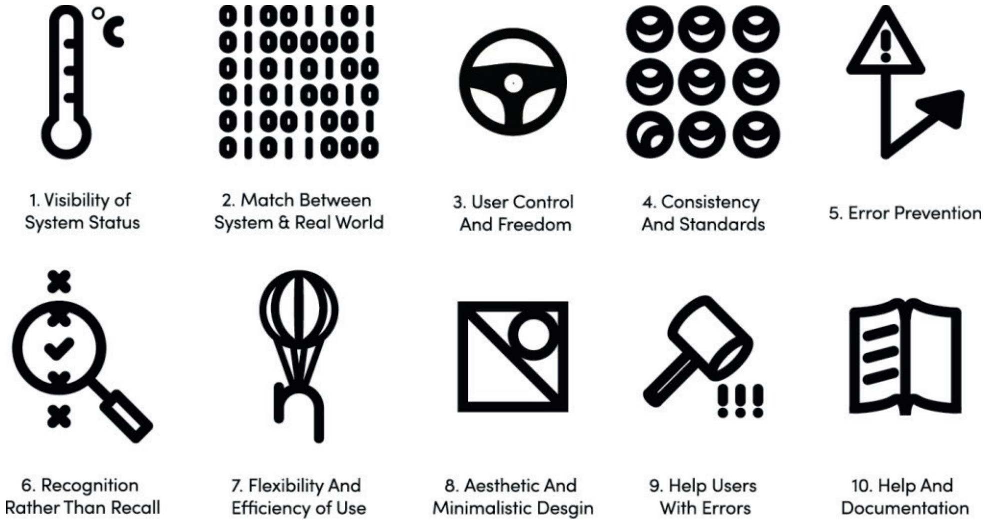


Figure 11. Nielsens 10 heuristics coined by Nielsen and Molich. Credit: Niklas Ekdahl.

The visibility, aesthetics, recognition, and consistency will help the user to easily see and understand what is going on. The control and freedom, error prevention and error assistance, and help and documentation will make sure that the user can operate freely without running into considerable issues and in those cases where the user needs detailed assistance, the product should provide instructions in an appropriate fashion.

To create a people-centred product as termed by WMO, more commonly referred to as the user-centered approach, the end users are the driving force of the product development[8]. Depending on the level of engagement, the developer will acquire an understanding of the needs of the end users and the potential problems that needs solving by the product. This is the first step in the four basic activities of ID which is illustrated in Figure 12[8]. This is an iterative process where the second step is to design alternatives that can satisfy the requirements, this can be done conceptually or with concrete designs. By developing a conceptual model, the action flow of the product can be grasped and used to understand the interaction between the product and the user. This step may reveal additional requirements that require additional attention and when these are included in the framework, a first prototype can be developed. The first prototype will allow the user to interact with a selected number of functions to be evaluated. This prototype can be anything from paper and cardboard to an advanced software depending on the product being created. Depending on time and resources, several rounds of prototyping can occur to ensure that most possible issues are dealt with before a final product is completed. If possible, a lo-fi prototype using paper and simple figures can quickly get an understanding if the conceptual model agrees with the end user needs. If a discrepancy between end user and product is realized late in the development, most likely valuable development time is lost. By evaluating the prototype, the developer will get feedback whether new requirements are needed, perhaps the conceptual model or the concrete designs were inappropriate and requires an alternative design and a new prototype can incorporate these changes. When a satisfactory result is achieved a final product can be developed based on the iterations evaluated[8].

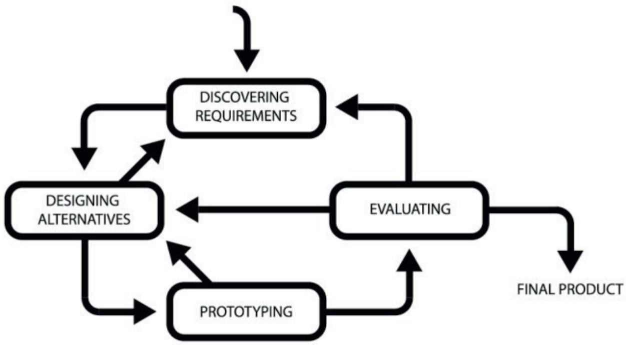


Figure 12. The iterative design process, where pathways to previous steps are available to improve the concept. The process is expected to take several rounds before resulting in a final product making it an iterative process. Modified from Sharp et al.[8]. Credit: Niklas Ekdahl.

Methods

To achieve the objectives of this thesis, a variety of research methodologies are applied. The appended papers in this thesis revolves around the EU-project Translating climate service into personalized adaptation strategies to cope with thermal climate stress (ClimApp) and the International Belmont Forum collaborative research project Addressing Extreme Weather Related Diarrheal Disease Risks in the Asia-Pacific Region (AWARD-APR). The aim of the ClimApp project was to develop a personalized early warning system using a smartphone as a platform to help individuals and vulnerable groups to reduce the risks of heat stress where the usability and validity are evaluated in this thesis. The AWARD-APR project aimed to develop a seasonal to subseasonal (S2S) warning system for diarrheal disease based on extreme weather to provide communities with sufficient lead times to prepare for diarrheal outbreaks. From the perspective of this thesis, the warning system for diarrheal diseases can similarly be utilized for a long-term thermal health warning system.

Table 1. Details of the appended papers including what type of study was performed, the collected data type and which analysis method was used to interpret the data. In terms of the first paper, the analysis method refers to the data collection method.

Paper	Title	Type of study	Data type	Analysis method
I	Is There a Need to Integrate Human Thermal Models with Weather Forecasts to Predict Thermal stress?	Literature review	Qualitative	Citation pearl growing and berry picking
II	The usability of ClimApp: A personalized thermal stress warning tool	Lab and field study	Qualitative and quantitative	Directed content analysis Chi-square
III	Validating an advanced smartphone application for thermal advising in cold environments	Field study	Quantitative	RMSD
IV	Spatiotemporal link between El Niño Southern Oscillation (ENSO), extreme heat, and thermal stress in the Asia-Pacific region	Modelling study	Quantitative	Mann-Kendall and Wilcoxon rank-sum test

Paper I - Literature review

Paper I applies the framework of a literature review explained by Grant and Booth, where the review describes published materials and synthesises it into a textual form[128]. The core of the manuscript was obtained through citation pearl growing[129] and berrypicking method[130]. By finding one key relevant citation using a precise search, in this case the “Calculating workplace WBGT from meteorological data: a tool for climate change assessment” by Lemke and Kjellström[59], new terms allow for other relevant articles to be found to construct the body of knowledge for the research question. The berrypicking method follows this methodology where the search terms evolve throughout the exploratory literature review. These methods stand in contrast to the systematic reviews where the body of knowledge is collected, preferably, by a specific key search on multiple databases. It can be argued that the systematic review provides rigor as it should collect all relevant articles but it is limited by the developed key search terms and selection bias[131]. The manuscript focused on relevant aspects of the ClimApp concept, where meteorological data was used to calculate thermal stress indices. Additional literature scoping was performed throughout the review to identify existing research gaps and limitations in the scope of the ClimApp project. The literature was obtained through Web of Science/Science Citation Index, PubMed, Scopus, and Google Scholar. Different key words were used to find the relevant articles. The gathered data was structured into heat, cold and indoor environments and the model possibilities and limitations in each setting. Studies that had applied the Liljegren et al.[58] approach of calculating WBGT using weather station data was included in the manuscript.

Paper II - Usability test

A working prototype was developed after a few hi-fi and lo-fi prototype iterations with stakeholder engagement and showcasing the concept. The prototype was tested in the usability lab at Ingvar Kamprads Designcentrum (IKDC) at Lund University, Sweden. The post-covid outbreak road map for Paper II is visualized in Figure 13 and the first part was to perform a small sample size (10 participants) of first-time users in the usability lab to find any obvious issues with the app navigation and functionality. This version of the prototype was named Iteration 1 and offered full functionality and navigation possibilities.

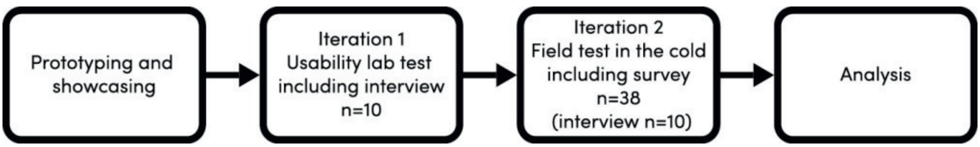


Figure 13. The roadmap of Paper II. Slightly modified from Eggeling et al.[132].

The first working prototype was named Iteration 1 and the follow-up, Iteration 2, was later tested in the field in cold environments with 38 new participants. The usability lab (Figure 14a) offers different video feeds that are able to keep track of participant interactions. The participants were given instructions through a Public Adress (PA) system and an over the shoulder camera recorded haptics while a direct video feed from the smartphone with pointer reaction enabled was recorded simultaneously (Figure 14b).

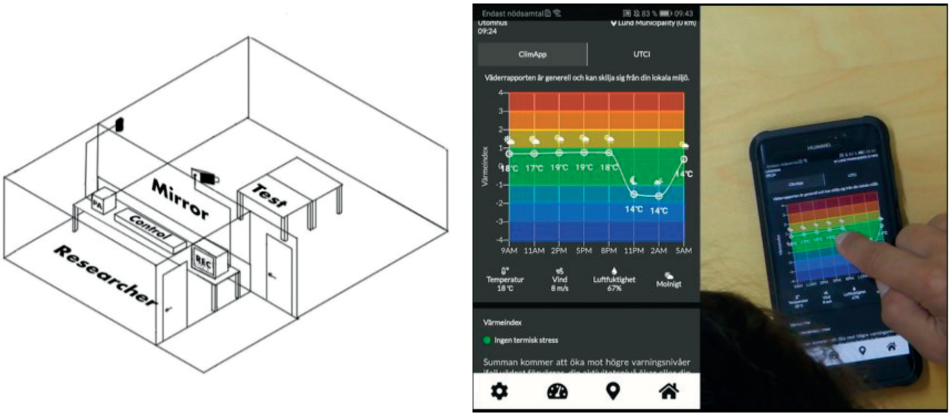


Figure 14a-b. 14a (left): The usability lab in which the usability test took place. **14b** (right): Screen recording and over the shoulder recording of participant testing ClimApp.

The test participant was asked to sit down by a table where a smartphone was lying with a single app available. When started, the app boots up into the main screen (Figure 15a) where the user is presented with a weather forecast at the top of the screen, a colourbar to represent thermal status with a colour scale from blue to red (cold to hot) with green (comfortable) in the middle. A marker in the colourbar represents the current ClimApp prediction of thermal sensation and a coloured figure highlight if the prediction is comfortable, hot or cold. By pressing a button labelled “Prognos” (Eng: Forecast), above the colourbar to the right, the user could find a 24 hour prediction forecast (Figure 15b) where the user can choose between a ClimApp index forecast or a UTCI forecast. The ClimApp index is calculated based on IREQ in the cold, and WBGT and PHS in the heat. If the user decides to scroll down on the first screen (Figure 15a), they can choose between receiving a personalized prediction or a prediction for different vulnerable groups (children or seniors) where the output focus on relevant advice. Below the personalized/group setting, the user can input information such as activity level, clothing level, anthropometric data, and a feedback system whether they agreed with the predicted thermal sensation (Figure 15c).

Figure 15a-c. 15a (left): The home screen of ClimApp with a bar representing thermal sensation. **15b** (middle): The 24-hour forecast of the thermal sensation prediction. **15c** (right): The clothing tab at which the user can modify the clothing insulation input of the app.

At the bottom of the screens in Figure 15a-c, four buttons can be pressed to navigate to additional screens seen in Figure 16a-b. By pressing the cog wheel icon, app build data can be found and a link to the ClimApp webpage. The speedometer returns the user to the home screen (Figure 15a). The map pin icon sends the user to the custom location screen (Figure 16a) where the user can select a location using a google maps application rather than the smartphone GPS location. The house icon opens up the indoor mode function (Figure 16b) where the thermal sensation is predicted using PMV where the indoor environment can either be set manually or predicted by ClimApp using weather station data and simple building characteristics[133].

When the test was completed, a semi-structured interview was performed with the goal to obtain nuances and thought processes from the test participants about navigation, functionality and app relevance[134]. The interviews were transcribed, and the tests and transcriptions were analyzed using the Nvivo software (QSR International, Australia).

The app was updated based on the input from the usability lab test and the new version, Iteration 2, was tested in the field. The updated version was completed in time for the boreal winter and the field test served to evaluate ClimApp in cold environments which was defined to be in the validity range of IREQ namely below +10°C. This fulfilled the ClimApp project sub deliverable to evaluate ClimApp in the cold, a previous study to evaluate ClimApp in the heat was performed in The

Netherlands[135]. The field test served as data collection of usability data and prediction data for both Paper II and Paper III where the latter explores the validity of the ClimApp index prediction. In the field test, first-time users were to spend 60 minutes outdoors in a natural environment without any unnatural heating such as bonfires or heat exhausts. The participants were allowed to wear their own clothes of choice and to perform any familiar activity that they had planned.

