Department of Geography and Environmental Science

Too Hot to Handle:
The Global Impact of Extreme Heat

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Declaration

I confirm that this is my own work and the use of all material from other sources has been properly and fully acknowledged.

Chloe Brimicombe

Abstract

Heatwaves are the deadliest weather hazard. Extreme heat also impacts cross-sections of society, from health to agriculture to infrastructure. The World Meteorological Organisation and the World Health Organisation recommend that countries should implement early warning systems to reduce the impacts of extreme heat. Despite this mandate no global heat hazard alert system currently exists. In addition, heatwave impacts are often under-reported by meteorological organisation databases and reports and in the English news media. This leads to them sometimes being known as silent or invisible killers.

An interdisciplinary approach is taken in this thesis to investigate the impact of extreme heat and policy measures and to explore the development of a global heat hazard early warning system. This is presented through a systems approach framed using an adapted version of the WHO framework *Operational framework for building climate resilient health systems.* There are 4 components addressing different aspects of the system each with an objective and these are: 1. Mobilization and governance: *assess policy prioritization and governance,*2. Health Information Systems: *evaluate the trends and modelling for extreme heat,* 3. Essential Technologies: *develop new technologies to reduce risk to heat* and 4. Service Delivery: *consider the communication of heat risks and impacts within wider culture.*

Overall, the research presented in this thesis provides research for a global heat hazard alert system focused on health impacts. An open-source python library for thermal comfort called *thermofeel* is developed and evaluated. In addition, the way in which extreme heat and heatwaves are communicated in English language research, policy and news media is explored, to start assessing what the best way to communicate heat stress risk might be on a global scale. All of this raises the profile of heatwave risk to ensure their impacts becomes more visible.

Authorship of Papers

This is a list of the academic papers that the author of the thesis contributed to whilst completing the PhD and therefore have in part informed the research presented here, full contribution statements where the paper is a chapter can be seen within the thesis:

Brimicombe, C, Lo, C.H.B., Pappenberger, F., Di Napoli, C., Maciel, P., Quintino, T., Cornforth, R. and Cloke, H., 2023. Wet Bulb Globe Temperature: indicating extreme heat risk on a global grid. *GeoHealth*. https://doi.org/10.1029/2022GH000701 **[IF: 4.60] [CB 75%]**

Brimicombe C, Quintino T, Pappenberger F, Smart S, Di Napoli C and Cloke H L 2022a Technical Memorandum: The cosine of the solar zenith angle for thermal comfort indices https://doi.org/10.21957/O7PCU1X2B **[CB 80%]** *n = 3*

Brimicombe C, Di Napoli C, Quintino T, Pappenberger F, Cornforth R and Cloke H L, 2022b, thermofeel: a python thermal comfort indices library 2022 *Software X*, https://doi.org/10.1016/j.softx.2022.101005 **[IF: 1.959,** *n*= *6*] **[CB 80%]**

Brimicombe C, Di Napoli C, Cornforth R, Pappenberger F, Petty C. and Cloke H.L., 2021a. Borderless heat hazards with bordered impacts. *Earth's Future*, https://doi.org/10.1029/2021EF002064 **[IF: 7.495,** *n*=9**] [CB 80%]**

Brimicombe C, Porter J J, Di Napoli C, Pappenberger F, Cornforth R, Petty C and Cloke H L, 2021b, Heatwaves: An invisible risk in UK policy and research, *Environ. Sci. Policy* 116 1–7 Online: https://linkinghub.elsevier.com/retrieve/pii/S1462901120313782 **[IF: 5.581;** *n* = 19**]**

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Emerton R, **Brimicombe C,**L Magnusson,C Roberts, C Di Napoli, H L Cloke and F Pappenberger, 2022, Predicting the Unprecedented: Forecasting the June 2021 Pacific Northwest Heatwave *Weather* https://doi.org/10.1002/wea.4257 **[IF: 2.239;** *n*= *10*] **[CB 40%]**

Di Napoli C; McGushin A; Romanello M; Ayeb-Karlsson S; Cai W; Chambers J; Dasgupta S; Escobar L E; Kelman I; Kjellstrom T; Kniveton D; Liu Y; Liu Z; Lowe R; Martinez-Urtaza J; McMichael C; Moradi-Lakeh M; Murray K A; Rabbaniha M; Semenza J C; Shi L; Tabatabaei M; Trinanes J M; Vu B M; **Brimicombe C**; Robinson E J 2022 Tracking the impacts of climate change on human health via indicators: lessons from the Lancet Countdown by Dr Claudia Di Napoli *BMC Public Health* https://doi.org/10.1186/s12889-022-13055-6 **[IF: 3.295,** *n*=*11*] **[CB 5%]**

Van de Walle J, Brousse O, Arnalsteen L, **Brimicombe C**, Byarugaba D, Jjemba E, Lwasa S, Misiani H, Nsangi G, Soetewey F,Sseviiri H, Thiery W, Vanhaeren R , Zaitchik B F, and van Lipzig N P M, 2022, Lack of vegetation exacerbates exposure to dangerous heat in dense settlements in a tropical African city. *Environmental Research Letters*, https://doi.org/10.1088/1748-9326/ac47c3 **[IF: 6.793;** *n* = 13**] [CB 10%]**

Brimicombe, C. 2022. Is there a climate change reporting bias? A case study of English-language news articles, 2017-2022. *Geoscience Communication*, *5*(3), 281–287. https://doi.org/10.5194/GC-5-281-2022 **[CB 100%]** *n = 1*
Burrows R and **Brimicombe C**, (In Prep) Extreme Heat and Child Stunted Growth in the West Sahel *Environmental Research Letters* **[IF: 6.793] [CB 50%]**

Authorship of other outputs

This is a list of other outputs (i.e. Software, Articles and Blog Posts) that the author of the thesis contributed to whilst completing the PhD and therefore have in part informed the research presented here:

Brimicombe C, Charlton-Perez A, Di Napoli C, Luo Z and Israelsson J 2022a Proposal for heat sanctuaries on our campus, *University of Reading Estates Committee* **[CB 60%]**

Brimicombe C, Di Napoli C, Quintino T, Pappenberger F, Cornforth R and Cloke H,2021a thermofeel: a python thermal comfort indices library https://doi.org/10.21957/mp6v-fd16 **[CB 80%]**

Brimicombe C. Killer Heat Hazards and Us, 202b1. Make Happen Key Stage 5 Coursebook, https://www.access-ed.ngo/killer-heat-hazards-and-us **[CB 100%]**

Brimicombe C 2022a Four things cool countries can learn from hot ones about dealing with heatwaves *The Conversation* Online: https://theconversation.com/four-things-cool-countries-can-learn-from-hot-ones-about-dealing-with-heatwaves-187117 **[CB 100%]**

Brimicombe C 2022b What science says about the best ways to cool down *The Conversation* Online: https://theconversation.com/what-science-says-about-the-best-ways-to-cool-down-185643 **[CB 100%]**

Brimicombe C 2022c Four surprising ways climate change is affecting people's health in England and Wales *The Conversation* Online: https://theconversation.com/four-surprising-ways-climate-change-is-affecting-peoples-health-in-england-and-wales-175099 **[CB 100%]**

Brimicombe C. 2021c Extreme heat warning what first ever met office alert means *The Conversation* Online: https://theconversation.com/extreme-heat-warning-what-first-ever-met-office-alert-means-164757 **[CB 100%]**

Brimicombe C, and Cloke H. 2021d one in three heat deaths since 1991 linked to climate change heres how else warming affects our health *The Conversation* Online: https://theconversation.com/one-in-three-heat-deaths-since-1991-linked-to-climate-change-heres-how-else-warming-affects-our-health-161761 **[CB 70%]**

Brimicombe C, Sainsbury E, Powell G and Chan W 2020a Overshadowed by COVID: the deadly extreme weather of 2020 *The Conversation* Online: https://theconversation.com/overshadowed-by-covid-the-deadly-extreme-weather-of-2020-151237 **[CB 40%]**

Brimicombe C, 2020b Heatwaves are an invisible killer – and the UK is woefully unprepared *The Conversation* Online: https://theconversation.com/heatwaves-are-an-invisible-killer-and-the-uk-is-woefully-unprepared-144703 **[CB 100%]**

Brimicombe C 2022d Guest post: What seasonal forecasts can tell us about extreme heat this summer Carbon Brief Online: https://www.carbonbrief.org/guest-post-what-seasonal-forecasts-can-tell-us-about-extreme-heat-thissummer/ **[CB 100%]**

Brimicombe C, Di Napoli C, Cloke H and Wanzala M, 2021e Guest post: Reviewing the summer of extreme weather in 2021 Carbon Brief Online: https://www.carbonbrief.org/guest-post-reviewing-the-summer-of-extreme-weather-in-2021 **[CB 80%]**

Brimicombe C and Lo Brian C. H. 2021f CMIP6 Data Hackathon The Social Metwork Online: https://socialmetwork.blog/2021/06/18/cmip6-data-hackathon/ **[CB 50%]**

Brimicombe C 2021g Science art helps climate change message hit home University of Reading Connecting Research Online: https://research.reading.ac.uk/research-blog/science-art-helps-climate-change-message-hit-home/ **[CB 100%]**

Brimicombe C and Coleman M 2021h The EGU experience: a PhD Student Perspective The Social Metwork Online: https://socialmetwork.blog/2021/05/14/the-egu-experience-2021-a-phd-student-perspective/ **[CB 50%]**

Brimicombe C, 2021i Challenges for extreme heat risks The Social Metwork Online: https://socialmetwork.blog/2021/02/05/main-challenges-for-extreme-heat-risk/ **[CB 100%]**

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Contents

1. Introduction

1.1 Silent Heat Impacts

Heatwaves have been named the deadliest weather hazard by the World Metorological Organisation (World Meteorological Organization, 2018a). On a global scale it is found that on average every year from 2000 to 2019, 480,000 people died (per year) as a result of extreme heat (Zhao et al., 2021). In addition, extreme heat is a cross-sectional risk, for example reducing crop yields (Deryng et al., 2014) and damaging and putting increased pressure on infrastructure such as power grids (Larcom et al., 2019). Extreme Heat impacts are severe but are underreported compared to other weather hazards such as storms and floods, demonstrating that heat impacts are silent or invisible (Harrington & Otto, 2020; Vogel et al., 2019). In addition, heatwaves and heat stress conditions are increasing in frequency, intensity and duration on a global scale (Perkins-Kirkpatrick & Lewis, 2020) , with this trend being faster over populated regions (Rogers et al., 2021). Therefore there is an urgent need through the WHO and WMO joint mandate to develop a global early warning system in response to the multiple impacts of heatwaves, this includes a communication strategy to prevent and build resilience to the silent impacts of heat, with a priority given to the health sector.

1.2 Thesis Motivation

Heatwaves are a type of extreme weather event that presents risks which can be defined as *"The potential for adverse consequences for human or ecological systems, recognising the diversity of values and objectives associated with such systems"* (IPCC et al., 2021). The risk of extreme heat is growing with climate change and the recent Physical Science basis IPCC report is now very confident that heatwaves have been increasing in frequency, duration and intensity over the whole land surface (IPCC et al., 2021). Impacts are the realisation of risk as it interacts with society and the risks of heatwaves are numbersome and cross-sectional, although are prominent within the health sector.

In the visualisation of risk, the main response that can be suggested to be a fundamental approach to address heat risks and impacts is a Global Heat Early Warning system because of the mandate set out by the WMO and WHO, but also because of the cost-benefit analysis carried out by the Committee on Climate Change in the UK which demonstrates it is one of the most cost-effective ways to reduce the impacts of heat. Heat hazard early warning systems can provide early information on the upcoming impacts of extreme heat, and as such are a type of climate service, moving away from more traditional weather forecasting as is set out in Basher et al., (2006).

Notwithstanding the known severe impacts of extreme heat and heatwaves there is currently not a global heat hazard awareness system, perhaps because of the difficulties around defining a heatwave. This is despite there being a mandate since 2004 for countries to put in place heat early warning systems after the 2003 heatwave caused the death of up to 55,000 people globally (WMO & WHO, 2015). In addition, whilst some countries do have early warning systems in place for extreme heat, there are regions of the world where very few countries have them (i.e. countries in the Tropics and the Continent of Africa) and there are big differences in the approach and definition used to issue a warning because of a lack of a global heatwave definition (Robinson, 2001; Russo et al., 2017). Some countries also make use of thermal comfort and heat stress indices as these have been shown to be useful in modelling mortality and morbidity responses (National Weather Service, 2022; Smoyer-Tomic & Rainham, 2001).

This thesis takes a systems approach to exploring the development of a global heat hazard early warning system, this is where a number of elements are assessed in consideration of the whole system in contrast to one element of an early warning system, this is a recommended approach proposed by Basher et al., (2006). It was developed iteratively as the field grew and developed from 2019 to 2021. The framework use is adapted from the WHO *Operational framework for building climate resilient health systems,* a schematic can be seen below, this framework has 10 components that should be addressed in order to build climate resilience within the health sector (WHO,2015)

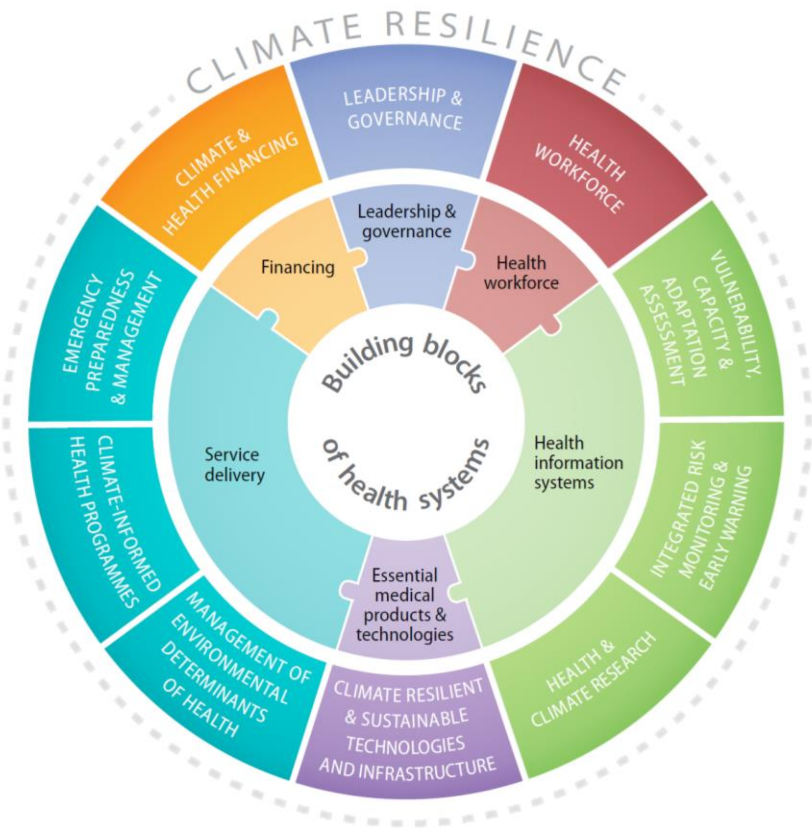

Figure 1.1: schematic of the framework set out by WHO in response to building resilience health services (WHO,2015).

This thesis also, builds on and complements the award-winning work of Di Napoli et al., 2021 and the development of ERA5-HEAT a freely acccessible global dataset of the thermal comfort index, the Universal Thermal Climate Index (UTCI) and Mean Radiant Temperature (MRT). These are calculated using other variables from the state-of-the-art ERA5 reanalysis product provided by the Copernicus data store, maintained by the European Centre for Medium Range Weather Forecasts (ECMWF) (Hersbach et al., 2020; Di Napoli et al., 2021).

1.3 Thesis Aims and Structure

This thesis is the first document to my knowledge that uses a systems approach to consider how each part of the system together contributes to a robust global heat early warning system in the context of resilient health systems. This has benefits over simply considering part of the system in detail in isolation, which can lead to widening gaps in some areas. Each component creates new scientific knowledge which interlinks with one another. Overall, the linked components and new research presented in this thesis aims to provide new knowledge that investigates the impact of extreme heat and policy measures and to explore the development of a global heat hazard early warning system. An adapted version of the components used by the WHO for building climate resilient systems is used to structure the thesis and define the objectives used (WHO,2015), this is visualised in figure 1.2.

Component 1, Mobilization and Governance:

Component 1 is brought together from Climate and Health, Financing, Leadership and Governance and Health Work Force to form Mobilization and governance. The objective of this component is *assess policy prioritization and governance*. This objective is designed to touch upon strengthening technical and professional capacity of organizations and health personnel, management of the scope and magnitude of climate related stress and investment in the health system to deal with climate shocks, key elements of the original framework components.

The two chapters in Component 1 are *Chapter 4: Borderless Heat Stress with bordered impacts* which makes key suggestions given the current reporting landscape of extreme heat impacts. In addition to Chapter *5: Heatwaves: an invisible risk in UK policy and research* which reveals key gaps for the UK and similarly makes suggestions that are aimed at assessing policy prioritization and governance.

Component 2, Health information systems:

Component 2 mirrors an overarching component that it is adapted from the WHO framework, to form *health information systems*. The key elements of this are to consider the risk, vulnerabilities, and adaptations of the health system to climate changes, as well as the monitoring of climate changes through early warning systems. Bringing these themes together gives objective 2: *evaluate the trends and modelling for extreme heat.*

The two chapters in Component 2 are *Chapter 6: Trends in African Heatwaves* which considers the trends of heat across the African continent and the impacts of this and *Chapter 7: thermofeel: a python library for thermal comfort indices* which frames and provides motivation for a global heat early warning system.

Component 3, Essential technologies:

Component 3 again mirrors a component that is adapted from the WHO framework to form *Essential technologies.* The key element that is considered here is *"Climate resilience can also be enhanced through the use of new technologies or approaches for better delivery of health interventions"* (WHO, 2015; page 25). This forms objective 3 *develop new technologies to reduce risk to heat.*

The 3 chapters in Component 3, all deal with the improvement or development of new technology for a global heat early warning system. They are *Chapter 8: tech memo: calculating the solar zenith angle for thermal comfort indices*, *Chapter 9: The Development of a UTCIsimple method* and *Chapter 10: Wet Bulb Globe Temperature: indicating extreme heat risk on a global grid.*

Component 4, Service Delivery:

Component 4 mirrors an overarching component that it is adapted from the WHO framework, to form *service delivery*. It considers the communication elements of the original overarching component touching on suggested collaborations and providing a wider context to how extreme fits within culture. This forms objective 4: *consider the communication of heat risks and impacts within wider culture.*

It is formed of 3 chapters Chapter *11: Is there a climate change reporting bias? A case study of English-language news articles, 2017–2022, Chapter 12: the portrayal of heatwaves in popular culture and Chapter 13: Towards a global heat early warning system.* The first two chapters focus more on communication within the news media and popular culture, whilst the third chapter focuses on drawing the key elements of the thesis together to present a vision for an early warning system.

Chapter 1 through 3 and Chapter 14 and 15 overlap all the 4 components derived from the WHO framework providing background and concluding remarks on the thesis as a whole.

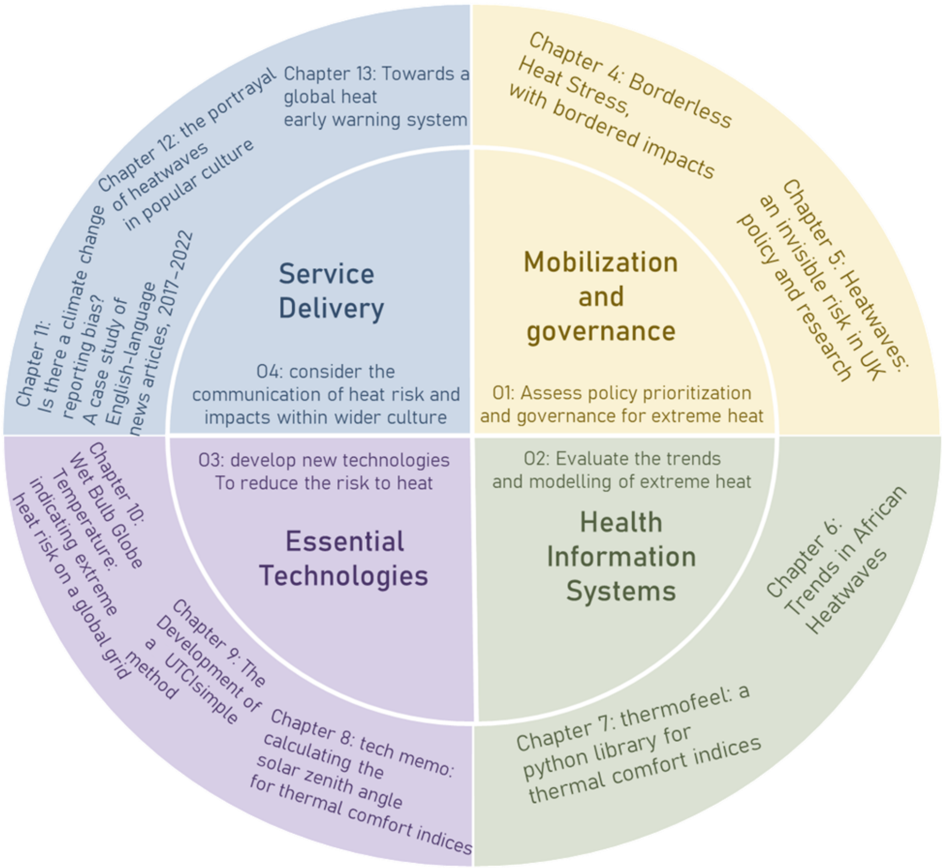

Figure 1.2: Systematic structure of the thesis and how this defines key elements that are important in the development of a global heat early warning system.

1.4 Thesis approach and research questions

The systems approach in this thesis allows for a large breadth of research and several research questions to be posed per component this is summarised in table 1.1.

Table 1.1 The main research questions presented in this thesis

Mobilization and Governance *Assess policy prioritization and governance*	
Chapter 4: Borderless Heat Stress with bordered impacts	Q: How does the area of heat stress change over this millennium and is this adequately captured by meteorological reporting?
Chapter 5: *Heatwaves: an invisible risk in UK policy and research*	Q: How are heatwaves presented in UK policy and what are the barriers to creating policy?
Health Information Systems *Evaluate the trends and modelling for extreme heat*	
Chapter 6: Trends in African Heatwaves	Q: How has the exposure to heat stress changed for Africa and what should forecasters look out for in heatwaves that present large impacts?
Chapter 7: thermofeel: a python library for thermal comfort indices	Q: Can I create accurate thermodynamical thermal comfort models for gridded data, that is open to the research community?
Essential Technologies *Develop new technologies to reduce risk to heat.*	
Chapter 8: tech memo: calculating the solar zenith angle for thermal comfort indices	Q: Can I improve the representation of Mean Radiant Temperature and thermal comfort indices in NWP services?
Chapter 9: The Development of a UTCIsimple method	Q: Can I create a less-computational expensive method for UTCI to make it more accessible?