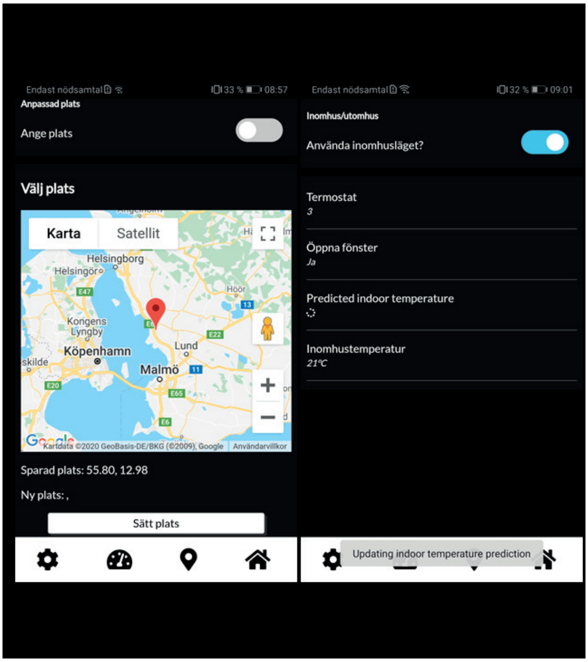


Figure 16a-b. 16a (left): The custom location panel. **16b** (right): The indoor function panel.

The participants were asked to record several information prior to their exposure:

- Air temperature
- Relative Humidity
- Wind speed
- Cloud cover (Clear sky, cloudy or overcast)
- Activity level chosen in ClimApp
- Clothing level chosen in ClimApp
- Clothing worn
- ClimApp index prediction
- UTCI

After the exposure, the participants filled in a study where they submitted the above recorded information, their perceived thermal sensation after 60 minutes as well as questions regarding their experience of using the app. The questions were a combination of closed questions with a Likert-scale response and open questions focusing on their thoughts when performing certain tasks in the app. A follow-up interview was offered and performed with 10 participants over the telephone. The interview was semi-structured like the usability lab test and was recorded and analyzed using NVivo. The field test was carried out by two first-time users as a pilot test to test the rigor of the instructions and survey.

The inclusion criteria for the field test were:

- Participant was aged 18 years or older
- Regularly spent 60 consecutive minutes or more outdoors in the cold

The exclusion criteria:

- History of complications from exposure to cold environments
- Medical conditions affecting thermoregulation or perception

38 participants completed the field test including the usability part. The group was well represented with an age range of 18-65 years (average 34.7) where 20 were male and 18 were female.

Analysis framework

The collected data was analyzed using a directed content analysis to explain and understand the relevant aspects of the participants interaction with the smartphone app, this with activity theory as the guiding theoretical framework[127,136,137,138]. Activity theory was chosen for its applicability to the ClimApp concept, where the system influences the subject through a multitude of pathways. In the work by Kaptelinin and Nardi in activity theory[127], it is assumed that the activity has a central role in the model. An activity can be an overarching desire such as being in harmony, where the action can be a part of a sequence of events and is directed towards an instrumental goal. The activity can itself be split up into several operations on an unconscious level while the action is on a conscious level. The theory is well portrayed by the Engeström triangle[139] seen in Figure 17. In the ClimApp concept, our perspective using the activity theory is that the user wants to be in balance with the environment to remain in a thermoneutral state. The subject (our participant) works with the object (functions in ClimApp) to obtain an outcome (thermal stress prediction) with the motive to mitigate thermal stress, to do this an instrument is needed (smartphone app). This activity takes place in the community (society) with a division of labor (data input, data retrieval, and model calculations) and under a set of rules (social and cultural norms, design conventions).

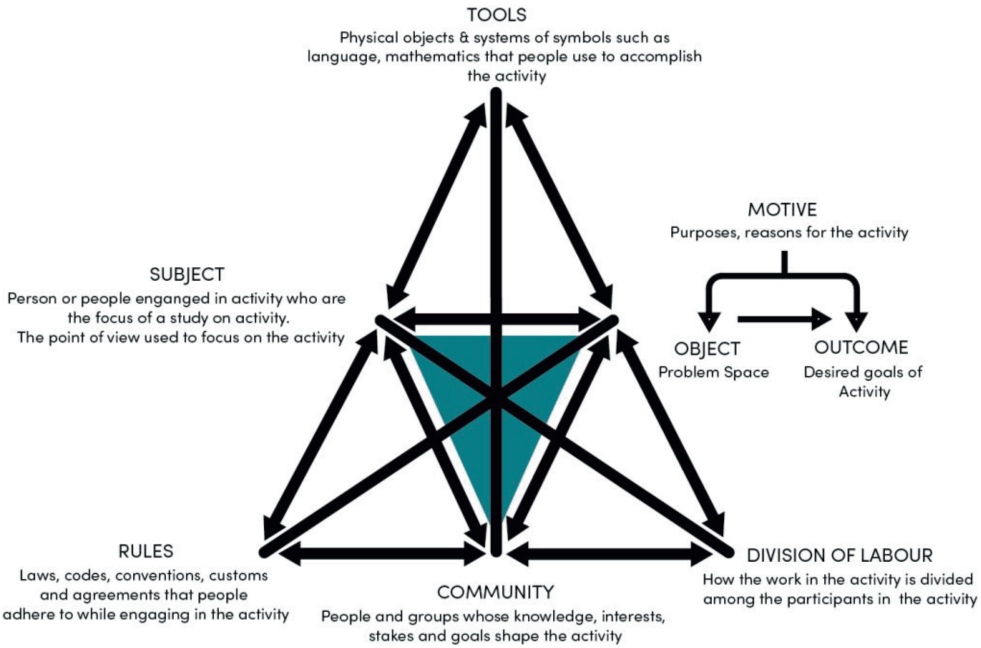


Figure 17. The Activity theory triangle, modified from Engeström et al.[139]. The triangle highlights the interaction between the different components. Credit: Niklas Ekdahl.

Paper III - Validation test

Paper III data was collected simultaneously with Paper II (the field study part) where the survey covered both quantitative data for the validation part and qualitative for the usability study where not all participants took part in the usability study. There is currently no international standard method how to assess outdoor thermal comfort to promote cross-study result comparisons[140]. Having a standard would simplify the development stage of the study protocol and allow for better comparisons between studies evaluating thermal comfort. A power calculation was performed using the GPower software to get an estimate of the required number of participants for statistical testing[141]. The GPower analysis computed that a sample size of 55 participants would be required to perform a statistical significance test. The computation was based on the “F test Linear multiple regression model, R2 deviation from zero” setting, a medium effect size which was used by Nie et al. when evaluating UTCI[142] meaning f2 = 0.15[143], the threshold for statistical significance $\alpha = 0.05$, Power = 0.80, and number of predictors being 1 was used. An additional 17 participants were recruited to complete the validation part of the field study following the same study protocol excluding the questionnaire questions about usability. Excel 2016 (Microsoft Corporation, U.S.A.) and RStudio version

1.4.1717 (RStudio, U.S.A.) were used for the data processing and analysis. As UTCI is represented as a temperature with the linear unit Celsius (°C) and the ClimApp index is dimensionless and represented as an ordinal index value, UTCI data collected was transformed into an indexed representation similar to ClimApp to improve the rigor of the analysis (Figure 18). The analysis compares the user perception to the ClimApp prediction Index and both the conventional UTCI and the UTCI index. The UTCI scale is originally indexed into thermal stress levels[118,144] similarly to ClimApp[26].

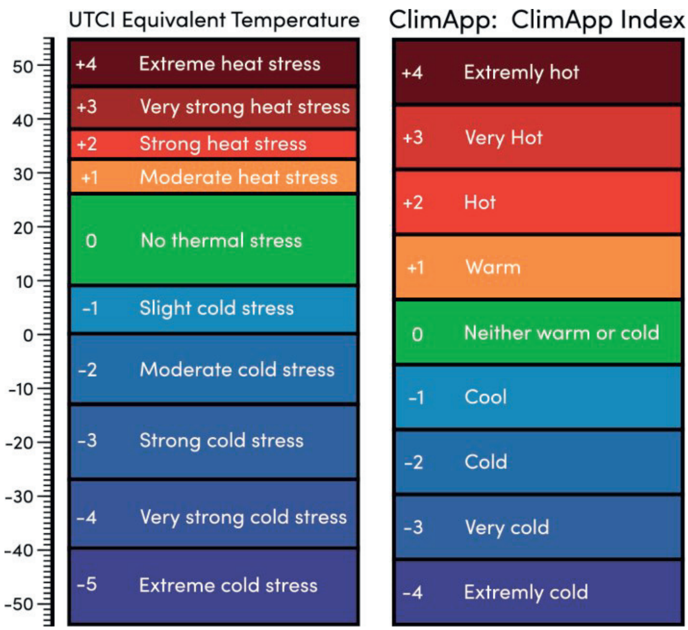


Figure 18. The UTCI scale to the left including indexed values from -5 to +4 and the ClimApp index to the right.

The statistical significance of the results was evaluated using the Root Mean Square Deviation (RMSD)[145]. The RMSD of the indices are compared to the Standard Deviation (SD) of the perceived thermal sensation and if the RMSD is lower than the SD (RMSD < SD), the prediction model or index is considered to be valid[146,147]. The validity was only evaluated in cold environments as a study by Folkerts et al. had already evaluated ClimApp in warm environments[135].

Paper IV - Spatial analysis of UTCI and T_a

The final paper evaluated the recent climate change in the Asia-Pacific region during 1990-2019 and how ENSO influences the thermal environment during the time period. The feasibility of the paper was promoted by the addition of UTCI to the fifth generation of reanalysis data, ERA5, provided by ECMWF in their Copernicus Climate Change service (C3S)[148]. The ERA5-HEAT specifically, where HEAT stands for Human thErmAl comforT, is the dataset which includes both mean radiant temperature (MRT) and UTCI as hourly data with 0.25° x 0.25° resolution. The data was processed in MATLAB R2020b (MathWorks, U.S.A.) to sort data, perform statistical analyses and generate figures. The max, mean, and min UTCI and Ta was evaluated throughout the study where max is defined as the 95th percentile and min as the 5th percentile. The Niño 3.4 SST (Sea Surface Temperature) index by the National Oceanic and Atmospheric Administration (NOAA) is used to classify the ENSO cycle where 0.5°C above/below of SST in the Niño 3.4 area (Figure 9) denotes a warm/cold episode known as El Niño/La Niña and the neutral phase in between. The ENSO influence in the region is studied on a seasonal level using the temperate seasons:

- Spring: March, April and May (MAM)
- Summer: June, July and August (JJA)
- Autumn: September, October and November (SON)
- Winter: December, January and February (DJF)

The seasonal influence of ENSO on both UTCI and T_a is evaluated for warm and cold episodes compared to the neutral phase and the Wilcoxon rank-sum test evaluates the equality between the phases. The change of UTCI and Ta during 1990-2019 was evaluated using the Mann-Kendall's (MK) trend test, this to evaluate if the trend is significantly increasing or decreasing. Building on the theory of DTR effect on health, the temperature range for a set number of days was evaluated to include longer shifts in the climate variables. The ranges were set to 3, 5 and 7 days where the highest and lowest value in each window resulted in the delta trend. A trend was evaluated by moving the window by one day making the first window for the 3-day delta trend being day 1, day 2 and day 3 with the second window being day 2, day 3 and day 4 etc. The delta trend was also evaluated using the MK test.

Ethical considerations

The studies in paper II and paper III took place during the covid-19 pandemic which required extensive safety precautions as the initial lock-down prohibited any research activities involving participants. As restrictions were lifted, usability testing was commenced with great efforts to limit interaction between individuals and extensive cleaning in the controlled laboratory environment. Each participant was informed of the state of the pandemic restrictions, the cleaning protocol, and the terms of the study. The participants signed a consent form and were informed that they could freely withdraw from the study at any time and that their information would be deleted and not included in the study. The participants were informed that the testing would be recorded by video and audio but not including the face, and that the data collected could not be connected to the person in any way. The free texts submitted in the survey could be used as material for analysis, as well as transcriptions and suitable quotes, without linking them to any personal information. When taking part in the field test, the participants were clearly informed to not make decisions based on ClimApp that were contradictory to their own habitual choices. They were instructed to evaluate only the information provided by ClimApp. The field test was conducted outdoors and remotely, and interviews were conducted over the telephone. Individuals with known medical conditions or reduced immune system were asked to not participate in the usability study in the controlled lab environment (Paper II iteration 1) due to the pandemic. Individuals with known sensitivity to thermal environment or with medical conditions were asked not to participate in the field test (Paper II iteration 2 and Paper III).