Chapter 10: Wet Bulb Globe Temperature: indicating extreme heat risk on a global grid.	Q: Can I create a WBGT that is designed for gridded dataset and is accurate in comparison to the gold standard method and observations?
Service Delivery *Consider the communication of heat risks and impacts within wider culture.*	
Chapter *11: Is there a climate change reporting bias? A case study of English-language news articles, 2017–2022*	Q: how has reporting of weather hazards in the English Language media changed in the last 5 years and are heatwaves under-reported?
Chapter 12: the portrayal of heatwaves in popular culture	Q: How are heatwaves presented in popular culture and how can this be employed to communicate risk?
Chapter 13: Towards a global heat early warning system	Q: What is needed for a robust global heat health early warning system to be developed?

The body of work presented in these components together provides new robust scientific evidence for the thesis aims of evidencing impacts and policy for extreme heat and working towards the development of a global heat hazard early warning system. This provides a framework and the information that is necessary to start implementing a global heat hazard early warning system within the wider health system for the first time in its entirety. This thesis was developed iteratively and not in isolation to the developing research field and therefore it is hoped the information would continue to develop in this manner. It is designed to be able to provide scientific answers to real world challenges that exist as a result of the increase in the incidence of extreme heat on a global scale.

2. Literature Review

This chapter sets out the wider research context that the objectives of this thesis fit within and demonstrates their importance to the field. First, it focuses on the individual terms that the definition 'extreme heat' covers and the challenges of defining extreme heat. Attention is then given to the drivers and the impacts of extreme heat. Finally it assesses what adaptations are in place for extreme heat and what challenges remain.

2.1 Definition of Extreme Heat

Extreme heat is an umbrella term that captures a number of other terms including heatwaves and heat stress. It is broadly used to refer to higher than average temperatures and hot weather. All the definitions that are covered under the term can be seen in figure 2.1. The different colours in figure 2.1 refer to the different sections that definition of extreme heat will be discussed in these are *Heatwaves, Heat Metrics, Thermal comfort and Heat Indices and Heat Illnesses*. The *Heatwaves* section is discussed as Marine Heatwaves and Land Heatwave, this thesis focuses on Land Heatwaves but Marine Heatwaves are included because of their robust definition. Under each section heading in figure 2.1 are the definitions that are discussed.

Figure 2.1 How the umbrella term extreme heat covers a number of other heat related terms

2.1.1 Marine Heatwaves

There is a universally agreed term for marine heatwaves, which is *"when seawater temperatures (surface or below sea surface) exceed a seasonally-varying threshold (usually the 90th percentile) for at least 5 consecutive days. Successive heatwaves with gaps of 2 days or less are considered part of the same event"* (Hobday et al., 2016). Where marine heatwaves occur in a region's winter season they are known as a winter warm spell (Hobday et al., 2016). Figure 2.2 visualises how a marine heatwave is defined.

An example of a marine heatwave is the North-Western Pacific Blob in 2014-15, which led to sea otters being known as a 'climate change hero' due to their role in conserving kelp forests (McPherson et al., 2021; Rogers-Bennett & Catton, 2019). Marine heatwaves are mentioned here because they have a formal definition. To continue, the review will focus upon land heatwaves, with a specific look at how land extreme heat impacts human health and society and therefore adaptations will also be specific to this part of extreme heat.

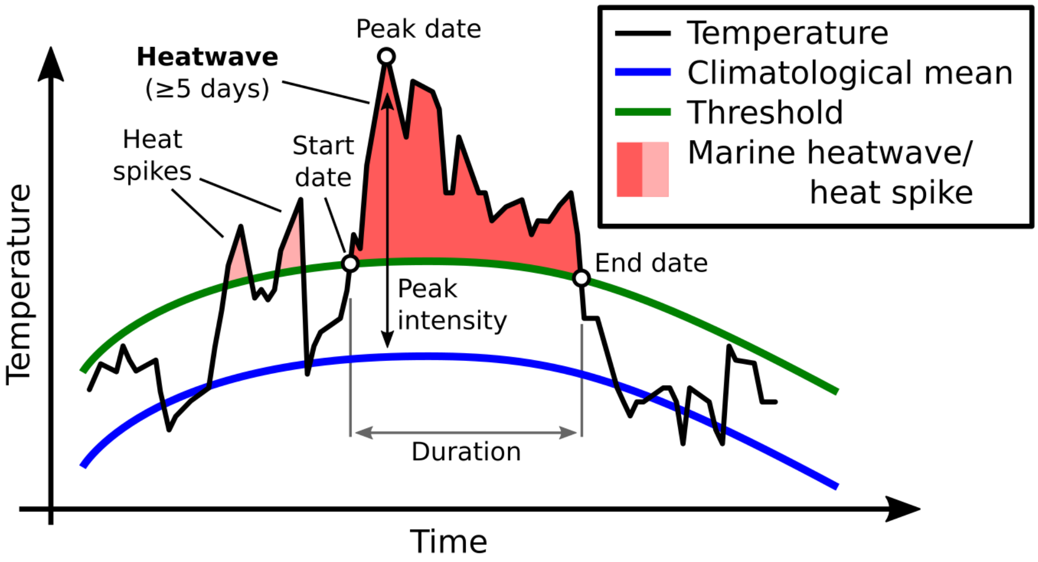

Figure 2.2 a visual representation of how a marine heatwave is defined from Hobday et al., 2016.

2.1.2 Land Heatwaves

Unlike their marine counterparts there is no globally agreed definition for the term heatwave when it occurs on land. There is draft global definition proposed by the World Meteorological Organisation (WMO), where they state a heatwave is *"A period of marked unusual hot weather (maximum, minimum and daily average temperature) over a region persisting at least three consecutive days during the warm period of the year based on local (station-based) climatological* *conditions, with thermal conditions recorded above given thresholds."*(World Meteorological Organization, 2018a, p. 4) .

In addition, in the context of Africa, the suggestion has been made by Russo *et al.*, (2016), that heatwaves can occur any time of year given the position of the continent. Intriguingly the Intergovernmental Panel on Climate Change (IPCC) define heatwaves as: "*a period of abnormally hot weather"* (IPCC., 2018, p. 551). This is a very vague definition. They further direct readers to definitions on warm spells and extreme weather in attempt to further develop the definition, but it remains subjective (ibid). Warm spells, is similar to the definition of a marine heatwave, refering to when heatwave conditions occur in a region's winter season and , they can also be known as Winter Heatwaves which for example can be the case in the UK (McCarthy et al., 2019).

The lack of a universal definition has led individual countries' meteorological organisations to create their own definitions, for example the Met Office in the UK defines a heatwave as *'when a location records a period of at least three consecutive days with maximum temperatures meeting or exceeding a heatwave temperature threshold'* (The Met Office, 2019). In comparison, the Meteorological Department of India defines a heatwave as *'When the temperature departs from normal by a given threshold at 2 stations in a region for 2 or more consecutive days'* (Department of Indian Meteorology, 2021). The National Weather Service in the US defines a heatwave as *"A heat wave is a period of abnormally hot weather generally lasting more than two days. Heat waves can occur with or without high humidity"*(National Weather Service, 2021).

Additionally, many studies makes use of the 90th or 95th percentile of temperature values to define a region at a given period as experiencing a heatwave (Fontaine *et al*., 2013; Moron *et al*., 2016; Oueslati.*et al*., 2017; Russo *et al*., 2014; Sambou, *et al*., 2019). Originally in the literature this value was static, whereby the percentile was used as the limit for a whole season or even a whole year (Sambou, *et al.*, 2019). This does not indicate heatwaves accurately especially in the tropics, because it does not take into account seasonality, temporal trends or different climate regimes (Fontaine et al., 2013). Recently studies for heatwaves in Africa have migrated to using a moving percentile which is defined by Sambou *et al.*, (2019) as being *"a percentile of maximum daily temperature of a window of a specific length"*. Moving percentiles more accurately depict heatwave events in the region (Fontaine *et al.*, 2013; Moron *et al.*, 2016; Oueslati *et al.*, 2017; Russo *et al.*, 2014; Sambou, *et al.*, 2019). In comparison, studies can use a certain shift in standard deviation from the mean climatology distribution (i.e. a period of 30 years average temperature 1991-2020) to define a heatwave, for example a standard deviation of 2 or more from the mean distribution may be used (Harrington & Otto, 2020), which is visualized in figure 2.3.

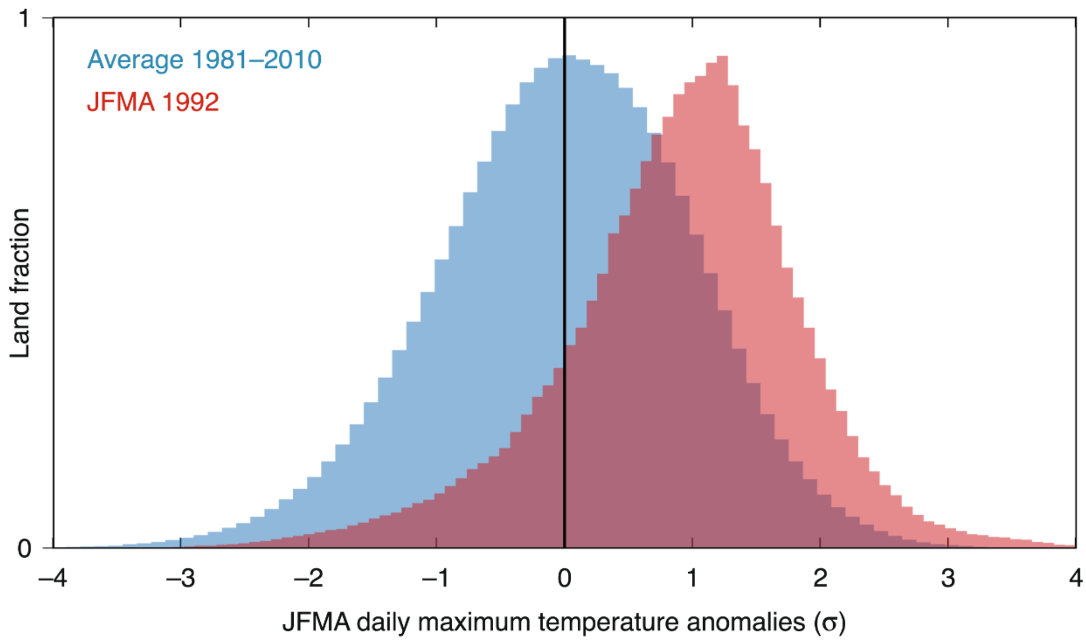

Figure 2.3 Normalized binned histogram for an area of average daily maximum temperatures in blue in comparison to the seasonal average for January, Feburary, March and April 1992.This example is for a South-African Heatwave in 1992 from Harrington & Otto, 2020

To further add to the complexity of land heatwaves, they are known to have different *flavours.* This is used in consideration of whether a heatwave has high humidity (humid) or low humidity (dry). An example of a recent humid heatwave is in Iran and Pakistan in July 2021 where conditions of the wet bulb temperature exceeded 35°C, which is 35°C air temperature and 100% relative humidity, for at least a few hours. This is the deadliest form of heatwave which when occurring for over 6 hours with no access to cooling is known to kill even the healthiest of humans, it is often also known as uninhabitable or unliveable extreme heat (Marx et al., 2021; Vecellio et al., 2022). In comparison, when the highest recorded temperature on earth record was broken in July 2021 in Death Valley California, US it was part of a dry *'flavour'* heatwave in this region.