Results and discussions

Insights from the thesis work

Properly distributing warnings regarding the thermal environment needs to fulfil several objectives which are also highlighted by the WMO EW4All initiative. These objectives, modified from the EW4All pillars in Figure 4, can be summarized as these four pillars:

i. Knowledge about the risk
ii. Monitoring the appropriate indicator
iii. THWS warning communication
iv. User response capacity

A THWS is required to integrate these pillars into the concept to effectively assist individuals and societies with thermal stress management. The literature review, Paper I, explored the feasibility of the ClimApp concept and the detailed the limitations. The limitations in terms of human thermal model validity ranges highlighted that there exist many research gaps to provide a product including the evaluated models to predict thermal stress for all reasonable environments on Earth for occupational and leisure settings, with the option of selecting a wide range of activities and clothing. The literature review gave valuable insights into pillars i and ii where the human thermal models are based on the risks associated with thermal stress and extensive studies have mapped out the relationship between the variables resulting in comprehensive indices and models. The usability study, Paper II, provided a good assessment of primarily pillar iii but partly also pillar iv. The validation study, Paper III, further provided information about pillars ii and iii. The final paper, Paper IV, explores the teleconnection influence which provides an additional layer of information which is beneficial for pillars i and ii. By building upon these pillars, THWS can provide relevant and effective warnings that the recipients can act upon. Returning to the EW4All action plan, Paper IV utilizes global level data which is then applied on a national and regional level in line with Figure 3 and the ClimApp concept and tool in Paper I-III is functioning on a local level. The integration of human thermal models into THWS may provide the UN with the desired tools to fulfil their goal of covering every individual on the planet by an EWS in 2027.

Paper I - The ClimApp concept

Paper I explored the feasibility of the ClimApp concept, where most limitations were found for occupational settings in the heat or by using a clothing ensemble with significantly unevenly distributed insulation in cold environments. The UTCI allows for ease of use in these environments but is limited by the fact that the user cannot select activity and clothing input making the UTCI prediction non-personalized. The strength of ClimApp is to provide the user with a tool to plan their exposure by mitigating the risk by selecting an appropriate combination of activity and clothing. What must be considered is that ClimApp forecasts the exposure based on a baseline where the user is at a thermoneutral state with a core temperature of 36.8°C. The literature review concluded that two challenges are of main concern with the approach:

i. The local microclimate exposure may differ from the weather forecast

ii. The human thermal models are validated in occupational settings for men

The first challenge can be solved by including additional models that evaluate known microclimate conditions such as the urban heat island effect (UHI). One such model is the Weather Research and Forecasting model[149] that may bridge the weather forecast into the exposure environment conditions. An offline model was developed to simulate urban air temperature requiring less computational power using open-access products, such models can further improve the urban microclimate prediction[150]. Another solution can be for the user to manually input the microclimate variables if known. The second challenge requires rigorous testing in multiple conditions where several recent studies have evaluated UTCI for both men and women and found no statistical difference[151,152] while some identified a discrepancy[153,154], Paper III provides additional data to this known gender research gap. Developing personalized tools is challenging as individual differences and preferences vary between populations where one population can accept or prefer thermal sensations which would be considered beyond the thermoneutral zone for another population[155].

One potential development step from the ClimApp concept is to integrate user wearables that can feed data on local environmental conditions and physiological responses into ClimApp to further personalize the output. These wearables could provide a wide range of data which could prove important in both hot and cold environments. Recently the Coolbit project assessed heat stress using a smartwatch measuring heart rate, skin temperature, and air temperature measured by the watch, these variables combined satisfactory predicted the core temperature for a small set of test participants[156]. There are several clothing types that can mitigate thermal stress such as Phase Change Material (PCM) vests, ventilated clothing, heated vests, socks and gloves. Companies have started to develop smart textiles such as textiles with sensors where sweat PH can be screened either by textile colour change or using integrated optical sensors. If integrated sensors were able to estimate the sweat loss, the combination of physiological responses such as skin temperature, heart rate, and sweat loss could quantify the risk of an individual being exposed to a challenging thermal environment. By calibrating a tool equipped with such sensors to assess individual specific responses with simple feedback to the user to reduce cognitive load, simple warnings and advice can effectively provide user-tailored advice. However, integrating these sensors or wearing available wearables is currently not feasible for most of the global population so these solutions would probably only cater to specific groups such as athletes and certain occupational work forces in the near future. An estimate of 54% of the global population owns a smartphone[157] and only 3% of the global population uses a smartwatch[158]. The smartphone penetration opens up for the feasibility to apply the ClimApp concept in most of the developed countries where the smartphone usage is high while countries with a lacking smartphone and internet infrastructure renders the concept unusable. Here alternative offline solutions are required to make the concept a possibility where hosts of smartphones or similar tech can act as communicators to those without. This is currently being investigated where an EWS is being developed for maternal health monitoring extreme heat[159]. This lack of smartphone penetration and research focus on maternal health which is a known vulnerable group in the heat puts further emphasis on the benefit of developing THWS that put the user in focus. However, as only 3% of the global population is wearing a smartwatch which is the most common wearable, the approach to collect additional data through wearables can be considered limited. In the UN initiative, Early Warning For All, the socio-economic barrier is an obstacle which still requires central governance where regional bodies or the government can issue effective warnings without the requirement of individuals owning the technical equipment to be capable to respond to the warning. With technical development and lowered production costs, the feasibility of applying concepts like ClimApp will increase in developing countries.

The concept of ClimApp can be further applied to certain occupational settings known to be exposed to thermal stress. The eighth SDG targets to promote sustainable and decent work for all[160] which thermal stress severely impacts. Construction sites could make use of the daily forecast to assist work leaders with daily mitigation strategies and scheduling of activities with known thermal exposures to the available time slots forecasted to be less thermally strenuous. Facilities housing vulnerable groups can benefit from the concept with a longer lead time to better prepare resources to protect individuals during heat waves and cold spells. First responders can benefit from the concept by being suggested with relevant turnout gear, where firefighters are known to respond to a multitude of emergencies ranging from extreme heat to extreme cold where one gear can promote work safety above others from a thermal environment perspective when a range of gear is available using a modular clothing system. The ongoing SYNERGISE project aims to promote safety of first responders developing integrated toolkits[161] where the modular clothing system could be beneficial.

Similar to the modular clothing system, the ClimApp concept could benefit from applying a wardrobe function. Instead of selecting predetermined clothing ensemble levels which may not be applicable for some users, a wardrobe can be developed using commonly used garments. The ensemble insulation can then be calculated for the garments chosen by the user by underlying equations such as the ISO 9920 summation equation for clothing insulation[7] which has been tested for modular ambulance clothing[162]. This ties in with the CoWEDA tool by Xu et al. which focus on cold protective clothing and risks of cold injuries[57]. This proposed function and functions such as the indoor thermal comfort prediction can benefit from machine learning and potentially AI, where a feedback-system can be applied using text generated advice or a chat system that can finetune the personalized experience and possibly improve the tool performance in general by better understanding user behaviour, input selection, and the influence of building characteristics on the indoor environment.

Another important aspect is the frequency of warnings and the cognitive load required. During extreme situations such as smoke diving and firefighting, a warning system cannot overload the already extreme situation of the firefighter. Firefighters in Japan have been found to prefer mobility over protection[163] and the environment require them to be actionable and task oriented. Integrating sensors and alarms with haptic, sound, or light signals may reduce the mobility of the clothing while also disrupting the focus of the firefighter. Warning systems in this scenario require extensive planning to allow warnings without sacrificing mobility.

Limitations of thermal indices

Commonly the human thermal models have been developed and validated using data from occupational, laboratory, and military settings with male participants. This limitation is often highlighted and require further attention where the models appear to predict physiological responses better for males[153]. The mentioned thermal indices have documented limitations highlighting the need for caution when assessing the index outputs. Extensive work have been carried out by d'Ambrosio Alfano et al. when evaluating PHS[164], PMV-PPD[165], IREQ[166], and WBGT[167]. There are several ways of calculating WBGT which signifies the risks of discrepancies when comparing WBGT measurements, Lemke and Kjellström suggests to use Liljegrens[58] model for outdoor WBGT and Bernard model[168] for indoor WBGT. Different equipment and variations are available for measuring WBGT where the size of the black globe affects the time to reach equilibrium. WBGT partially offer personalization with integrated activity, acclimatization and clothing factor[169] which makes WBGT suitable as a screening tool or complement to weather forecasts. However, the WBGT index should be assessed carefully as WBGT values over

30°C may be interpreted as non-severe based on experience and its resemblance to T_a leading to underestimated heat stress[167]. Contrary, PHS makes detailed predictions of the core temperature of the person and the sweat rate and is less suited as a screening tool. Issues with PHS has reported that the prediction underestimates the core temperature but that the sweat prediction is accurate[153,170,171]. PHS also estimates the person to be at 36.8°C when starting the calculation, whereas it can be expected that workers may already be at elevated core temperatures when starting their work shift[70]. A common way to alleviate thermal stress is to take breaks in the shade or cool areas which puts PHS in a problematic position as it cannot deal with dynamic conditions[172]. The model is also limited to 3 m/s of air velocity which greatly affects the evaporation rate which is the main avenue of heat loss in very hot environments. The model is also limited to clothing insulation between 0.1-1.0 clo where 1.0 clo is equivalent to a business uniform/costume and can therefore not be used for workers using Personal Protective Equipment[173,174]. To increase the applicability of the models, the range of clothing insulation and permeability properties require further evaluation as well as harmonisation to ISO 9920 may be beneficial[164]. It can be expected that workers self-regulate their pace when possible and the models must be able to consider uneven activity intensities throughout the prediction calculations. Models evaluating heat stress such as WBGT, PHS, and UTCI could benefit greatly by studying and validating impacts of rest periods or intermittent work.

As IREQ calculates whole body cooling and assumes an evenly distributed insulation, it does not consider unevenly layered zones such as extremities or upper/lower body discrepancies. This opens up for misinterpretations of the index when individuals estimate their whole-body insulation poorly due to improper extremity protection[175]. Another identified discrepancy in the calculation of IREQ as the available web tool for calculating IREQ differs that from that given in the ISO standard[166], where the web tool prediction seem to offer higher accuracy[176]. WCT offers some complement to the IREQ calculation by focusing on the need for protection of exposed skin, yet IREQ refers to standard EN 511 for insulation requirements for gloves[177]. The tool CoWEDA by Xu et al. offers predictions using different zones of the body including extremities which provides potential to predict required insulation for extremities[57]. Further development of IREQ is suggested to emphasize body zones and extremities to increase the versatility of the model.

The biggest criticism for PMV is the difficulty with prediction accuracy, the uncertainties of the variables may affect the output with +/- 1 on the PMV scale which is on a scale from +3 to -3[165]. There are many aspects which affect the local indoor climate such as heating/cooling system, room orientation, windows, behavioural and social aspects[178]. The parameters required to calculate PMV are not readily available in most buildings and must be predicted using the weather forecast which calls for advanced prediction tools which are affected by building material, shape, and orientation etc. To improve the prediction, the parameters should be obtained by local sensors or user input. By developing tools to provide PMV input for a wide range of modern and old buildings, the solid foundation of PMV would benefit greatly from validation studies using such approaches.

Paper II - Usability of the ClimApp smartphone app

Paper II evaluated the user interaction with ClimApp using data from a lab study but also through questionnaire survey and interviews. The first iteration which was tested in the usability lab identified several interaction issues, particularly with the function that allows the user to manually set the location to receive an index forecast from that location. To make the function activate properly, the user had to perform actions in a series which were not guided nor provided any error message or error prevention. In one case, the user believed that they had performed the correct actions and had received the custom locations forecast, but the participant had failed to set the custom location and was given the automatic GPS-provided location instead without realizing it. The participant exclaimed:

> "It's OK. Apparently they have the same weather as us!"

Here the communication between ClimApp and the user was obviously not working as intended, the user expected to receive some kind of error message if the action was non-successful which is reasonable according to Nielsen heuristics, including a clear guidance on how to perform the correct action[53]. The visibility of buttons, lack of navigation features and a disconnection with external consistency where ClimApp used the house icon to represent indoor mode, which is commonly established to represent home, where pressing the house will return the user to the welcome screen. ClimApp was developed in a research project with scientific and technological advancement in focus where potential users and stakeholders only partially engaged during the initial development phase, the product therefore lacked a match with the users where specifically the terminology did not match that of the test users. This mismatch made the test participants feel that they were not the intended target group and felt overwhelmed by information that they could not process. Throughout the development phase, the scientific and technological core was increasingly covered by an interface better matching the needs of non-expert users. It was clear from the usability lab study that the first iteration struggled with several of the heuristics, arguably the 2nd, 3rd, 4th, 5^{th,} and the 9th heuristic (Figure 11). Between the iterations, several improvements were made regarding navigation and error management. In the case of the custom location, the function is hidden until the user activates it by a slider whereas in iteration one, a map could be manipulated even if the function was not active (Figure 19a-b). Also, the house button for the indoor mode was removed from the home screen and the indoor function was moved to the custom location screen which is accessed by the map pin button at the bottom panel and the user could then select either custom location or indoor mode using buttons on top of the screen (Figure 19c-d). A tutorial was added to assist first time users with navigating around the screens when pressing the question mark button in the bottom panel.

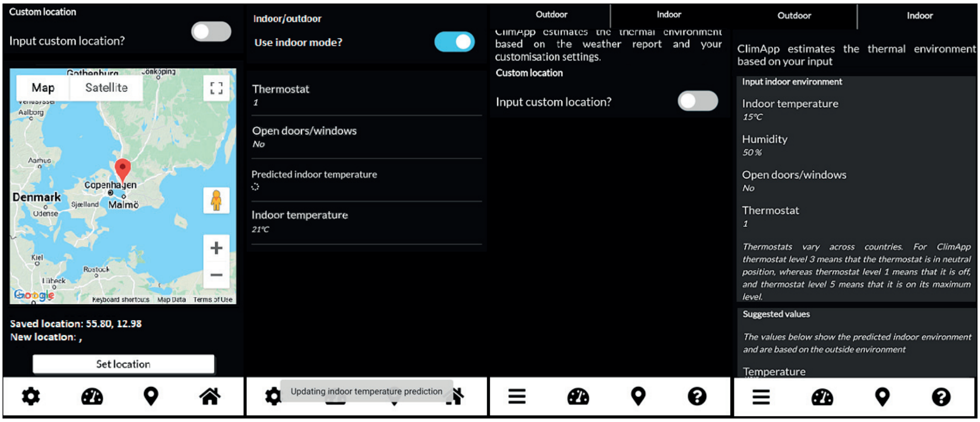


Figure 19a-d. 19a (far left): The first iteration custom location panel, note the slider being to the left meaning non-activated yet the map was still interactable. **19b** (middle left): The first iteration indoor mode. **19c** (middle right): The second iteration custom location mode. **19d** (far right): The second iteration indoor mode.

The results from the field test indicated that previous issues had partly been fixed as both the follow-up interview and survey only listed a few comments to make slight improvements of the custom location and regarding the information level. The major issues identified in the field test were connected to navigation in general (Table 2, statement 1) and finding functions (Table 2, statement 7), where the indoor mode was difficult to find (Table 2, statement 10), and when pressing the integrated return button on the smartphone, the user closed the software, but their intention was to return to the previous screen. But the overall response from the test participants was positive where the feasibility of the concept is further supported as the test was completed without issues and the validity was evaluated in Paper III, the possibility to connect their activity and clothing to the local weather being emphasized as valuable. The users believe that they can see themselves using ClimApp in cases of extreme weather approaching (Table 2, statement 15), but for everyday use only about half see it as a part of their routine (Table 2, statement 14) which can still be considered a success as integrating such a system into a person's daily life rather substantial as they found it meaningful[127,137]. The field test was only performed in cold conditions and the overall environments were not close to extreme which can impact the perception of relevancy if the prediction did not suggest a change in clothing or activity compared to the users expected input. This ties in with the first pillar of EW4All about risk knowledge, where in this case the users may be familiar with the exposure.

Table 2. The statement results from the field test survey where the participants could select options between strongly disagree to strongly agree. The significance is evaluated using a chi-square test when comparing the combined agreeing options to the disagreeing options, the significance symbols (in brackets) are interpreted as; *** for p ≤ 0.001, ** for P ≤ 0.01, * for P ≤ 0.05, - for P ≈ 0.05 and ns for P > 0.05.

	Strongly disagree	Partly disagree	Neither agree nor disagree	Partly agree	Strongly agree	Median agree or disagree (Significance)
1. It was easy to orient myself in ClimApp.	3 (7.9%)	5 (13.2%)	5 (13.2%)	21 (55.3%)	4 (10.5%)	Agree (**)
2. I understood what ClimApp's prediction of thermal stress meant.	1 (2.6%)	3 (7.9%)	4 (10.5%)	16 (42.1%)	14 (36.8%)	Agree (***)
3. I understood what the different levels for clothing meant.	0 (0.0%)	4 (10.5%)	1 (2.6%)	27 (71.1%)	6 (15.8%)	Agree (***)
4. I understood what the different levels for activity meant.	0 (0.0%)	0 (0.0%)	2 (5.3%)	22 (57.9%)	14 (36.8%)	Agree (***)
5. I believe I received sufficient information on what the functions in ClimApp did in order to use ClimApp.	0 (0.0%)	3 (7.9%)	9 (23.7%)	13 (34.2%)	13 (34.2%)	Agree (***)
6. I want to be able to make more detailed choices and receive more detailed information from ClimApp. (Neither agree nor disagree means that current level is desirable.)	1 (2.6%)	5 (13.2%)	12 (31.6%)	15 (39.5%)	5 (13.2%)	Agree (**)
7. I quickly found the function I was looking for.	2 (5.3%)	9 (23.7%)	5 (13.2%)	16 (42.1%)	6 (15.8%)	Agree (-)
8. I found and used forecast without any problems.	0 (0.0%)	6 (15.8%)	0 (0.0%)	11 (28.9%)	21 (55.3%)	Agree (***)
9. I found and changed activity and clothing levels without any problems.	1 (2.6%)	2 (5.3%)	0 (0.0%)	13 (34.2%)	22 (57.9%)	Agree (***)
10. I found and used the indoor mode without any problems.	4 (10.5%)	9 (23.7%)	7 (18.4%)	9 (23.7%)	9 (23.7%)	Neither agree nor disagree (ns)
11. I found and used custom location without any problems.	1 (2.6%)	6 (15.8%)	4 (10.5%)	12 (31.6%)	15 (39.5%)	Agree (***)
12. I believe it was easy to find the advice and recommendations in ClimApp.	2 (5.3%)	3 (7.9%)	7 (18.4%)	16 (42.1%)	10 (26.3%)	Agree (***)
13. I believe it was easy to understand the advice and recommendations in ClimApp.	2 (5.3%)	1 (2.6%)	8 (21.1%)	13 (34.2%)	14 (36.8%)	Agree (***)
14. I can see myself using ClimApp on a daily basis.	0 (0.0%)	10 (26.3%)	12 (31.6%)	12 (31.6%)	4 (10.5%)	Neither agree nor disagree (ns)
15. I can see myself using ClimApp during extreme weather events.	0 (0.0%)	2 (5.3%)	8 (21.1%)	11 (28.9%)	17 (44.7%)	Agree (***)

One central aspect of the ClimApp tool is the information level, where the usability test participants felt mistargeted and bombarded with details and information that they did not know how to utilize properly. Suggestions throughout the tests were to further simplify the information presented and perhaps include an expert mode where detailed and advanced information could be presented to experienced users. By hiding the complex details, the risk of alienating users is reduced[179]. This is in line with the third EW4All pillar that communication must be effective and appropriate for the user to act upon without second guessing the credibility and relevancy. The test participants felt that they understood the variables being used in the app and that they could make use of the prediction index, which is the second pillar of EW4All, monitoring appropriate variables. Several participants highlighted that they were unfamiliar and did not truly understand what clo meant, which is the unit for clothing insulation which could be better explained or hidden from the user. However, users with knowledge how to interpret the information may benefit from being able to adjust estimates by the tool to better match their actual properties. The output of ClimApp is not only the ClimApp index, but also coupled warnings and advice on how to act accordingly based on the predicted exposure. This is related to the fourth pillar of EW4All where the capacity of the recipient to act upon the issued warning is detrimental for the outcome. By providing the user with simple text and images to promote recognition of the risk in line with the usability heuristics, communication can be effective and reduce the risk of a language barrier. The usability test allowed an analysis of the operational level interaction whereas the field test provided situated data where the intended real context of use support the feasibility of the ClimApp as a personalized THWS[125].

Paper III - ClimApp index performance

The field test collected performance data of ClimApp in terms of the perceived thermal sensation of the participants and the corresponding predicted ClimApp index and UTCI. The average weather conditions during the field tests can be seen in Table 3. The tests were collected during late winter in Sweden so it can be assumed that the participants were acclimatized to the cold.

Table 3. The mean environmental conditions during the field test.

	Air temperature (C°)	Relative Humidity (%)	Air velocity (m/s)	Wind Chill Temperature (C°)
Mean	1.4	74.9	4.7	-2.2
SD	5.6	16.1	2.6	6.5
Range	-13.0 – 10.0	46.0 – 100.0	0.0 – 12.0	-19.1 – 10.0

The participants were asked to submit their chosen clothing level and activity level in ClimApp as well as an overview of the clothing worn, and a description of the activity performed during the exposure to make sure they had selected the most appropriate input. Table 4 displays the input data that were confirmed by the author of this thesis and the first interesting results from the study.

Table 4. The personal input data from the outdoor field test.

	ClimApp activity (W/m²)	UTCI activity (W/m²)	ClimApp clothing (clo)	UTCI clothing (clo)
Mean	148.2	135	1.6	1.3
SD	30.6	-	0.5	0.1
Range	57 – 260	-	0.5 – 2.5	1.1 – 1.5

We can see from Table 4 that both the selected activity and clothing in ClimApp were higher than that of the UTCI model. The UTCI model has a fixed activity level. The clothing insulation worn is calculated based on the air temperature[180]. These findings are valuable in connection to the UTCI output in Table 5 where UTCI appears to overpredict the cold sensation.

Table 5. The RMSD and SD of the perceived thermal sensation, predicted ClimApp index and UTCI results from the field test.

	Perceived thermal sensation	ClimApp	UTCI
RMSD		1.05	15.65
Mean	0.27	0.39	-1.48
SD	1.31	0.84	0.93
Range	-3 - 2	-3 - 2	-3 - 0

On average the transformed UTCI was -1.48 indicating slight cold stress, when applying the original UTCI results the average was -2.13°C which on the original UTCI scale correlates to moderate cold stress while the average participant perceived their thermal sensation slightly on the warmer side of a thermoneutral state. It is feasible to assume that more evaluations are required but these results suggest that the clothing model may be underestimating the clothing worn in this environment. The model expects users to underdress, but our findings suggest that the participants wore 23% more insulation than what UTCI calculated. As the participants were on the warm side, roughly 15% higher insulation than calculated by UTCI would be more appropriate according to our findings (1.5 clo). Similarly, the activity level of UTCI is set to 135 W/m^2 whereas our participants most often selected 150 W/m^2 which could be the reason why UTCI overpredicted the cold sensation as the participants opted for the higher activity load.

When evaluating the model predictions, the ClimApp index RMSD is lower than the Perception SD while the UTCI RMSD is far above the Perception SD, indicating that the ClimApp index was valid in predicting the participant sensation in this field test[132]. The study further evaluated if any significant difference could be found when comparing males to females, but no significant results could be found.

These results solidify the feasibility of the ClimApp concept, where the users are able to not only interpret and interact with the system, but also obtain accurate warnings highlighting that the second pillar, monitoring the appropriate variables, is fulfilled. From the usability study it was also found that the participants understood what the thermal stress prediction meant (Table 2, statement 2) and how to interpret the advice and recommendations (Table 2, statement 13), so the third pillar, warning communication, is realized. The advice and recommendations provided by ClimApp is intended to not only mitigate the immediate risk of the exposure, but also provide the user with knowledge about the risk and how to properly react to the risk which are the two remaining pillars. By providing effective thermal stress mitigation strategies depending on the situation, the individual can effectively react to the risk and improve their response capacity[181].

The study by Casanueva et al.[100] found that most HHWS in Europe rely on variations of T_a although several are including indices such as Perceived Temperature. UTCI has been proved to accurately indicate the mortality rates in Europe in both extreme cold[182,183] and extreme heat[183,184,185] periods. In cold regions the commonly included index is the WCT which combines T_a and v_a which adds a layer of information but without taking into account physiological responses, mortality and morbidity assessment may fall short. One example is the combination of low temperatures and low humidity which is associated with increased occurrences of respiratory tract infections[186]. By further extending national weather services or warning systems commonly developed by the national weather service to include UTCI or other feasible models to evaluate thermal stress in both heat and cold then the societal resilience could increase.

Paper IV - Regional thermal climate and health warnings

Paper IV explored the impact of ENSO on regional climate and health to expand the possibility of monitoring the risk on a larger scale to tie in with EW4All in Figure 4 where large-scale monitoring can be downscaled to local warning systems. When it comes to monitoring the variables such as the weather forecast, most national weather reports are based on regional models that are fed with boundary conditions from global models. ENSO, like other teleconnections, are driven by the atmospheric and hydrological cycles which affect the regional climate depending on the state of the teleconnection. The first results from the study were that both UTCI and T_a has increased between 1990-2019, particularly $T_{a,\max}$ which can be seen in Figure 20. The data is based on reanalysis data and the greatest increases are found in high-altitude regions which are very complex and introduce uncertainties as weather stations are far apart compared to the lowlands which decrease the spatial accuracy in this region. However, by evaluating the difference between UTCI and T_a the combination of the non-evaluated climatic parameters of humidity, air velocity, and solar radiation mitigates heat stress as the UTCI increase is lower than the T_a increase. The Manipur province of India and northwestern Myanmar which borders the Manipur province show a great increase in $T_{a,\max}$ which emphasises increasing risks of heat stress which is not prominent in $UTCI_{\max}$. $UTCI_{\min}$ and $T_{a,\min}$ show a large decrease in most of the western half of China, southern half of Japan, and India while most of the region sees slight increases. These increases in min temperatures can result in reduced capacity for recuperation of heat stress. The difference between the highest and lowest UTCI and T_a was evaluated for a 3-day, 5-day, and 7-day window similar to the DTR concept and it was found that most of the region found a decreasing temperature range except for the Manipur Province, Myanmar, parts of southeastern China, and easter Inner Mongolia where the temperature range increase. An increase in the temperature range can indicate high temperature shifts leading to negative health impacts while a decrease in the temperature range combined with the knowledge that UTCI and T_a is increasing may highlight that recuperation possibilities are decreasing while the exposure to heat increases.