2.1.3 Heat related illness

Exposure to extreme heat can lead to the development of a number of heat related conditions which at the most extreme can result in death (WMO and WHO, 2015, 2:6). The first condition is known as hyperthermia. This occurs when the core body temperature is between 37.5 and 40°C (the opposite to the cold terminology Hypothermia) (Kuht & Farmery, 2021).

Another common condition is heat stress which can be defined as '*a build-up of body heat either as a result of exertion and/or external environment*' (McGregor & Vanos, 2018). 'Heat stress' is the term for which thermal comfort and heat stress indices can be used to indicate risk (Section 2.1.5). In addition, there is 'heat stroke' a type of heat illness that can be categorised into 'exertional' (i.e. to do with exercise) and 'classic' which is to do with external environment (Glaser et al., 2016; Székely et al., 2015). Heat related illnesses often co-occur with dehydration (Glaser et al., 2016). It can be seen that there are a number of heat illness conditions or heat stress related conditions that have an overlap. Several of these are restricted to use in the health sector literature. These include 'heat syncope' which results from excess sweating, 'heat tetany' which is hyperventilation, 'heat cramps' and 'heat exhaustion' to name a few (Glaser et al., 2016; Jong & Sanford, 2008; Kuht & Farmery, 2021; Székely et al., 2015).

2.1.4 Heat Metrics

Alongside the heatwave and heat stress definition a number of heat metrics exist to aid comparison across both temporal and spatial scales. These can be used to address extreme heat more broadly or focus on aspects of heatwaves, and are summarised in Table 2.1. Here heat metrics are considered differently from heat indices because they are only based on temperature, whereas heat indices take into account other meteorological parameters and are therefore denoted as indices to avoid confusion (Section 2.1.5). Many of the heat metrics included here are set out by Perkins, 2015 where some of the history and motivation for their development as part of Expert Team on Climate Change Detection, Monitoring and Indices (ETCCDI) is described in detail.

Table 2.1 Description of different Heat Metrics

Metric	Description	Units	References
Heatwave duration	Length of longest period of consecutive heatwave days in a year	No. days	(Hulley et al., 2020)
Heatwave frequency	Total number of heatwaves in a year	No. days	(Perkins-Kirkpatrick & Lewis, 2020)

Heatwave amplitude	Maximum 2m air temperature reached in a single heatwave	°C	(Perkins & Alexander, 2013)
Heatwave mean	Average 2m air temperature for all heatwaves in a year	°C	(Perkins & Alexander, 2013)
Heatwave duration index (HWDI)	Maximum period of at least five consecutive days where daily maximum temperature is above the 1961-1990 mean +5°C	No. days	(Perkins, 2015)
EHF (Excess Heat Factor) Significant	where the daily mean temperature is higher than the 95th climatology percentile for 3 days or more	Dimensionless (Normalized Factor)	(Nairn et al., 2018; Varghese et al., 2019)
EHF (Excess Heat Factor) Acclimatized	Where the difference between a 3 day average and a 30 day average is positive.	Dimensionless (Normalized Factor)	(Nairn et al., 2018; Varghese et al., 2019)
HWMId	the maximum magnitude of the heat waves in a year	No. days	(Ceccherini et al., 2017; Russo et al., 2014)
Deadly Days	Daily maximum wet-bulb temperature over 24°C	No. days	(Lee et al., 2021)

Hot Days	Daily maximum 2m air temperature over 35°C	No. days	(Fontaine et al., 2013)
Tropical Nights	Daily minimum 2m air temperature over 20°C	No. nights	(Fontaine et al., 2013)
TN90p	Amount of time when the daily minimum temperature is above the 90th percentile.	No. Days	(Perkins, 2015)
TX90p	Amount of time when the daily maximum temperature is above the 90th percentile.	No. Days	(Perkins, 2015)
TXx	Maximum Daily maximum (day,month,year)	°C	(Perkins, 2015)
TNx	Maximum Daily minimum (day,month,year)	°C	(Perkins, 2015)
ETR	Difference between the highest temperature and lowest temperature in a year.	°C	(Perkins, 2015)

2.1.5 Heat and Thermal Comfort Indices

The heat indices discussed here feature in reviews that compare their methods and whether one can be seen to perform better than the other indices (Blazejczyk et al., 2012; Jendritzky et al., 2012; Zare et al., 2019). One study that assesses major heat indices, including some of those mentioned here, demonstrates that for 17 criteria (i.e. mean body temperature and dehydration) the heat index that performs best is wet bulb globe temperature (WBGT) (both Indoor and Outdoor), meeting 55.4% and 55.1% of the criteria. Following this in the rankings was the Universal Thermal Climate Index (UTCI) (Ioannou et al., 2022). The methodology of each of these indices is discussed in Chapter 3.

Here, the background to indices and some of their related research will now be presented, each index was developed with a different application in mind or for a different region. It is therefore challenging to choose an index that stands out amongst the others. It would be most advantageous for more research to make comparisons such as Ioannou, et al., 2022 for impacts across sectors.

Wet Bulb Globe Temperature (WBGT) is the most widely used heat index (Budd, 2008a; Buzan et al., 2015). It was originally developed in the 1950s as part of a campaign to lower the risk of heat disorders during the training of US Army and Marine troops (Minard, 1961). The WBGT has many applications and is used widely in many research areas such as the occupation and public health sectors. In addition, it is used in the sports and exercise field, industrial hygiene and also in climate change research (Heo et al., 2019; Kjellstrom et al., 2009; Lemke & Kjellstrom, 2012; Lucas et al., 2014; Racinais et al., 2015). Wet Bulb Temperature is the index that sets out the theoretical threshold for when healthy humans start to die (Marx et al., 2021; Vecellio et al., 2022). It is shown that the number of high wet bulb temperature days has increased and increased at a faster rate over populated areas (Rogers et al., 2021). It is therefore an important stand-alone heat index, whilst also being a component of the WBGT.

The Universal Thermal Climate Index (UTCI) is a thermal index representing the likely risk of an individual to experience heat stress. It makes use of the meteorological parameters of 2m temperature, water vapour pressure, 10m wind speed and mean radiant temperature, and a human body thermophysiological model (Jendritzky et al., 2012). It has been compared to many other thermal indices such as apparent temperature and heat index, and captures well an average body response to the thermal environment (Blazejczyk et al., 2012; Zare et al., 2018). In addition, the UTCI is demonstrated to be able to accurately indicate mortality rates during both extreme heat and extreme cold periods across Europe (Di Napoli et al., 2018a, 2019; Urban et al., 2021). The UTCI has also been used as a thermal index to forecast heatwaves internationally (Pappenberger et al., 2015) and accurately indicate extreme heat, for example in Africa in both the West Sahel and South Africa (Guigma et al., 2020; van der Walt & Fitchett, 2021).

Humidex is a heat index that was developed by the Canadian meteorological service as a thermal comfort index (Blazejczyk et al., 2012; Smoyer-Tomic & Rainham, 2001). It has been demonstrated that mortality rates start to increase between 30-35°C for humidex in Toronto (Smoyer-Tomic & Rainham, 2001). Another study demonstrates that the average humidex for the Galician region of Spain will increase from 18°C to 21°C by 2030 and that the maximum projected value will be 43°C, one of the highest heat stress risk levels for humidex (Orosa et al., 2014). In addition, it is shown that observations from densely built-up regions of Kampala over 2 years experienced above 40°C, 68% of the time in the daily maximum and that humidex had a strong correlation with the Normalized Difference Vegetation Index a land-cover metric, demonstrating vegetation has an important cooling effect (Van De Walle et al., 2022).

Normal Effective Temperature (NET) is a heat index that has been adapted for use by many countries meteorological services, including Hong Kong and Poland (Blazejczyk et al., 2012; Li & Chan, 2000). However, there has been very little research since the original paper on NET. Many papers linking to Li & Chan, (2000) do not discuss NET but other indices such as Heat Index or Humidex (Smoyer-Tomic & Rainham, 2001).

Apparent Temperature is a heat index (Steadman, 1984) that has been used to show for East Africa that a 2°C rise in apparent temperature from 2005 to 2035 is projected to cost nations on average $51 billion over the period in addition cooling costs (Parkes et al., 2019). In addition, for countries bordering Lake Victoria it is found that under a RCP8.5 the increase in population exposure to heat stress values as indicated by Apparent Temperature will be 269-fold by the end of the century (Asefi-Najafabady et al., 2018).

Wind Chill is a cold stress index that was developed for conditions in Antarctica (Siple & Passel, 1945). From 1960/70 to 2013/14 the month with the highest risk level for Wind Chill in North America and Canada was January, with the coldest value reached being -62°C in Hudson Bay Canada (Howarth & Laird, 2017). On average over the winter season (December, January and February) the highest risk level for Wind Chill is only experienced 5% of the time in the daily mean (Howarth & Laird, 2017). In comparison, it is demonstrated that Wind Chill may underestimate the risk of frostbite, and this is thought to be especially true for those doing low levels of exercise (Gavhed et al., 2003).

Heat Index is a heat stress index, used by the National Weather Service in the US (National Weather Service, 2022). It has been shown that the daily mean heat index value can be used as an accurate predictor of mortality rates in 6 cities across Taiwan in the over 65s (Sung et al., 2013). In addition, it is shown that for New York from 1997 to 2006 from May to September Heat Index is as accurate at modelling mortality rates as a combination of other meteorological factors (including temperature, dew point temperature and sea level pressure) used in a general additive model (GAM) which the study indicates is a more complex approach to the same question (Metzger et al., 2010).

2.2 Evaluation of the drivers and impacts of extreme heat

2.2.1 Heatwaves and Climate Change

There is an increase in the number of heatwaves over the land surface due to climate change (Harrington & Otto, 2020; Perkins-Kirkpatrick & Lewis, 2020; Rogers et al., 2021; Russo et al., 2016). In the most recent IPCC report it was shown that for almost all regions of the land surface there is now very high confidence that heatwaves are increasing in frequency, duration and intensity (IPCC et al., 2021). Climate change increases the number of heatwaves because at its simplest it is a rise in baseline temperatures. This alters the distribution of temperature, therefore the mean temperature increases and the end of the distribution is skewed which causes an increase in extreme heat and heatwaves (Perkins-Kirkpatrick & Gibson, 2017). To put this into some more context it is suggested that someone born in 1960 is on average across the land surface likely to have experienced around 4 heatwaves whereas someone born in 2020 is likely to experience 30 heatwaves with a 1.5°C warming (Thiery et al., 2021). However, the tropics has more exposure and is projected to have a bigger increase in the number of heatwaves than other regions of the world (Thiery et al., 2021).

2.2.2 Drivers of Land Heatwave conditions

Land heatwaves have many drivers and are influenced by a range of processes across the earth's surface. These include soil moisture content, anticyclonic blocking patterns, incoming solar radiation and teleconnections (Wehrli et al., 2019). The characteristics of a heatwave are influenced by its geography, for example near the equator does not experience blocking patterns (Russo et al., 2014). In addition, the drivers of a heatwave influence whether it occurs at night or during the day or both, which is considered more dangerous because of exposure times (Nazarian & Lee, 2021).

Blocking patterns are one example of drivers of heatwaves. This is where a high pressure pattern persists for a period of several days. High pressure persists either when a pressure system is blocked from a jet stream's zonal flow or where the system remains stationary due to a Rossby wave train (Perkins, 2015). During the Pacific Northwest heatwave in June 2021 this was in part caused by a blocking high which was given the term 'heat dome' a schematic of this can be seen in figure 2.4. Other examples of blocking patterns causing heatwaves are in Europe 2003, Russia 2010 and Chicago 1995 (Perkins, 2015).