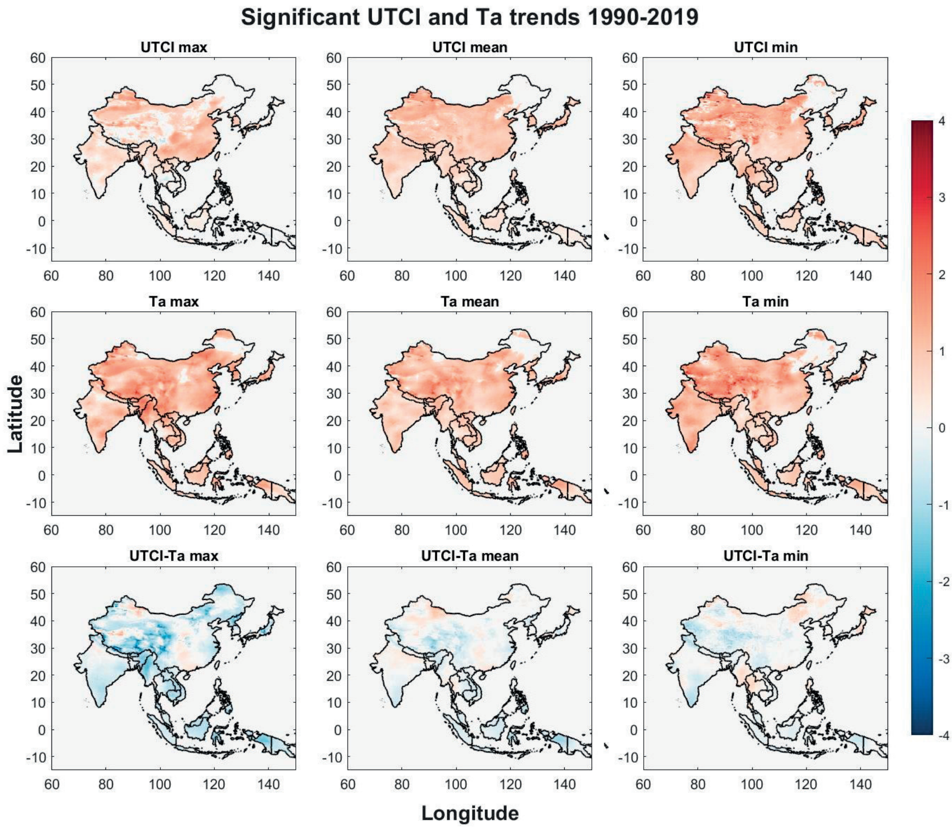


Figure 20. The significant UTCI (top row) and T_a (middle row) trends between 1990-2019 with the difference calculated at the bottom row. The left column represents max values ($UTCI_{max}$ and $T_{a,max}$), middle column mean values ($UCTI_{mean}$ and $T_{a,mean}$), and right column min values ($UTCI_{min}$ and $T_{a,min}$). The coloured scale represent absolute temperature change for UTCI and T_a during the study period.

The seasonal influence of El Niño on UTCI can be seen in Figure 21 and La Niña on UTCI in Figure 22. These results are useful when developing long lead time warning systems as regular forecast accuracy decrease sharply after only a few days. By understanding and monitoring the correct variables, the accuracy and credibility of the system is improved. Based on the findings, El Niño and La Niña increases UTCI in eastern Inner Mongolia during winter, particularly for El Niño meaning that winters during years with the normal phase can be expected to be the coldest.

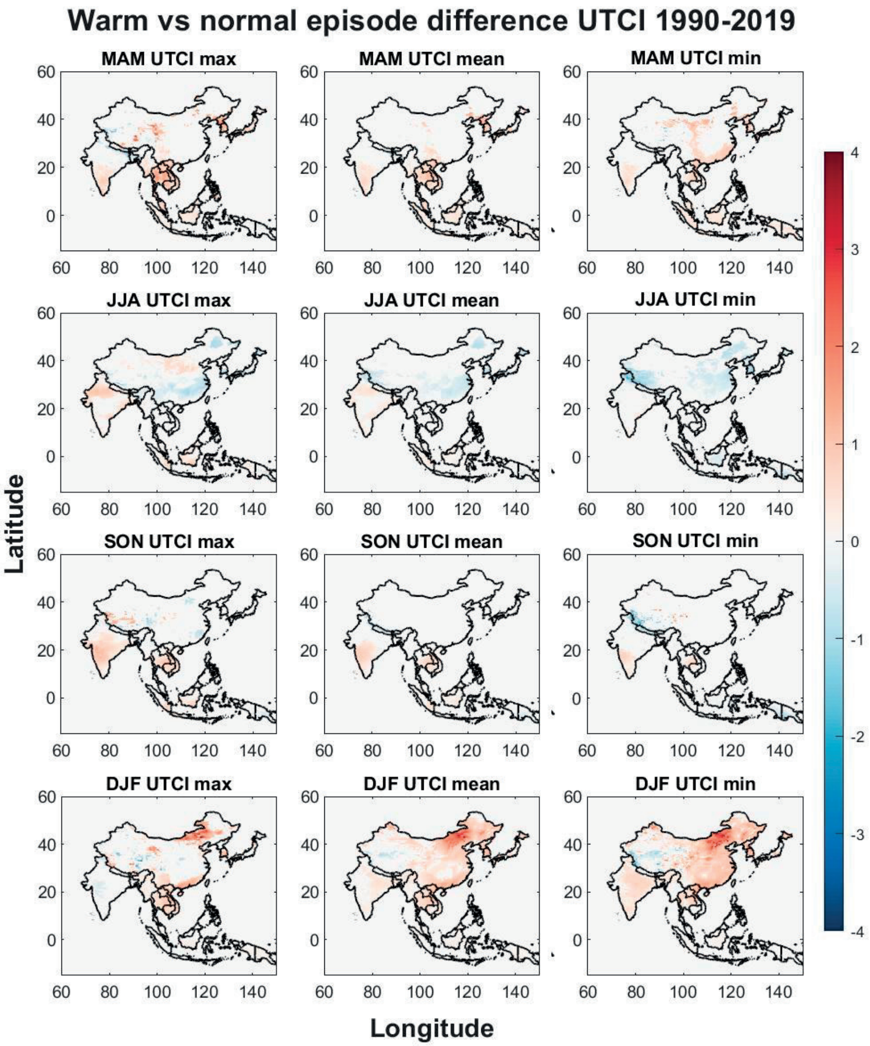


Figure 21. The significant El Niño influence for each season (rows) for max (left column), mean (middle column), and min values (right column). The seasons are MAM: March-April-May, JJA: June-July-August, SON: September-October-November and DJF: December-January-February.

During spring, El Niño is associated with an increase of UTCI in northern Thailand which for La Niña is associated with a decrease. The study region in general follows this trend with slight increases during El Niño spring and slight decrease for La Niña spring except in southern Tibet for the latter where increases can be seen.

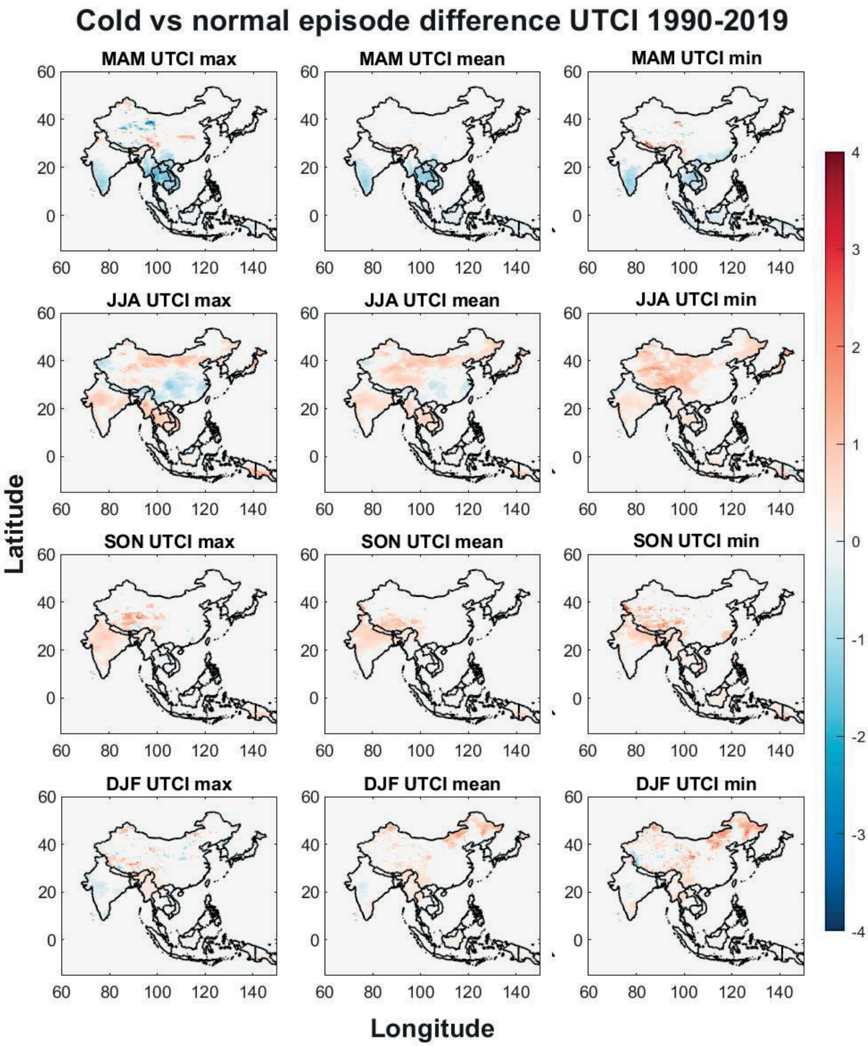


Figure 22. The significant La Niña influence for each season (rows) for max (left column), mean (middle column), and min values (right column). The seasons are MAM: March-April-May, JJA: June-July-August, SON: September-October-November and DJF: December-January-February.

The direct association between La Niña and UTCI is primarily increasing during summer, autumn, and winter apart from southeastern China which is decreasing similar to spring as described previously. These findings highlight that a few regions can benefit greatly by a warning system taking the seasonal influence of ENSO into account. The Belmont AWARD-APR project developed a S2S lead time warning system to predict diarrheal outbreak risks based on the weather station data and the phase of ENSO. Similarly, a warning system can be developed based on historical data of hospital admissions based on thermal stress, UTCI, and ENSO phases to forecast regional risks of thermal stress. Such large-scale warning system with a longer lead time can be applied on a national level similar to the Belmont AWARD-APR warning system which follows the EW4All concept (Figure 3) with downscaling of global monitoring into national, regional, or local systems.

Conclusions and the future of THWS

Coming back to the pillars of a warning system, research and observations will further improve the knowledge basis regarding thermal stress mortality and morbidity. The ClimApp concept is supported by all four pillars and the ClimApp EWS promotes user understanding of the risk by identifying and portraying the risk and provides advice how to reduce the risk. By detecting the association between thermal stress and phenomena such as ENSO, novel monitoring systems may provide feasible options to forecast the thermal stress risk level. Heat waves are becoming more frequent and more intense in most parts of the world, HHWS with sufficient lead time will ensure that the warning can be communicated in good time. The integration of thermal indices applying our understanding of the heat balance will provide comprehensive assessments that the air temperature alone cannot do. The air temperature is commonly applied in epidemiological studies as a proxy for the environmental factors, but it is the belief of this author that further research should be made to investigate the correlation between thermal indices and morbidity/mortality rates. ClimApp was proposed to be particularly usable during extreme events when the user requires effective measures to reduce the risks. The difficulty of the ClimApp tools lies in the cognitive load required by the user, the benefits of using the tool must be great to encourage user time investment. The conventional weather forecast allows a format acceptable by the user, by further integration of human thermal models the forecasts can supply an additional layer of information such as UTCI or a set of representative ClimApp profiles to the user without cognitive overload.

As mentioned earlier, the credibility of the system is important to ensure that the warning and recommendations are accepted and acted upon. Particularly, incorporating the advice and recommendations with the warnings will allow the recipients to increase their preparedness and improve the resilience of the system. DWD provides additional output from the Klima-Michel model that targets the elderly where a senior reference person is used in the calculations[187] which allows for further improving the resilience of the elderly where fewer hospital admissions in the heat has been observed[188]. By further incorporating the vulnerable groups into THWS, with the examples of the seniors in the DWD HHWS[187], outdoor workers by HEAT-SHEILD[60] and maternal health in Horizon-HIGH[159], societal resilience and wellbeing can be improved which is in line with the third SDG, Good health and wellbeing[24]. A collaboration between the World Health Organization (WHO) and WMO aims to advance climate and health sciences and services in order to improve resilience towards climate change, extreme weather, environmental hazards etc[189]. This collaboration aims to deliver innovative approaches and advancing integrated health services which is well in line with the EW4All and this thesis work. It also follows the SDG 13 where parts of the target is to improve education, awareness, capacity, impact reduction and early warning (target 13.3)[190].