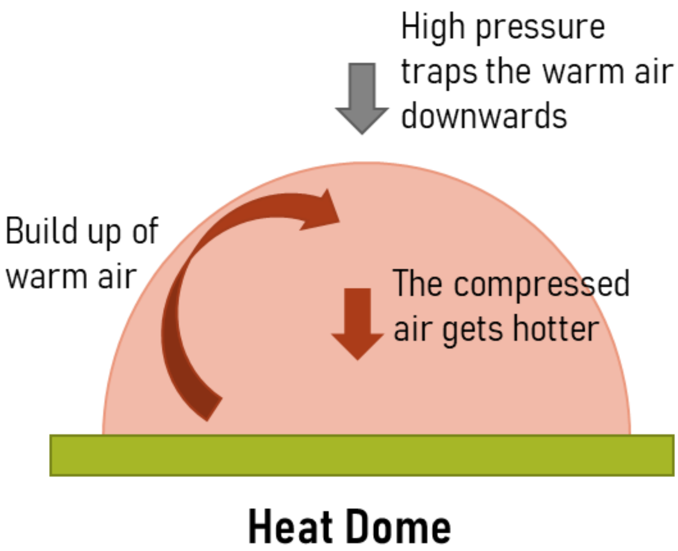

Figure 2.4 a schematic of a heatdome based on https://www.bbc.com/news/world-us-canada-57665715.

Soil moisture is also a key driver in heatwaves, because it influences how radiation from the earth's surface returns to the atmosphere and this is mostly in the form of two heat fluxes, sensible and latent (Alexander, 2011; Perkins, 2015). During dry conditions there is an increase in the sensible heat flux, whilst in wetter soil conditions there is an increase in the latent heat flux which appears as an increase in water vapour as shown in figure 2.5. Furthermore, this cycle is known to impact both the boudary layer of the atmosphere and the hydrological cycle (Alexander, 2011).

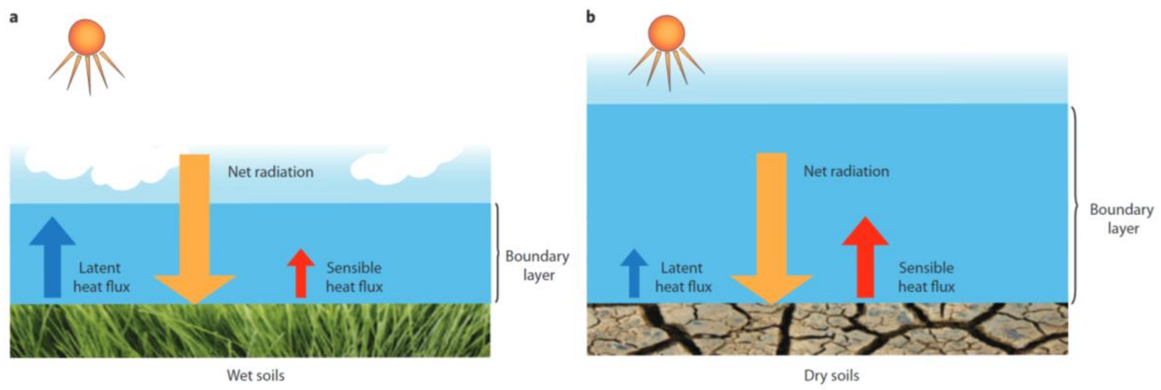

Figure 2.5 a schematic of incoming radiation and outgoing heat fluxes given certain soil conditions (Alexander, 2011).

Dry soil conditions therefore promote higher maximum temperatures (Alexander, 2011; Herold et al., 2016; Whan et al., 2015). For example, it is demonstrated that for Europe there is a negative relationship between soil moisture content and temperatures with a reduction in maximum temperatures of 1.5°C for a soil moisture content of 100 mm (Whan et al., 2015). In comparison, for Australia it is also found that there is a negative relationship between antecedent soil moisture and the intensity of heatwaves (i.e. the maximum temperature likely to be experienced), but a longer duration heatwave doesn't necessarily mean that there is low soil moisture content (Herold et al., 2016). In contrast, in Illinois in the United States it is found that higher soil moisture content in the spring season has a positive relationship with higher equivalent temperature, a measure that is used to indicate near surface response of both latent and sensible heat fluxes in the summer (Ford & Schoof, 2016), this leads to more oppressive humid heat than the dry heatwaves experience with low soil moisture content.

Teleconnections can play and important role in driving heatwaves and influencing them. For example, it is suggested that the North Atlantic Oscillation influences heatwaves in the West Sahel. Historically, the region has been shown to be influenced by climate events in the North-Atlantic (Fontaine et al., 2013). In addition it is claimed that the Sahel temperature change is linked with the increase in sea surface temperatures in the Atlantic (Fontaine et al., 2013). It is true that the majority of synoptic atmospheric systems in North-Africa are defined by Atlantic temperature gradients, but Land-surface feedbacks and more localised systems also further influence this relationship (Cornforth et al., 2016).

There is also evidence for teleconnections between the El Nino Southern Oscillation (ENSO) and heatwaves in the West Sahel region (Moron et al., 2016) but only with use of observation data in the form of global summary of the day synoptic observation data (GSOD), where missing data was constructed using probabilistic principal component analysis (PPCA). The research shows that the region has a lagged response to ENSO, of around 3 to 4 months and this is due to the complex interactions between the Pacific and the Sahel. This lag is of concern because the region appears to lag the phase of ENSO where the warming is at its most mature and intense (Moron et al., 2016).

2.2.3 The influence of extreme heat on health

The human body has to thermoregulate as a homeotherm (an organism whose core temperature has to be maintained despite the external environment) to an optimum core operational temperature of around 37°C. This has a circadian rhythm, being less by around 0.5°C in the morning than the afternoon (Kuht & Farmery, 2021). This thermoregulation acts as a feedback loop similar to the interaction between solar radiation and soil moisture in some respects, and is controlled by the brain through the hypothalamus at the base of the brain near the pituitary gland which defines what is known as a set point (Kuht & Farmery, 2021). When no responses by the body are initiated in response to the external environment and the core temperature can be maintained between 36 to 37.5°C this is known as the thermoneutral zone (TNZ) (Mekjavic & Eiken, 2006). Figure 2.6 is a schematic of the way different external factors on the human body impact the core temperature.

The body's main sensor for temperature is in the hypothalamus, there are also sensors in the spinal cord, the upper organs in the Abdominal Viscera and the great blood vessels. In addition, receptors for both cold and heat are present in the skin (Kuht & Farmery, 2021). When signals are sent from the receptors and sensors to the hypothalamus, it initiates a full body response; when someone is too hot this is an increase in sweat production and blood flows nearer the surface to carry heat away (Castillo, 2014; Kuht & Farmery, 2021). The hypothalamus also controls our thirst levels so when we lose moisture due to sweating, more when hot, the response to produce the hormone to tell us to drink more is initiated but also the response to tell our kidney's to retain more moisture (Castillo, 2014).

As previously mentioned, alarmingly, above 35°C in a 100% humidity heatwave (or an air temperature of 46°C at 50% humidity) (Marx et al., 2021), it is suggested that even a healthy person is at risk of death, because the body cannot cool the internal system to the operational temperature of 37°C. However, this 35°C is theoretical and it has recently been found that there is a range of temperatures around this depending on the surrounding climate for a healthy adult that is not acclimatized to higher heat conditions (Vecellio et al., 2022). When someone dies as a result of hyperthermia there are 27 different pathways that indicate the different pathways the body shuts down in, most often the kidneys are the organ to fail first, whilst a cardiac arrest is also common (Mora, Dousset, et al., 2017).

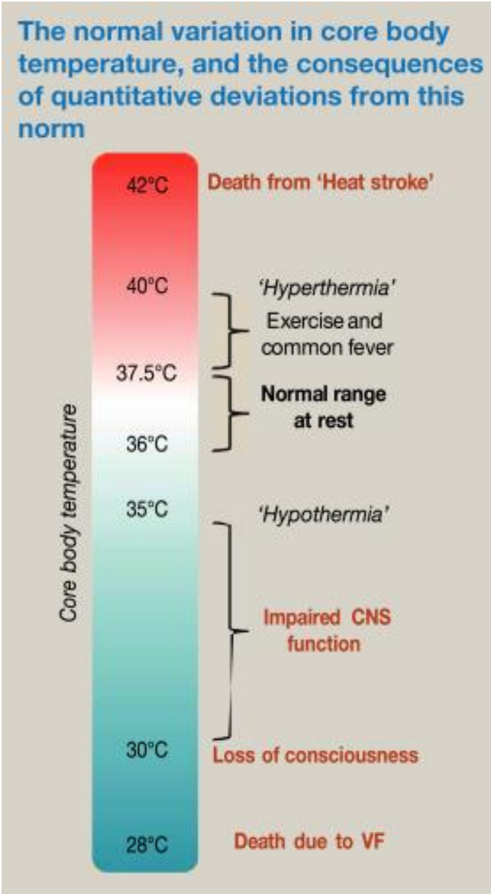

Figure 2.6 the thermal comfort range for humans where CNS is Central Nervous System and VF is Ventricular fibrillation which is heart arrhythmia (Kuht & Farmery, 2021)

Groups that are most vulnerable to the effects of extreme heat and heatwaves are those who have limited capacity to thermoregulate. This includes children, pregnant women, elderly, and those with a range of existing medical conditions (McLafferty, 2010). Additionally, those who work outside are more vulnerable because of their prolonged exposure to extreme heat (McLafferty, 2010).

Children (those up to the age of 12) have historically been seen as an at risk group because they have a smaller surface area to heat up and therefore heat up more quickly (Tsuzuki-Hayakawa et al., 1995). In addition, they have less of a capacity to sweat than an adult and less cardiac output than a healthy adult controlling the rate of blood flow around the body

(Rowland, 2008). However, there is a lack of evidence that demonstrates that children have impaired thermoregulation in comparison to healthy adults and it can be argued that a child's capacity to adapt to heat is the main cause of them being more vulnerable to heat (i.e. being left in a locked car or the ability to cool themselves down) (Rowland, 2008; Smith, 2019).

Pregnant women are considered an at risk group to extreme heat because it is widely considered that if their core body temperature exceeds 39°C that this can have a negative impact on foetal health (Ravanelli et al., 2019; Smallcombe et al., 2021). This has led to advice previously that women who are pregnant in certain climates should not exercise to avoid reaching this critical limit. Recent research shows that pregnant women can exercise for 45 mins in a climate of 32°C at 40% humidity without reaching this limit (Smallcombe et al., 2021). However, there is no evidence available to suggest whether there is an impairment or change in the thermoregulatory system whilst being pregnant (Ravanelli et al., 2019; Smallcombe et al., 2021).

Those who are elderly (above age 65) similarly to children have been seen as an at risk group to extreme heat (McLafferty, 2010). Those that are elderly often take longer to respond to a cool or hot stimuli, which slows down their body's response (Shibasaki et al., 2013; Taylor et al., 1995). Another reason elderly are more vulnerable to extreme heat is because as humans age their ability to sweat is reduced; each sweat gland on average produces less sweat and this is sometimes seen to start occurring as early as 40 years of age (Millyard et al., 2020). It has been shown that older adults (>50 years of age) have a heat load 1.3-1.8 times higher than younger adults (18-30 years of age) when exposed to heat conditions both whilst resting and exercising (Kenny et al., 2016; Millyard et al., 2020). In addition, elderly people experience a reduction in total blood volume, this means there is less blood to carry heat away from the surface of the skin, and some of this limiting of the thermoregulatory ability is negated by staying active throughout life (Millyard et al., 2020).

Many pre-existing medical conditions can reduce someone's body's ability to thermoregulate or/and their capacity to be able to react to a change in their thermal environment. These include: obesity, diabetes and cardio-vascular diseases, which are discussed in more detail below. Obesity is defined by a body-mass index (BMI) of 30 kg m2 or greater (Kopelman, 2000); we consider it here as a pre-existing medical condition but it should be noted that some do not consider it a medical condition but a self-inflicted condition (Kopelman, 2000). The number of people who are obese has increased significantly over the last 50 years (Blüher, 2019). Obesity causes a rise in the amount of fatty tissue in someone's body also known as adipose tissue and this has an insulating effect in comparison to lean tissue (Speakman, 2018). It is apparently shown that those with a high body fat content cool up to half as fast as those with a lower body fat content (Speakman, 2018; Tikuisis et al., 2000). However, it is not entirely clear from the study because the focus is on demonstrating that female do not have a significantly altered thermoregulatory response to males (Tikuisis et al., 2000).A further study suggests that fatty tissue surrounding the abdominal region may reduce the rate of heat transfer in this region, but that an increased heat transfer in extremities such as the hands might act to counterbalance this (Savastano et al., 2009). However, it has previously been shown that obesity increases the risk of heat related mortality by up to 3.5 times in the US (Henschel, 1967).

Diabetes is a condition that causes less insulin to be created impairing blood sugar absorption. It is projected that the number of people worldwide with all types of diabetes will have increased by 55% from 382 million in 2013 to 592 million in 2035 (Zimmet et al., 2014). Diabetes reduces someone's ability to thermoregulate, through decreasing their ability to sweat and reducing their overall rate of cooling. It is demonstrated that in most studies that diabetes increases both risk of heat mortality and hospitalization rates (Vallianou et al., 2021). However, it can also be suggested that more research on this disease and thermoregulation is needed (Yardley et al., 2013). In addition, it is important to note that type 2 diabetes has raised risk of occurrence in those with obesity, which further could limit thermoregulation ability (Kopelman, 2000; Zimmet et al., 2014).

Cardio-vascular diseases are the leading cause of death globally (WHO, 2021). The term includes diseases such as types of heart disease (i.e. coronary or rheumatic), deep vein thrombosis, cerebrovascular disease, vascular dementia, strokes and cardia/heart attacks (WHO, 2021). Cardio-vascular diseases limit the capacity of the body's ability to thermoregulate (Kuht & Farmery, 2021; Lin et al., 2013). This can include where blood flow is restricted therefore the ability to pump blood to dissipate heat is hindered or brain function is damaged (i.e. strokes or vascular dementia) which could impact the pituitary gland and hypothalamus in the brain stem (Kuht & Farmery, 2021; Lin et al., 2013; Liu et al., 2015). Several studies are the subject of a detailed review by Liu et al., (2015) which demonstrates that there is a rise in hospital admissions for those with cardio-vascular diseases during 'hot' weather encompassing heatwaves. For example, across 9 cities in Europe, on average 44% of people who died over the age of 65 during heatwaves died as a result of cardio-vascular diseases (D'Ippoliti et al., 2010). In addition, it is shown that for Sydney Australia those with cardiovascular diseases have a 1.01 odds ratio of being admitted to hospital when the temperature exceeds the 95th percentile in comparison to other days of the year (Vaneckova & Bambrick, 2013).

Further, of note many cardio-vascular disease studies made reference to the fact that often those with respiratory diseases (i.e. lung diseases, or conditions like asthma) also see a rise in mortality and hospital admissions during a heatwave. This is because of their limited capacity to thermoregulate as well as, because often a heatwave is accompanied with high pollution levels and an increase in particulate matter (Lin et al., 2013; Liu et al., 2015; Vaneckova & Bambrick, 2013). For example over 12 European cities, it was found that for every 1°C above the average apparent temperature there was a 4.3% rise in hospital admissions for those with respiratory diseases (Michelozzi et al., 2012).

Considering the first 2000 papers from a keyword search for 'thermoregulation' on the paper database Scopus, helps to further reveal what authors consider in their papers when discussing thermoregulation. This can be seen in Figure 2.7. Interestingly, heat stress and hyperthermia have more papers than hypothermia (i.e. Cold Stress). Many papers also discuss metabolism (which is a way to measure cooling) and cardiac arrests which as mentioned previously significantly increase during a heatwave (Lin et al., 2013; Liu et al., 2015).

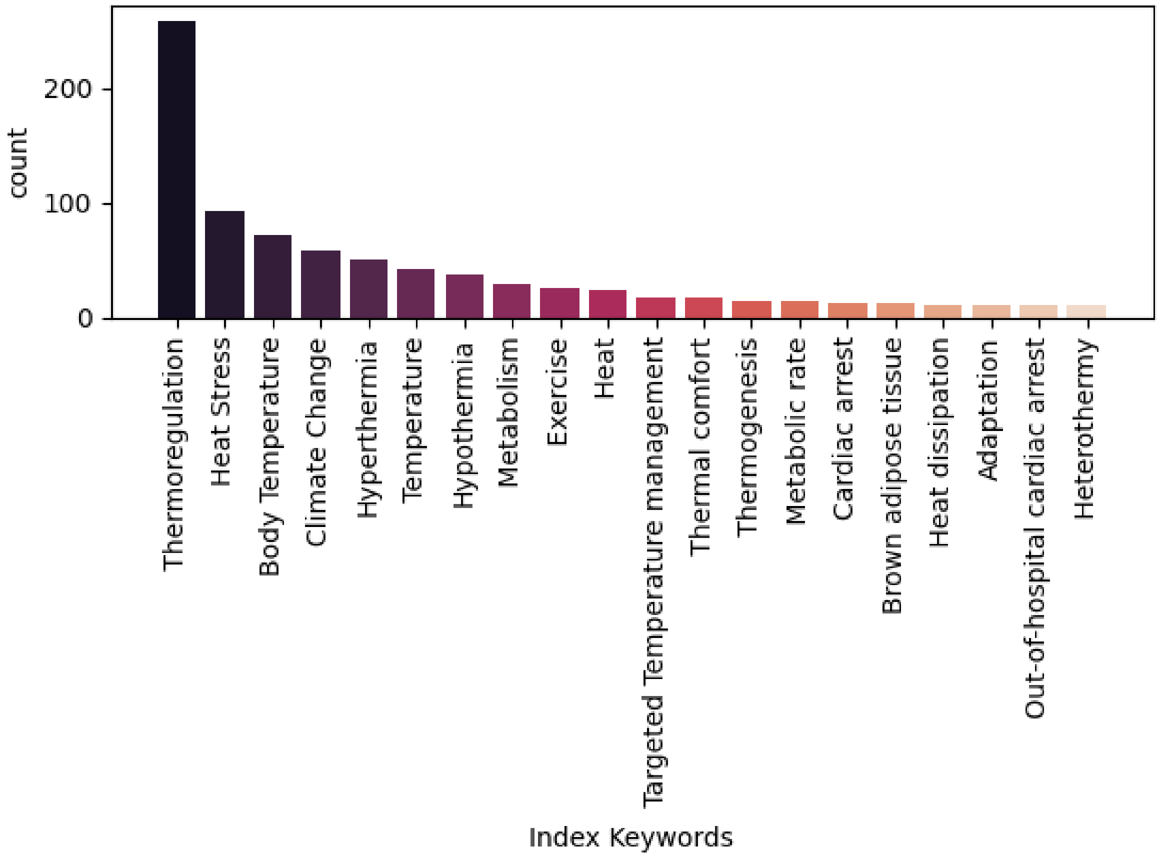

Figure 2.7 the top 20 index keyword used by academic papers on thermoregulation.

2.2.4 The Health impact of extreme heat

The influence of extreme heat on health means that heatwaves are notable for their health impacts, most commonly their high mortality rate. Heatwaves are currently reported to be the deadliest natural hazard of the last 5 years (WMO, 2018). The most common statistic for considering heatwave deaths is excess mortality, this is the number of deaths above the 5 year rolling average, and in this thesis deaths refers to this statistic unless otherwise noted (Office for National Statistics, 2021). Heatwaves caused the death of more than 70,000 and 55,000 people globally in 2003 and 2010 (Schubert et al 2011, Robine et al 2008). In the UK in 2019, up to 892 people died as a result of heatwaves over summer and in 2020 over 2,500 people died (Public Health England 2020, 2019). In Europe in the 2021 summer preliminary data shows over 5,000 people died during the Mediterranean heatwave (Coi & Mathiesen, 2021). In Northern Ghana, the districts of Kasena-Nankana, a study finds that the mortality rate was 1.8% for every 1°C above 30.6°C, using a time series Poisson distribution regression on mortality data in comparison with mean daily temperature (Azongo et al., 2012). However, for the UK it is currently found for age-weighted mortality, defined as “The age-standardized mortality rate is a weighted average of the age-specific mortality rates per 100 000 persons, where the weights are the proportions of persons in the corresponding age groups of the WHO standard population" (World Health Organisation, 2022) that there is not an increase in the death rate, because as previously seen age is a key factor in increasing heat-related death likelihood (Walkeden et al., 2022). In contrast, a study found that 1 in 3 heat related deaths could be linked to climate change since the 1970s (Vicedo-Cabrera et al., 2021).

Heat is widely known to have an impact on foetal health during pregnancy and the birth outcome for babies (Bonell et al., 2020; Chersich et al., 2020; MacVicar et al., 2017; McElroy et al., 2022; Syed et al., 2022). However, there is a lack of evidence on how heat interacts with foetal development during pregnancy (Bonell et al., 2020; MacVicar et al., 2017; Syed et al., 2022). Studies often demonstrate that exposure to extreme heat increases the likelihood of pre-term births, with one study suggesting the for every 1°C above average there was a 1.05 fold increase in the likelihood of pre-term birth (Bonell et al., 2020). In addition, it is often found by studies that birth weight of a baby is less in cases when there has been exposure to extreme heat and the relationship is greater where the mother is from a lower socio-economic background (Bonell et al., 2020). In addition, extreme heat exposure can also lead to a raised likelihood of still-birth, for example in a study of 14 lower-economical developed countries it was found the risk of a still-birth was larger where the maximum temperature is about 20°C and that in addition, small diurnal range, which suggests more consistently high temperatures also raised the risk of still-birth (McElroy et al., 2022). A real limitation is the lack of research on the impact of extreme heat throughout pregnancy and a sparse literature base for the African continent and parts of the tropics (MacVicar et al., 2017; Syed et al., 2022).

Further to this, heat causes a rise in cases of some types of diseases, and these can also result in death. An example of this is meningococcal meningitis (CSM), which is prevalent during the dry season in Western Africa, including in Ghana, with most cases occurring in the Northern region of the country (Codjoe & Nabie, 2014). There is a 5%-10% chance of mortality even with treatment, and in 10%-20% of survivors, they have further complications, for example, brain damage. Every 8-12 years there is a new epidemic of CSM in Ghana (Codjoe & Nabie, 2014). There is evidence that exposure to extreme heat can cause a rise in cases of kidney disease in outdoor workers, thought to be a result of dehydration (Glaser et al., 2016). In addition, it is demonstrated for South Australia that there is an increase of heat related mortality for those admitted to hospital with kidney disease with a incidence rate ratio of 1.1

(this is the ratio of those impacted in comparison to the control population) and with kidney failure with a incidence rate ratio 1.3 (Hansen et al., 2008).