Our disconnection to the outdoor environment risks getting further detached as we spend most of our time indoors[191], in many cases in air-conditioned environments which cause us to become unacclimatized to our surroundings. In particular, the elderly are known to spend most of their time indoors[192] which reduce their physiological capacity to thermoregulate accordingly. This combined with the reduced thermophysiological response capacity by aging put them at additional risk making them vulnerable to thermal stress hazards such as heat waves[193]. Therefore, another approach to promote elderly resilience could be to develop indoor thermal stress models focusing on elder care homes. The recently initiated project HEATWISE Sweden aims to increase our knowledge of heat exposure indoors based on the outdoor environment, the influence of building characteristics, and to define an acceptable upper limit of indoor air temperature[194]. To develop and maintain an effective THWS, the recipient must have proper knowledge about the risk and understanding of how to respond to the risk. By raising public awareness of the risk and the health-protective behaviours[195], a THWS can be expected to become increasingly effective.

Future research

Based on the findings in this thesis, several areas require further research. In order to improve societal resilience, human health and well-being, new products can be developed which builds on existing or newfound associations between thermal exposure and health.

- Concepts like ClimApp require extensive testing in varied environments to evaluate a universal solution. Rigorous testing combined with a simple feedback system can detect areas of improvement.
- The validity ranges of underlying models require further testing in ClimApp in order to develop specialized settings such as firefighting or biochemical protection in extreme environments where heavy work in protective gear is not covered by human thermal models.
- The link between outdoor environment on indoor thermal stress and wellbeing will benefit from advancing products and monitoring systems for indoor environments.
- Workplace targeted solutions could provide effective tools to mitigate thermal stress such as a construction site profile or an incident tool to promote certain turnout gear depending on the task and weather conditions.

- Inclusion of wearables to monitoring systems to improve personalized thermal stress management.
- User needs in concepts like ClimApp require further attention were desired input such as clothing wardrobe and activity selection are crucial for the output accuracy.
- Applying machine learning and/or AI to improve prediction models and user input experience which requires large sets of data.
- Further development of both local- and large-scale monitoring systems that incorporate physiological responses would benefit societies to improve risk assessment.
- New and available services, like ClimApp, can benefit from adapting personas such as the DWD senior profile to obtain vulnerable group predictions for targeted warning systems.

References

1. NOAA. Origin of Wind 2023 [updated 2023-04-03; accessed 21 March 2024]. Available from: https://www.noaa.gov/jetstream/synoptic/origin-of-wind.
2. ISO. Ergonomics of the Thermal Environment — Assessment of heat stress using the WBGT (wet bulb globe temperature) index. ISO 7243. Geneva: ISO; 2017.
3. Pörtner HO, Roberts DC, Adams H, Adler C, Aldunce P, Ali E, et al. Climate change 2022: impacts, adaptation and vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC; 2022.
4. ISO. Ergonomics of the Thermal Environment — vocabulary and symbols. ISO 13731. Geneva, Switzerland: ISO; 2001.
5. Parsons K. Human thermal environments: the effects of hot, moderate, and cold environments on human health, comfort, and performance: CRC press; 2014.
6. Masson-Delmotte V, Zhai P, Pirani A, Connors SL, Péan C, Berger S, et al. Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Reportof the Intergovernmental Panel on Climate Change. Cambridge University Press.: IPCC; 2021.
7. ISO. Ergonomics of the Thermal Environment — Estimation of thermal insulation and water vapour resistance of a clothing ensemble. ISO 9920. Geneva: ISO; 2007.
8. Rogers Y, Sharp H, Preece J. Interaction design: beyond human-computer interaction: John Wiley & Sons; 2011.
9. Houghton JT, Jenkins G, Ephraums J. Climate change: the IPCC scientific assessment. Intergovernmental Panel on Climate Change. World Meteorological Organization, United Nations Environmental Programme Cambridge Univ Press. 1990.
10. Hasan J, Goldbloom-Helzner D, Ichida A, Rouse T, Gibson M. Technologies and techniques for early warning systems to monitor and evaluate drinking water quality: A state-of-the-art review. Environmental Protection Agency Washington DC Office of Water: Washington, DC, USA. 2005.
11. Koppe C, Kovats S, Jendritzky G, Menne B. Heat-waves: risks and responses: World Health Organization. Regional Office for Europe; 2004.
12. White-Newsome JL, Sánchez BN, Jolliet O, Zhang Z, Parker EA, Dvonch JT, et al. Climate change and health: indoor heat exposure in vulnerable populations. Environmental research. 2012;112:20-7.
13. Tarsi K, Tuff T. Introduction to population demographics. Nature Education Knowledge 3 (11): 3. 2012.
14. Rogers M, Rogers M. The definition and measurement of productivity: Melbourne Institute of Applied Economic and Social Research Melbourne, Australia; 1998.

15. UNDP. Sustainable Development Goals 2024 [accessed 5 May 2024]. Available from: https://www.undp.org/sustainable-development-goals.
16. C3S. Demonstrating heat stress in European cities: Copernicus Climate Change Service; n.d. [accessed 2 May 2024]. Available from: https://climate.copernicus.eu/demonstrating-heat-stress-european-cities.
17. ISO. Ergonomics of human-system interaction. Part 11: Usability: Definitions and concepts. ISO 9241-11. Geneva, Switzerland: ISO; 2018.
18. Armstrong McKay DI, Staal A, Abrams JF, Winkelmann R, Sakschewski B, Loriani S, et al. Exceeding 1.5 C global warming could trigger multiple climate tipping points. Science. 2022;377(6611):eabn7950.
19. Lenton TM, Held H, Kriegler E, Hall JW, Lucht W, Rahmstorf S, et al. Tipping elements in the Earth's climate system. Proceedings of the national Academy of Sciences. 2008;105(6):1786-93.
20. Lenton TM, Rockström J, Gaffney O, Rahmstorf S, Richardson K, Steffen W, et al. Climate tipping points—too risky to bet against. Nature. 2019;575(7784):592-5.
21. WMO. Early Warnings For All - The UN Global Warning Initiative for the Implementation of Climate Adaptation. Geneva: World Meteorological Organization; 2023.
22. Basu R, Dominici F, Samet JM. Temperature and mortality among the elderly in the United States: a comparison of epidemiologic methods. Epidemiology. 2005:58-66.
23. Reuters T. Senior Swiss women prevail in landmark climate case at Europe's human rights court: CBC; 2024 [accessed 9th of April 2024]. Available from: https://www.cbc.ca/news/world/european-human-rights-court-climate-1.7167866.
24. UN. 3 Ensure healthy lives and promote well-being for all at all ages: United Nations Department of Economic and Social Affairs; n.d. [accessed 21 March 2024]. Available from: https://sdgs.un.org/goals/goal3.
25. Masselot P, Mistry M, Vanoli J, Schneider R, Iungman T, Garcia-Leon D, et al. Excess mortality attributed to heat and cold: a health impact assessment study in 854 cities in Europe. The Lancet Planetary Health. 2023;7(4):e271-e81.
26. Kingma B, Steenhoff H, Toftum J, Daanen H, Folkerts M, Gerrett N, et al. Climapp—integrating personal factors with weather forecasts for individualised warning and guidance on thermal stress. International Journal of Environmental Research and Public Health. 2021;18(21):11317.
27. Hansen J, Sato M. Regional climate change and national responsibilities. Environmental Research Letters. 2016;11(3):034009.
28. Mora C, Dousset B, Caldwell IR, Powell FE, Geronimo RC, Bielecki CR, et al. Global risk of deadly heat. Nature Climate Change. 2017;7(7):501.
29. ILO. Ensuring safety and health at work in a changing climate. Geneva: International Labour Office: International Labour Organization; 2024.
30. Dunne JP, Stouffer RJ, John JG. Reductions in labour capacity from heat stress under climate warming. Nature Climate Change. 2013;3(6):563.

31. Kjellstrom T, Lemke B, Otto M. Climate conditions, workplace heat and occupational health in South-East Asia in the context of climate change. WHO South-East Asia journal of public health. 2017;6(2):15-21.
32. Kjellström E, Nikulin G, Strandberg G, Christensen OB, Jacob D, Keuler K, et al. European climate change at global mean temperature increases of 1.5 and 2 °C above pre-industrial conditions as simulated by the EURO-CORDEX regional climate models. Earth System Dynamics. 2018;9(2):459-78.
33. Forzieri G, Cescatti A, e Silva FB, Feyen L. Increasing risk over time of weather-related hazards to the European population: a data-driven prognostic study. The Lancet Planetary Health. 2017;1(5):e200-e8.
34. Kjellström E, Nikulin G, Strandberg G, Christensen OB, Jacob D, Keuler K, et al. European climate change at global mean temperature increases of 1.5 and 2 degrees C above pre-industrial conditions as simulated by the EURO-CORDEX regional climate models. Earth System Dynamics. 2018;9(2):459-78.
35. Karmalkar AV, Bradley RS. Consequences of Global Warming of 1.5 degrees C and 2 degrees C for Regional Temperature and Precipitation Changes in the Contiguous United States. PLoS One. 2017;12(1):e0168697.
36. Wang F, Zhang J. Heat Stress Response to National-Committed Emission Reductions under the Paris Agreement. International journal of environmental research and public health. 2019;16(12):2202.
37. Moda HM, Minhas A. Impacts of climate change on outdoor workers and their safety: some research priorities. International journal of environmental research and public health. 2019;16(18):3458.
38. ECMWF. How close are we to reaching a global warming of 1.5˚C? 2021 [accessed 5 May 2021]. Available from: https://cds.climate.copernicus.eu/cdsapp#!/software/app-c3s-global-temperature-trend-monitor?tab=app.
39. Mellouki A, Wallington T, Chen J. Atmospheric chemistry of oxygenated volatile organic compounds: impacts on air quality and climate. Chemical reviews. 2015;115(10):3984-4014.
40. Jacob DJ, Winner DA. Effect of climate change on air quality. Atmospheric environment. 2009;43(1):51-63.
41. Ribeiro I, Valente J, Amorim JH, Miranda AI, Lopes M, Borrego C, et al. Air quality modelling and its applications. Current environmental issues and challenges. 2014:45-56.
42. WMO. State of Climate Services: Health. Geneva: World Meteorological Organization; 2023.
43. Hollnagel E. The four cornerstones of resilience engineering. Resilience Engineering Perspectives, Volume 2: CRC Press; 2016. p. 139-56.
44. Kotharkar R, Ghosh A. Progress in extreme heat management and warning systems: A systematic review of heat-health action plans (1995-2020). Sustainable Cities and Society. 2022;76:103487.

45. Wu Y, Wang X, Wu J, Wang R, Yang S. Performance of heat-health warning systems in Shanghai evaluated by using local heat-related illness data. Science of the total environment. 2020;715:136883.
46. Ioannou LG, Tsoutsoubi L, Mantzios K, Gkikas G, Piil JF, Dinas PC, et al. The impacts of sun exposure on worker physiology and cognition: multi-country evidence and interventions. International Journal of Environmental Research and Public Health. 2021;18(14):7698.
47. Ioannou LG, Mantzios K, Tsoutsoubi L, Nintou E, Vliora M, Gkiata P, et al. Occupational heat stress: multi-country observations and interventions. International journal of environmental research and public health. 2021;18(12):6303.
48. Piil JF, Lundbye-Jensen J, Christiansen L, Ioannou L, Tsoutsoubi L, Dallas CN, et al. High prevalence of hypohydration in occupations with heat stress—Perspectives for performance in combined cognitive and motor tasks. PLoS One. 2018;13(10):e0205321.
49. Piil JF, Christiansen L, Morris NB, Mikkelsen CJ, Ioannou LG, Flouris AD, et al. Direct exposure of the head to solar heat radiation impairs motor-cognitive performance. Scientific reports. 2020;10(1):1-10.
50. Toloo G, FitzGerald G, Aitken P, Verrall K, Tong S. Evaluating the effectiveness of heat warning systems: systematic review of epidemiological evidence. International journal of public health. 2013;58:667-81.
51. Ebi KL, Teisberg TJ, Kalkstein LS, Robinson L, Weiher RF. Heat watch/warning systems save lives: estimated costs and benefits for Philadelphia 1995–98. Bulletin of the American Meteorological Society. 2004;85(8):1067-74.
52. Jamali L. lilyjamali.com. 2012. [cited 2024]. Available from: https://www.lilyjamali.com/radio/reporting-abroad/south-asia/the-maldives/.
53. Nielsen J, editor Enhancing the explanatory power of usability heuristics. Proceedings of the SIGCHI conference on Human Factors in Computing Systems; 1994.
54. Rausand M. Risk assessment: theory, methods, and applications: John Wiley & Sons; 2013.
55. Basarin B, Lukić T, Matzarakis A. Review of biometeorology of heatwaves and warm extremes in Europe. Atmosphere. 2020;11(12):1276.
56. Lindell MK, Perry RW. The protective action decision model: Theoretical modifications and additional evidence. Risk Analysis: An International Journal. 2012;32(4):616-32.
57. Xu X, Rioux TP, Gonzalez J, Hansen EO, Castellani JW, Santee WR, et al. A digital tool for prevention and management of cold weather injuries—Cold Weather Ensemble Decision Aid (CoWEDA). International Journal of Biometeorology. 2021:1-12.
58. Liljegren JC, Carhart RA, Lawday P, Tschopp S, Sharp R. Modeling the wet bulb globe temperature using standard meteorological measurements. J Occup Environ Hyg. 2008;5(10):645-55.
59. Lemke B, Kjellstrom T. Calculating workplace WBGT from meteorological data: a tool for climate change assessment. Industrial Health. 2012;50(4):267-78.