2.2.6 The Socio-Economic and Environmental impacts of extreme heat

Several cross-sectional impacts occur as a result of heatwaves and extreme heat, as well as, health risks. Here some of the impacts are discussed, it should be noted this is not an exhaustive list These include decreasing crop yields (Vercillo et al 2020, Abass et al 2018), putting a strain on power grids (Larcom et al 2019) and reducing the productivity of labourers (Oppermann et al 2017). For example, rice is a staple food for billions of people especially in Asia with a growing market in parts of Africa (Farhat et al., 2021). Exposure to extreme heat levels reduces the yield of rice (Farhat et al., 2021; Muehe et al., 2019; Sun et al., 2021; Zhang et al., 2017). With one study suggesting with an increase of temperature during rice growing of 38°C with carbon cioxide at 850ppm would cause a 17% reduction in overall rice yield (Muehe et al., 2019). Rice however is also known to absorb arsenic as it grows; this occurs naturally in rice paddies but is also in increased volumes due to farming chemicals. The amount of arsenic also promotes a reduction in overall rice yield and the take up of arsenic is also greater with exposure of a rice plant to extreme heat levels (including over the whole growing period and at certain times) (Farhat et al., 2021; Muehe et al., 2019). In addition, other crops experience a reduction in yields. For example, it is suggested that maize, wheat and soybeans will all experience a reduction in yield with wheat seeing as much as a 52% reduction in comparison to 1980 levels under a RCP8.5 scenario (Deryng et al., 2014). However, this study has many assumptions and crop models may be inaccurate in their estimation of the impact of weather such as extreme heat (Siebert & Ewert, 2014). Crop yield reduction and the impact of extreme heat is an important area of research because it raises problems for food security and livelihoods especially in regions reliant on rain-fed agriculture (Abass et al., 2018; Larcom et al., 2019; Muehe et al., 2019; Vercillo et al., 2020).

Extreme heat is known to put a strain on power grids and also result in power outages as was the situation in a South American heatwave that effected Argentina in January 2021 (Raszewski, 2022) and has been the case in parts of California in both the Summers of 2020 and 2021 (Miller et al., 2020). This is because of the increase in energy demand from air conditioning which is often seen as a maladaptation (an adaptation measure that has negative consquences) to extreme heat because it exacerbates temperatures in the surrounding area (Larcom et al., 2019). Some parts of the Arabian penisular (i.e. Qatar) sees populations already living lives dependent on air conditioning because of the harsh temperatures experienced outside this has led to studies reviewing what impact this has on ways of living (Hitchings, 2020, 2022).

Productivity of outdoor workers and labourers is reduced during periods of extreme heat (Oppermann et al., 2017; Xiang et al., 2014). For example, for those who harvest rice in Asian countries there is a a projected decrease in their productivity of 2% with a 1.5°C rise in baseline temperature which is modelled making use of a type of WBGT (Simpson et al., 2021) and another study showed a 5% reduction in productivity for WBGT values of between 26 and 32°C (Sahu et al., 2013). In addition, subsistence farming is the main livelihood in Ghana, from a psychological perspective, everyone has an emotional response to the acute and sub-acute impacts of climate change. In Northern Ghana, farmers emotional response to 4 events associated with climate change, floods, droughts, extreme heat and erratic rainfall patterns were reviewed (Acharibasam & Anuga, 2018), to see whether this had an impact on their adaptive capacity which can be defined as *"the potential or capability of a system to adjust to climate change, including climate variability and extremes, to moderate potential damages, to take advantage of opportunities, or to cope with consequences"* (Smit & Wandel, 2006). The study found that for excessive heat, farmers were most likely to tolerate or conceal in response, meaning that they were more likely to put in place measures that would be maladaptive as a result of a psychological limit on their adaptive capacity (Acharibasam & Anuga, 2018). It can also be seen that the risk associated with an event is influenced by the availability effect and where farmers saw climate change as a local level risk, they were more likely to adapt (Abrahamson et al., 2008; Acharibasam & Anuga, 2018). Extreme heat also impacts those in the mining sector. In Ghana, ~82% of mine workers in a study perceived heat as a risk and that 81% perceived themselves as have experienced heat related morbidity, did in some way autonomously adapt to the excess heat risk (Nunfam, Oosthuizen, et al., 2019).

Other environmental examples include, impacting species migration patterns especially types of bird (Hiltunen et al., 2006) and impacting the diversity of species across ecosystems (Bastos et al., 2020; Meehl et al., 2000) including in fluvial environments where it is found that a low flow rate and a high water temperature up to 40°C in the Kiamichi river in the southern US led to a rise in mortality of temperate freshwater mussels (Galbraith et al., 2010).

2.3 Adapting to extreme heat

Adaptation is defined as *"The process of adjustment to actual or expected climate and its effects. In human systems, adaptation seeks to moderate or avoid harm or. exploit beneficial* *opportunities."*(IPCC,2021). A suite of option to adapt to extreme heat is outlined by Turek-Hankins, et al., 2021. In addition, one way to categorise climate change adaptations including extreme heat adaptations is to use a framework set out by the European Environment agency into *soft, green and grey* (Abhold et al., 2015). *Soft* is defined as corresponding to the design and application of policies and procedures, as well as land-use controls management strategies, information and dissemination programs, or economic incentives to reduce or prevent disaster vulnerability (Abhold et al., 2015). They require careful management of the underlying human systems. *Green* is defined as ecosystem-based approaches that use the multiple services of nature, this category covers nature-based solutions (Abhold et al., 2015). *Grey* is defined as infrastructure approaches are physical interventions, construction measures or the use of engineering services to make buildings and infrastructure essential for the social and economic well-being of society more capable of withstanding extreme events (Abhold et al., 2015).

Using a Scopus keyword search of all open access papers using the words heatwave or heat wave and/or extreme heat and adaptation returned 1,364 academic papers, categorising these into soft, green, grey, multi and none showed that most papers 685 were a none category not fitting the define categories because they discussed factors such as a marine environment or how heat impact a protein or gene in a certain specie of plant. Soft had 253, multi 145, grey 144 and green 143 the type of adaptations mentionned in these categories will be discussed in more detail below.

Multi was where studies discussed a mix of the adaptation measures discussed below but also where general reference was made to adaptation, whilst reviewing the academic papers it was often the case that specific adaptation strategy was absent from the abstract, it can be suggested that this could be a hinderance to such studies being useful in the creation of policy because it is not clearly signposted what the most advantageous adaptation might be from the view of a policymaker or other stakeholders such as hospital managers.

2.3.1 Soft Extreme Heat Adaptation

Soft adaptation covers types of adaptation such as communication, education and individual behaviour change including cooling strategies. It makes sense that soft would be the type of adaptation that is included most in academic papers because this mirrors policy where the suggested adaptation for extreme heat are mostly to do with behaviour change and 'common' sense also known as 'autonomous' adaptation (Porter et al., 2014).

The majority of studies that were considering soft adaptation strategies were also discussing them in response to the health impact of extreme heat, which in previous sections of this review have been seen to be abundant.

Research shows that whilst putting feet in cold water can be used to reduce core body temperature (Arens et al., 2006; Clapp et al., 2001; Livingstone et al., 1995), the fastest and recommended approach to treat heat stress/stroke is whole body submersion there is no benefit in using ice water the water must simply be cooler than the individual (Cheshire, 2016; Wasserman et al., 2021). In addition, no benefit was found from cooling feet instead of hands or face, each provided cooling as quickly as the other approaches (Clapp et al., 2001).

2.3.2 Green Extreme Heat Adaptation

There are 2 main broad types of green adapation considered in this category. These are crop adaptation where impact on food security and yield is included, and nature-based solutions (i.e. open spaces and parks in cities) as a cooling strategy. Given the move in recent years to nature-based solutions, it is of surprise that this category had the least studies out of all the types of adaptation.

Urban greening is used as an adaptation to reduce the impact of the urban heat island (UHI) effect which causes a rise in temperatures in cities in comparison to it's surroundings (Aflaki et al., 2017; Alexandri & Jones, 2008; Tomlinson et al., 2011). Another benefit of this type of adaptation is if it has a good design it can be used to not only reduce heat but also levels of pollution and capture rainfall (Busker et al., 2022). One study shows that green walls and roofs provide more cooling than just green walls or a green roof alone, and found a 8.4°C decrease in maximum temperatures in buildings in Hong Kong with green walls and a green roof (Alexandri & Jones, 2008). In addition, another study finds that for Kuala Lumpa, Hong Kong and Singapore on average green roofs provide a reduction in average temperature of 4°C and average mean radiant temperatures of 4.5°C this study concludes green roofs and effective way to reduce the UHI (Aflaki et al., 2017). Further, a study in the Greater Boston area demonstrates that green roofs reduce summer-time temperatures weighted by population on average by 0.35C and this was associated with a 0.26% reduction in the heat mortality rate in the area (He et al., 2020).

Crop yield adaptations that focus on food security are also considered a type of green adaptation by this thesis. Under a high emission SSPS8.5 scenario one study finds a 4.2% reduction of wheat yield in the North China Plains in the 2080s, they find this is reduced when sowing later and using crop varieties that flower later in the season (Bai et al., 2022). In addition, a study found that cotton in Greece was vulnerable to extreme heat and cold shocks and heat shocks were projected to impact the crop more over time. As such they suggested that the breeding of heat and drought resistant varieties should take place but in the short term changes in sustainable irrigation and crop spacing could be beneficial adapatation methods (Engonopoulos et al., 2021).

2.3.3 Grey Extreme Heat Adaptation

Grey adaptation includes building retrofitting, cooling centres and air conditioning and early warning systems. Building retrofitting includes factors such as adding insulation to a building or shutters to a window. One study shows that the building material of houses in urban areas in Ghana significantly raises someones risk level to experiencing overheating and heat stress (Wilby et al., 2021). In comparison, it is projected for the UK that overheating will increase across the whole country by the 2050s and 2080s with terrace houses overheating moreso than semi detached and detached houses and in addition natural ventilation and solar shading could be used to reduce thermal comfort to comfortable levels in northern regions (Wright & Venskunas, 2022).

In addition, air conditioning is a grey adapatation which is used in cooling centres which are buildings opened to the public during the period of heatwaves (Widerynski et al., 2017). As mentioned previously air conditioning can be seen as a maladpatation as it raises the surrounding temperature (Larcom et al., 2019). But cooling centres are often a necessary part of a heatwave plan to protect vulnerable groups as is discussed in detail by Widerynski et al., (2017), demonstrating the trade-offs that have to be considered when putting in place any adaptation strategy.

Early warning systems are considered a grey type of adaptation because of the technological capability needed to provide an accurate weather forecast. Early warning systems are widely considered the most efficent and cost effective way to reduce the impact and risk of heatwaves (Committee on Climate Change, 2020; WMO & WHO, 2015). It is important to state that early warning systems are most successful when they are combined with soft adaptation strategies especially communication. For example, a recent study in Germany found that adaptation was most effective if a warning was accompanied with a type of soft adapatation suggestion (Heidenreich et al., 2021).

2.3.4 Heat Early Warning Systems

During the course of human history there have been a number of paradigms that have existed for disaster risk reduction, the production of knowledge and early warning systems, here the history of early warning systems is briefly outlined using the framing provided in Basher et al., 2006, with reference to the wider disaster risk reduction landscape made. In addition, it is important to note that many countries do have heat early warning systems but there are noticeable discrepancies between them, for example whether they are applied to health or are weather warnings (Casanueva et al., 2019).