60. Morabito M, Messeri A, Noti P, Casanueva A, Crisci A, Kotlarski S, et al. An Occupational Heat–Health Warning System for Europe: The HEAT-SHIELD Platform. International journal of environmental research and public health. 2019;16(16):2890.
61. Ioannou LG, Ciuha U, Fisher JT, Tsoutsoubi L, Tobita K, Bonell A, et al. Novel technological advances to protect people who exercise or work in thermally stressful conditions: A transition to more personalized guidelines. Applied Sciences. 2023;13(15):8561.
62. Miller V, Bates G, Schneider JD, Thomsen J. Self-pacing as a protective mechanism against the effects of heat stress. Annals of occupational hygiene. 2011;55(5):548-55.
63. Spengler JD, Sexton K. Indoor air pollution: a public health perspective. Science. 1983;221(4605):9-17.
64. Golden JS. The built environment induced urban heat island effect in rapidly urbanizing arid regions–a sustainable urban engineering complexity. Environmental Sciences. 2004;1(4):321-49.
65. Tan J, Zheng Y, Tang X, Guo C, Li L, Song G, et al. The urban heat island and its impact on heat waves and human health in Shanghai. International journal of biometeorology. 2010;54(1):75-84.
66. Feyisa GL, Dons K, Meilby H. Efficiency of parks in mitigating urban heat island effect: An example from Addis Ababa. Landscape and Urban Planning. 2014;123:87-95.
67. Steeneveld GJ, Koopmans S, Heusinkveld BG, Theeuwes NE. Refreshing the role of open water surfaces on mitigating the maximum urban heat island effect. Landscape and Urban Planning. 2014;121:92-6.
68. Susca T, Gaffin SR, Dell'osso GR. Positive effects of vegetation: urban heat island and green roofs. Environ Pollut. 2011;159(8-9):2119-26.
69. Kuklane K, Lundgren K, Gao C, Löndahl J, Hornyanszky ED, Östergren P-O, et al. Ebola: improving the design of protective clothing for emergency workers allows them to better cope with heat stress and help to contain the epidemic. Annals of Occupational Hygiene. 2015;59(2):258-61.
70. Lundgren K, Kuklane K, Venugopal V. Occupational heat stress and associated productivity loss estimation using the PHS model (ISO 7933): a case study from workplaces in Chennai, India. Glob Health Action. 2014;7:25283.
71. Kuklane K, Eggeling J, Kemmeren M, Heus R. Local effects of printed logos and reflective striping fixed to firefighter clothing material packages under low radiation exposure. Industrial health. 2023;61(5):357-67.
72. Kuklane K, Eggeling J, Kemmeren M, Heus R. A database of static thermal insulation and evaporative resistance values of Dutch firefighter clothing items and ensembles. Biology. 2022;11(12):1813.
73. Petersson J, Kuklane K, Gao C. Is there a need to integrate human thermal models with weather forecasts to predict thermal stress? International journal of environmental research and public health. 2019;16(22):4586.
74. Kjellstrom T. Climate change, direct heat exposure, health and well-being in low and middle-income countries. Glob Health Action. 2009;2.

75. Dell M, Jones BF, Olken BA. What do we learn from the weather? The new climate-economy literature. Journal of Economic literature. 2014;52(3):740-98.
76. Seppanen O, Fisk WJ, Faulkner D, editors. Cost benefit analysis of the night-time ventilative cooling in office building. 7th International Conference—Healthy Buildings 2003; 2003 7-11 December 2003; National University of Singapore. Singapore2003.
77. Lõhmus M. Possible biological mechanisms linking mental health and heat—a contemplative review. International journal of environmental research and public health. 2018;15(7):1515.
78. Hajat S, Vardoulakis S, Heaviside C, Eggen B. Climate change effects on human health: projections of temperature-related mortality for the UK during the 2020s, 2050s and 2080s. J Epidemiol Community Health. 2014;68(7):641-8.
79. Hansson E, Glaser J, Jakobsson K, Weiss I, Wesseling C, Lucas RA, et al. Pathophysiological mechanisms by which heat stress potentially induces kidney inflammation and chronic kidney disease in sugarcane workers. Nutrients. 2020;12(6):1639.
80. Lee JK, Nio AQ, Ang WH, Law LY, Lim CL. Effects of ingesting a sports drink during exercise and recovery on subsequent endurance capacity. European Journal of Sport Science. 2011;11(2):77-86.
81. Byrne C, Owen C, Cosnefroy A, Lee JKW. Self-paced exercise performance in the heat after pre-exercise cold-fluid ingestion. National Athletic Trainers' Association, Inc; 2011. p. 592-9.
82. Lee JK, Shirreffs SM, Maughan RJ. Cold drink ingestion improves exercise endurance capacity in the heat. Medicine & Science in Sports & Exercise. 2008;40(9):1637-44.
83. Cheng J, Xu Z, Zhu R, Wang X, Jin L, Song J, et al. Impact of diurnal temperature range on human health: a systematic review. International journal of biometeorology. 2014;58:2011-24.
84. Braganza K, Karoly DJ, Arblaster JM. Diurnal temperature range as an index of global climate change during the twentieth century. Geophysical research letters. 2004;31(13).
85. Lee W, Bell ML, Gasparrini A, Armstrong BG, Sera F, Hwang S, et al. Mortality burden of diurnal temperature range and its temporal changes: a multi-country study. Environment international. 2018;110:123-30.
86. NOAA. Global Atmospheric Circulations 2023 [updated 2023-10-03; accessed 21 March 2024]. Available from: https://www.noaa.gov/jetstream/global/global-atmospheric-circulations.
87. NOAA. The Jet Stream 2023 [updated 2023-09-20; accessed 21 March 2024]. Available from: https://www.noaa.gov/jetstream/global/jet-stream.
88. Ahmed M, Alam MS, Yousuf AHM, Islam M. A long-term trend in precipitation of different spatial regions of Bangladesh and its teleconnections with El Niño/Southern Oscillation and Indian Ocean Dipole. Theoretical and Applied Climatology. 2017;129(1):473-86.

89. An D, Eggeling J, Zhang L, He H, Sapkota A, Wang Y-C, et al. Extreme precipitation patterns in the Asia–Pacific region and its correlation with El Niño-Southern Oscillation (ENSO). Scientific Reports. 2023;13(1):11068.
90. Tangang F, Juneng L, Aldrian E. Observed changes in extreme temperature and precipitation over Indonesia. International Journal of Climatology. 2017;37(4):1979-97.
91. NOAA. El Niño/Southern Oscillation (ENSO) 2023 [updated 2023-09-26; accessed 21 March 2024]. Available from: https://www.noaa.gov/jetstream/tropical/enso.
92. McGregor GR, Ebi K. El Niño Southern Oscillation (ENSO) and health: An overview for climate and health researchers. Atmosphere. 2018;9(7):282.
93. Troeger C, Colombara DV, Rao PC, Khalil IA, Brown A, Brewer TG, et al. Global disability-adjusted life-year estimates of long-term health burden and undernutrition attributable to diarrhoeal diseases in children younger than 5 years. The Lancet Global Health. 2018;6(3):e255-e69.
94. Beck H, McVicar T, Vergopolan N, Berg A, Lutsko N, Dufour A, et al. High-resolution (1 km) Köppen-Geiger maps for 1901–2099 based on constrained CMIP6 projections for seven socio-economic scenarios. Copernicus Meetings; 2023.
95. Eichna LW, Park CR, Nelson N, Horvath SM, Palmes ED. Thermal regulation during acclimatization in a hot, dry (desert type) environment. American Journal of Physiology-Legacy Content. 1950;163(3):585-97.
96. Hori S. Adaptation to heat. The Japanese journal of physiology. 1995;45(6):921-46.
97. Taylor NA. Human heat adaptation. Comprehensive Physiology. 2011;4(1):325-65.
98. Castellani JW, Young AJ. Human physiological responses to cold exposure: Acute responses and acclimatization to prolonged exposure. Autonomic Neuroscience. 2016;196:63-74.
99. Cannon B, Nedergaard J. Brown adipose tissue: function and physiological significance. Physiological reviews. 2004.
100. Casanueva A, Burgstall A, Kotlarski S, Messeri A, Morabito M, Flouris AD, et al. Overview of existing heat-health warning systems in Europe. International journal of environmental research and public health. 2019;16(15):2657.
101. Burgstall A, Casanueva A, Kotlarski S, Schwierz C. Heat warnings in Switzerland: reassessing the choice of the current heat stress index. International journal of environmental research and public health. 2019;16(15):2684.
102. Analitis A, Katsouyanni K, Biggeri A, Baccini M, Forsberg B, Bisanti L, et al. Effects of cold weather on mortality: results from 15 European cities within the PHEWE project. American journal of epidemiology. 2008;168(12):1397-408.
103. Ebi KL, Mills D. Winter mortality in a warming climate: a reassessment. Wiley Interdisciplinary Reviews: Climate Change. 2013;4(3):203-12.
104. Holmér I, Hassi J, Ikäheimo TM, Jaakkola JJ. Cold stress: effects on performance and health. NY, USA: John Wiley and Sons: New York; 2012. 1-26 p.
105. Jendritzky G, Sönning W, Swantes HJ. Ein objektives Bewertungsverfahren zur Beschreibung des thermischen Milieus in der Stadt-und Landschaftsplanung (" Klima-Michel-Modell"): Schroedel; 1979.

106. Jendritzky G. Methodik zur Räumlichen Bewertung der Thermischen Komponente im Bioklima des Menschen: Fortgeschriebenes Klima-Michel-Modell: na; 1990.
107. Fanger PO. Thermal comfort. Analysis and applications in environmental engineering. Thermal comfort Analysis and applications in environmental engineering. 1970.
108. Blazejczyk K, Epstein Y, Jendritzky G, Staiger H, Tinz B. Comparison of UTCI to selected thermal indices. International journal of biometeorology. 2012;56(3):515-35.
109. Di Napoli C, Barnard C, Prudhomme C, Pappenberger F. A heat health hazard index based on ECMWF data ECMWF.int: ECMWF; 2020 [accessed 26 February 2024]. Available from: https://www.ecmwf.int/en/newsletter/162/news/heat-health-hazard-index-based-ecmwf-data.
110. Xu X, Rioux T, Gonzalez J, Hansen E, Castellani J, Santee W, et al. Development of a cold injury prevention tool: The Cold Weather Ensemble Decision Aid (CoWEDA). TECHNICAL REPORT NO. T19-06. 2019.
111. hackAIR. hackAIR 2021 [accessed 23 May 2024]. Available from: https://www.hackair.eu/.
112. Kosmidis E, Syropoulou P, Tekes S, Schneider P, Spyromitros-Xioufis E, Riga M, et al. hackAIR: Towards raising awareness about air quality in Europe by developing a collective online platform. ISPRS International Journal of Geo-Information. 2018;7(5):187.
113. HeatWatch. HeatWatch: The University of Sydney; 2022 [accessed 23 May 2024]. Available from: https://heatwatch.sydney.edu.au/.
114. Ioannou LG, Mantzios K, Tsoutsoubi L, Notley SR, Dinas PC, Brearley M, et al. Indicators to assess physiological heat strain–Part 1: Systematic review. Temperature. 2022;9(3):227-62.
115. de Freitas CR, Grigorieva EA. A comprehensive catalogue and classification of human thermal climate indices. International journal of biometeorology. 2015;59(1):109-20.
116. ISO_7933. Ergonomics of the thermal environment -- Analytical determination and interpretation of heat stress using calculation of the predicted heat strain. ISO Geneva. 2004.
117. ISO. Ergonomics of the Thermal Environment — Determination and Interpretation of Cold Stress when Using Required Clothing Insulation (IREQ) and Local Cooling Effects. ISO 11079. Geneva: ISO; 2007.
118. Błażejczyk K, Jendritzky G, Bröde P, Fiala D, Havenith G, Epstein Y, et al. An introduction to the universal thermal climate index (UTCI). Geographia Polonica. 2013;86(1):5-10.
119. ISO. Ergonomics of the Thermal Environment — Analytical Determination and Interpretation of Thermal Comfort Using Calculation of the PMV and PPD Indices and Local Thermal Comfort Criteria. ISO 7730 Geneva: ISO; 2005.
120. Canada E. Wind Chill. In: Defence DoN, editor. Toronto2010.
121. Yaglou CP, Minard D. Prevention of heat casualties at Marine Corps training centers. HARVARD SCHOOL OF PUBLIC HEALTH BOSTON MA; 1956.

122. Davis FD. Perceived usefulness, perceived ease of use, and user acceptance of information technology. MIS quarterly. 1989:319-40.
123. Card SK. The psychology of human-computer interaction: Crc Press; 2018.
124. Norman DA. The Design of Everyday Things, 1988. Currency Doubleday, New York. 1990.
125. Suchman L, Suchman LA. Human-machine reconfigurations: Plans and situated actions: Cambridge university press; 2007.
126. Dourish P. Where the action is: the foundations of embodied interaction: MIT press; 2001.
127. Kaptelinin V, Nardi BA. Acting with technology: Activity theory and interaction design: MIT press; 2006.
128. Grant MJ, Booth A. A typology of reviews: an analysis of 14 review types and associated methodologies. Health information & libraries journal. 2009;26(2):91-108.
129. Booth A. Unpacking your literature search toolbox: on search styles and tactics. Health information and libraries journal. 2008;25(4):313.
130. Bates MJ. The design of browsing and berrypicking techniques for the online search interface. Online review. 1989;13(5):407-24.
131. Uttley L, Quintana DS, Montgomery P, Carroll C, Page MJ, Falzon L, et al. The problems with systematic reviews: a living systematic review. Journal of Clinical Epidemiology. 2023;156:30-41.
132. Eggeling J, Rydenfält C, Kingma B, Toftum J, Gao C. The usability of ClimApp: A personalized thermal stress warning tool. Climate Services. 2022;27:100310.
133. Aguilera JJ, Korsholm Andersen R, Toftum J. Prediction of indoor air temperature using weather data and simple building descriptors. International journal of environmental research and public health. 2019;16(22):4349.
134. Kvale S. Doing interviews: Sage; 2008.
135. Folkerts M, Boshuizen A, Gosselink G, Gerrett N, Daanen H, Gao C, et al. Predicted and user perceived heat strain using the ClimApp mobile tool for individualized alert and advice. Climate Risk Management. 2021;34:100381.
136. Hsieh H-F, Shannon SE. Three approaches to qualitative content analysis. Qualitative health research. 2005;15(9):1277-88.
137. Kuutti K. Activity theory as a potential framework for human-computer interaction research. Context and consciousness: Activity theory and human-computer interaction. 1996;1744.
138. Vygotsky LS. Mind in society: The development of higher mental processes (E. Rice, Ed. & Trans.). Cambridge, MA: Harvard University Press.(Original work published 1930, 1933 …; 1978.
139. Engeström Y. Learning by expanding: Cambridge University Press; 2015.
140. Johansson E, Thorsson S, Emmanuel R, Krüger E. Instruments and methods in outdoor thermal comfort studies–The need for standardization. Urban climate. 2014;10:346-66.

141. Faul F, Erdfelder E, Lang A-G, Buchner A. G* Power 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences. Behavior research methods. 2007;39(2):175-91.
142. Nie T, Lai D, Liu K, Lian Z, Yuan Y, Sun L. Discussion on inapplicability of Universal Thermal Climate Index (UTCI) for outdoor thermal comfort in cold region. Urban Climate. 2022;46:101304.
143. Cohen J. Statistical power analysis for the behavioral sciences: Routledge; 2013.
144. Broede P, Blazejczyk K, Fiala D, Havenith G, Holmer I, Jendritzky G, et al. The Universal Thermal Climate Index UTCI compared to ergonomics standards for assessing the thermal environment. Industrial health. 2013;51(1):16-24.
145. Haslam R, Parsons K. Using computer-based models for predicting human thermal responses to hot and cold environments. Ergonomics. 1994;37(3):399-416.
146. Xu X, Tikuisis P, Gonzalez R, Giesbrecht G. Thermoregulatory model for prediction of long-term cold exposure. Computers in biology and medicine. 2005;35(4):287-98.
147. Castellani JW, O'Brien C, Tikuisis P, Sils IV, Xu X. Evaluation of two cold thermoregulatory models for prediction of core temperature during exercise in cold water. Journal of Applied Physiology. 2007;103(6):2034-41.
148. C3S. ERA5: Fifth generation of ECMWF atmospheric reanalyses of the global climate. Copernicus Climate Change Service Climate Data Store (CDS). 2017;15(2):2020.
149. Jandaghian Z, Berardi U. Comparing urban canopy models for microclimate simulations in Weather Research and Forecasting Models. Sustainable Cities and Society. 2020;55:102025.
150. Wang F, Belušić D, Amorim JH, Ribeiro I. Assessing the impacts of physiography refinement on Stockholm summer urban temperature simulated with an offline land surface model. Urban Climate. 2023;49:101531.
151. Pantavou K, Theoharatos G, Santamouris M, Asimakopoulos D. Outdoor thermal sensation of pedestrians in a Mediterranean climate and a comparison with UTCI. Building and environment. 2013;66:82-95.
152. Bröde P, Krüger EL, Rossi FA, Fiala D. Predicting urban outdoor thermal comfort by the Universal Thermal Climate Index UTCI—a case study in Southern Brazil. International journal of biometeorology. 2012;56:471-80.
153. Lundgren-Kownacki K, Martinez N, Johansson B, Psikuta A, Annaheim S, Kuklane K. Human responses in heat - comparison of the Predicted Heat Strain and the Fiala multi-node model for a case of intermittent work. J Therm Biol. 2017;70(Pt A):45-52.
154. Jin H, Liu S, Kang J. Gender differences in thermal comfort on pedestrian streets in cold and transitional seasons in severe cold regions in China. Building and environment. 2020;168:106488.
155. Johansson E, Yahia MW, Arroyo I, Bengs C. Outdoor thermal comfort in public space in warm-humid Guayaquil, Ecuador. International journal of biometeorology. 2018;62:387-99.

156. Nazarian N, Liu S, Kohler M, Lee JK, Miller C, Chow WT, et al. Project Coolbit: can your watch predict heat stress and thermal comfort sensation? Environmental Research Letters. 2021;16(3):034031.
157. GSMA. Smartphone owners are now the global majority, New GSMA report reveals 2023 [accessed 12 March 2024]. Available from: https://www.gsma.com/newsroom/press-release/smartphone-owners-are-now-the-global-majority-new-gsma-report-reveals/.
158. Statista. Smartwatches - Worldwide n.d. [accessed 13 March 2024]. Available from: https://www.statista.com/outlook/hmo/digital-health/digital-fitness-well-being/fitness-trackers/smartwatches/worldwide.
159. Orru H, Guo J, Veber T, editors. Conference on connecting health and climate change: abstracts book. Conference on Connecting Health and Climate Change, Stockholm, Sweden, October 11-12, 2023; 2024: Umeå University.
160. UN. 8 Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all: United Nations Department of Economic and Social Affairs; n.d. [accessed 21 March 2024]. Available from: https://sdgs.un.org/goals/goal8.
161. SYNERGISE. SYNERGISE for Improved Disaster Management 2023 [accessed 23 May 2024]. Available from: https://www.synergise-project.eu/.
162. Kuklane K, Toma R. Validation of ISO 9920 clothing item insulation summation method based on an ambulance personnel clothing system. Industrial health. 2020.
163. Tochihara Y, Chou C, Fujita M, Ogawa T. Protective clothing-related heat stress on firefighters in Japan. Environmental ergonomics XI. 2005:137-9.
164. d'Ambrosio Alfano FR, Palella BI, Riccio G, Malchaire J. On the Effect of Thermophysical Properties of Clothing on the Heat Strain Predicted by PHS Model. Ann Occup Hyg. 2016;60(2):231-51.
165. d’Ambrosio Alfano FR, Palella BI, Riccio G. The role of measurement accuracy on the thermal environment assessment by means of PMV index. Building and Environment. 2011;46(7):1361-9.
166. d'Ambrosio Alfano FR, Palella BI, Riccio G. Notes on the implementation of the IREQ model for the assessment of extreme cold environments. Ergonomics. 2013;56(4):707-24.
167. d'Ambrosio Alfano FR, Malchaire J, Palella BI, Riccio G. WBGT index revisited after 60 years of use. Ann Occup Hyg. 2014;58(8):955-70.
168. Bernard TE. Prediction of workplace wet bulb global temperature. Applied occupational and environmental hygiene. 1999;14(2):126-34.
169. Bernard TE, Ashley CD, Garzon XP, Kim J-H, Coca A. Prediction of WBGT-based clothing adjustment values from evaporative resistance. Industrial health. 2017;55(6):549-54.
170. Kampmann B, Brode P, Fiala D. Physiological responses to temperature and humidity compared to the assessment by UTCI, WGBT and PHS. Int J Biometeorol. 2012;56(3):505-13.

171. Kopečková B, Pokorný J, Jícha M. Comparison of the Predicted Heat Strain and the Fiala-based Human Thermophysiological Model for normal and protective clothing under various ambient temperatures. The 18th International Conference on Environmental Ergonomics; July; Netherlands2019. p. 90.
172. Gebhardt H, Kampmann B, Müller BH, Bux K. Calculation of cooling phases in warm and hot environments using the PHS-model. Occupational Ergonomics. 2008;8(4):195-204.
173. Malchaire J, Piette A, Kampmann B, Mehnert P, Gebhardt H, Havenith G, et al. Development and validation of the predicted heat strain model. Annals of Occupational Hygiene. 2001;45(2):123-35.
174. Wang F, Kuklane K, Gao C, Holmér I. Can the PHS model (ISO7933) predict reasonable thermophysiological responses while wearing protective clothing in hot environments? Physiological measurement. 2011;32(2):239.
175. Petersson J, Halder A, Lundgren Kownacki K, Kuklane K, Gao C. Required clothing insulation (IREQ - ISO 11079) and difference of thermal sensations between genders. The 18th International Conference on Environmental Ergonomics; 7-12 July 2019; Amsterdam, The Netherlands7-12 July 2019. p. 171.
176. Kuklane K, Toma R. Common clothing area factor estimation equations are inaccurate for highly insulating (Icl> 2 clo) and non-western loose-fitting clothing ensembles. Industrial Health. 2020.
177. CEN. EN511:2006 - Protective gloves against cold. Brussels: European Committee for Standardization; 2006. p. 19.
178. Lundgren Kownacki K, Gao C, Kuklane K, Wierzbicka A. Heat stress in Indoor environments of Scandinavian urban areas: A literature review. International journal of environmental research and public health. 2019;16(4):560.
179. Steinfeld E, Maisel J. Universal design: Creating inclusive environments: John Wiley & Sons; 2012.
180. Havenith G, Fiala D, Blazejczyk K, Richards M, Brode P, Holmer I, et al. The UTCI-clothing model. Int J Biometeorol. 2012;56(3):461-70.
181. Lee JK, Kenefick RW, Cheuvront SN. Novel cooling strategies for military training and operations. The Journal of Strength & Conditioning Research. 2015;29:S77-S81.
182. Urban A, Kyselý J. Comparison of UTCI with other thermal indices in the assessment of heat and cold effects on cardiovascular mortality in the Czech Republic. International journal of environmental research and public health. 2014;11(1):952-67.
183. Kuchcik M. Mortality and thermal environment (UTCI) in Poland—long-term, multi-city study. International journal of biometeorology. 2021;65(9):1529-41.
184. Di Napoli C, Pappenberger F, Cloke HL. Assessing heat-related health risk in Europe via the Universal Thermal Climate Index (UTCI). International journal of biometeorology. 2018;62:1155-65.
185. Di Napoli C, Pappenberger F, Cloke HL. Verification of heat stress thresholds for a health-based heat-wave definition. Journal of Applied Meteorology and Climatology. 2019;58(6):1177-94.

186. Mäkinen TM, Hassi J. Health problems in cold work. Industrial health. 2009;47(3):207-20.
187. Matzarakis A, Laschewski G, Muthers S. The heat health warning system in Germany—Application and warnings for 2005 to 2019. Atmosphere. 2020;11(2):170.
188. Koppe C. The heat health warning system of the German Meteorological Service. UMID Spec Issue Clim Change Health. 2009;3:39-43.
189. ClimaHealth. Accelerating the Use of Climate, Weather, and Environmental Science and Services for Public Health Policy and Practice n.d. [accessed 21 March 2024]. Available from: https://climahealth.info/who-wmo-joint-programme/.
190. UN. 13 Take urgent action to combat climate change and its impacts: United Nations Department of Economic and Social Affairs; n.d. [accessed 21 March 2024]. Available from: https://sdgs.un.org/goals/goal13.
191. Goldstein AH, Nazaroff WW, Weschler CJ, Williams J. How do indoor environments affect air pollution exposure? Environmental science & technology. 2020;55(1):100-8.
192. Almeida-Silva M, Wolterbeek HT, Almeida S. Elderly exposure to indoor air pollutants. Atmospheric Environment. 2014;85:54-63.
193. Díaz J, Jordán A, García R, López C, Alberdi J, Hernández E, et al. Heat waves in Madrid 1986–1997: effects on the health of the elderly. International archives of occupational and environmental health. 2002;75:163-70.
194. Sweden H. HEATWISE Sweden 2024 [accessed 23 May 2024]. Available from: https://ki.se/imm/heatwise-sweden.
195. Kim M, Kim H, You M. The role of public awareness in health-protective behaviours to reduce heat wave risk. Meteorological Applications. 2014;21(4):867-72.