1. **Pre-science early warning systems:** In the era prior to scientific understanding societies and cultures understood disasters and risk through stories past down as myths (Basher & Ono, 2022). This is also sometimes tied to an extreme fatalist view of the world where disasters are seen as an act of divine beings, instead of the interactions of nature with human society (Schipper, 2010).
2. **Ad hoc science-based early warning systems:** These are signals from nature that were understood by societies to indicate a certain hazard was about to occur. For example, frogs are suggested to leave an area prior to a volcanic eruption, or the idea that cows lie down before it rains (Atkins, 2009; Spear et al., 2012) . Pre-science and ad hoc science fit within the paradigm of understanding disasters prior to the Lisbon Earthquake of 1755, which is attributed to being the first 'modern' disaster with an emergency response(Chester, 2001).
3. **Systematic end-to-end early warning systems:** It can be argued that most operational early warning systems in place now are still Systematic end-to-end early warning systems, for example the Global Flood Awareness System GloFAS (Alfieri et al., 2013; Emerton et al., 2016) . Where forecasts are issued and then sectors are expected to issue warnings(Alcántara-Ayala & Oliver-Smith, 2019). This fits within the Disaster Risk Reduction paradigms that exist for resilience and sustainability, the idea of community and political economy that developed from the 1980s to the 1990s (van Aalst et al., 2008; Adger, 2000; Gallopín, 2006; Neumayer et al., 2014).
4. **Integrated Early Warning System:** are a participatory approach to disaster risk reduction, where there is collaboration across sectors on warnings and what resources and infrastructure is needed to dissemination and put in place preparedness(Mapfumo et al., 2013; Neumayer et al., 2014). Integrated Early warning systems should acknowledge people's interaction within the environment, including

adaptive capacity and their stories as a key element to reducing risk through an early warning system (Alcántara-Ayala & Oliver-Smith, 2019; Hillbruner & Moloney, 2012). These systems fit within the move in the humanitarian sector towards anticipatory action (Coughlan de Perez et al., 2022). Integrated Early Warning Systems have 4 main elements as outlined in figure 2.8: *Risk Knowledge, Response Capability, Monitoring and Warning and Dissemination and Communication.*

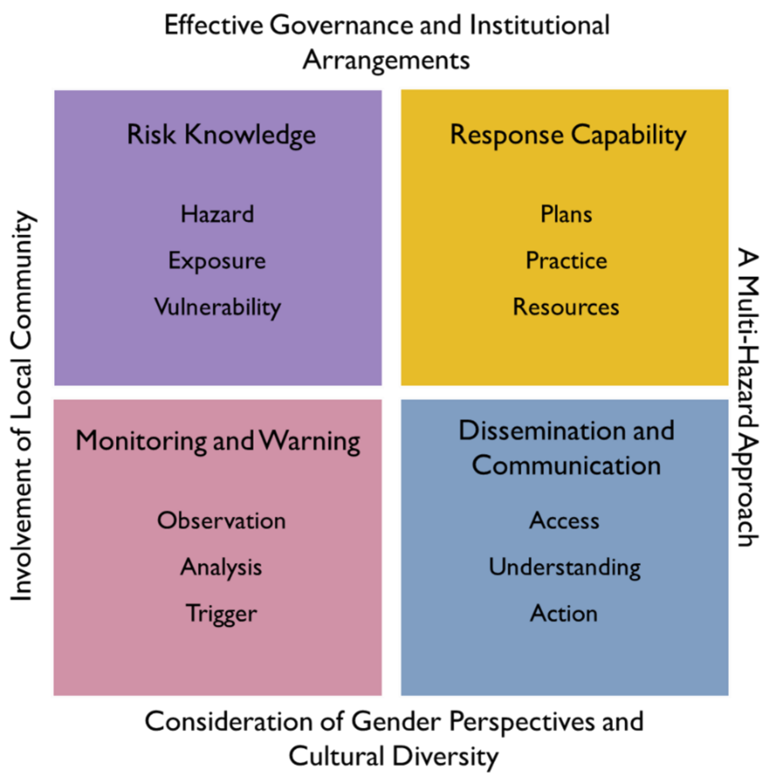

Figure 2.8: The Current Paradigm of Early Warning Systems as set out by Climate Risk and Early Warning Systems. Adapted from (Practical Action, 2020)

2.4 Challenges for adaptions

As explored in section 2.3 there are many adaptations that can be put in place to reduce the impact and risk of extreme heat. But there are also a plethora of challenges and barriers that currently exist to putting in place many of these adaptations, it is important to highlight these in an attempt to work toward resolving them. Challenges for adaptation are interlinking with one another and are summarised in figure 2.9.

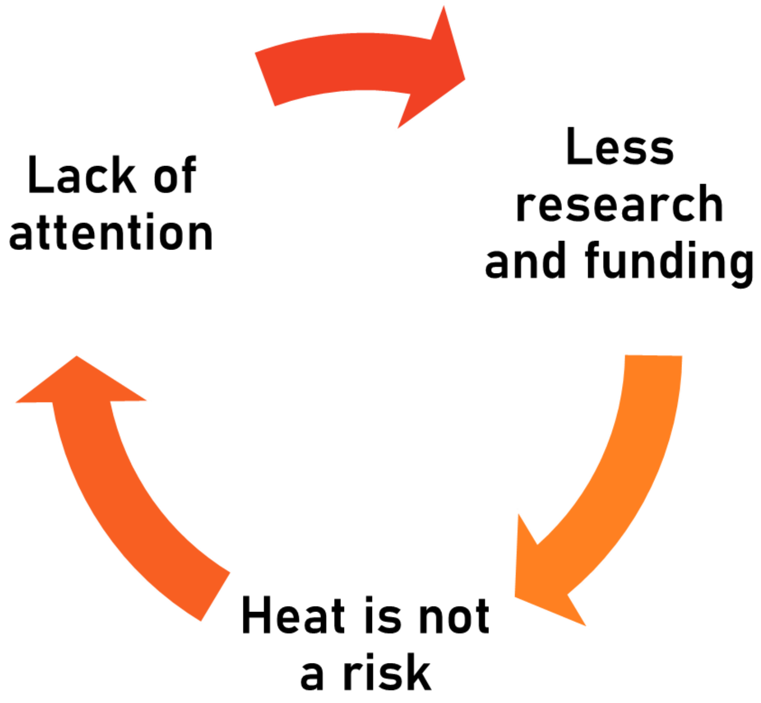

Figure 2.9 A cycle of how challenges to heat adaptation interlink with one another and therefore resolving challenges or barriers is can be seen as complex.

This thesis considers heatwaves to be an invisible risk and a silent killer. The origin of this statement is rooted in literature (Harrington & Otto, 2020; Howarth et al., 2019; Wolf et al., 2010). This is where studies demonstrate that heatwaves are underreported for sub-saharan Africa (Harrington & Otto, 2020) or globally (Vogel et al., 2019). In addition, it is found that many in a UK setting who are vulnerable to extreme heat do not perceive themselves as such and those under 45 do not sufficently adapt to heat and see it in a positive way (Williams et al., 2019).

Another simple way to demonstrate the lack of attention is to use the open access Google Search trend tool for worldwide hazard interest trends. In figure 2.10 it is clear to see that heatwave the red line has the least interest in comparison to the other hazards and that there is only interest in heatwaves during the week where a significant one occurs here the Pacific North-West heatwave (Sjoukje Philip et al., 2021). Storms and floods have a more consistent and higher search rate for interest than the other hazards but also peak when there is an occurrence of their hazard.

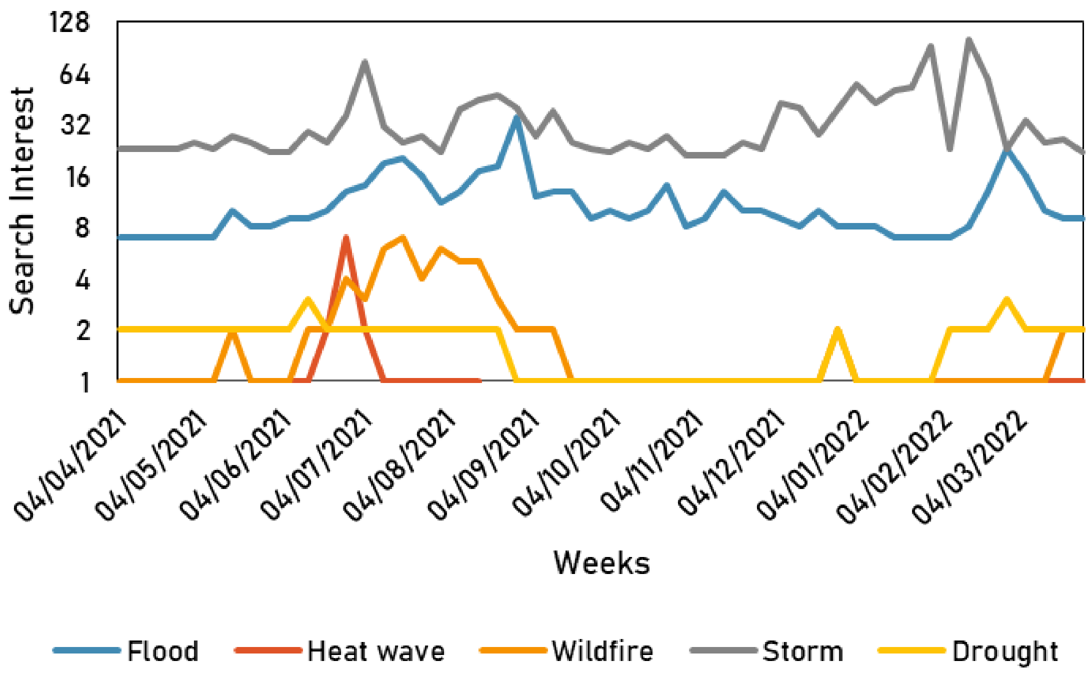

Figure 2.10 Google search interest for the world for the search terms: Flood,Heat wave, Wildfire, Storm and Drought at a weekly interval for the April 2021 to April 2022.

The lack of attention for heatwaves is mirrored in funding and research, although it is easier to evidence in research. Considering another Scopus keyword search of the academic literature highlights the descrepancy at an international level for heatwaves in comparison to other hazards. Heatwaves (Heatwave and Heat wave) returns 68,172 academic papers, Floods (Flood*) returns 265,566 academic papers, Storm (Storm) returns 148,793 academic papers and Drought (Drought) returns 128,792 academic papers. Wildfire is the only hazard with less academic papers at 20,157 (Wildfire*) which although interesting is out of scope of this thesis.

Perception and adaptive capacity are important factors in resilient heat adaptation. For example, one study found that in Phoenix, US those who were the lowest earners were the most likely to say that heat was a catastrophe. In addition, it found very different thermal perception and actions whether people saw 'heat is an inconvenience', 'heat is a manageable problem' and 'heat is a catastrophe'. The study concludes that narratives people build about heat are an important factor missing from many vulnerability heat indexes and policy (Guardaro et al., 2022). As mentionned previously, younger people in the UK having a positive bias associated with extreme heat makes them more likely to report heat related illnesses and not effectively adapt to extreme heat (Williams et al., 2019). In addition, older people in the UK not seeing themselves as vulnerable hinders their likelihood to adapt to extreme heat (Wolf et al., 2010).

2.5 Summary

Extreme heat is a fast growing area of research that covers a wide range of topics and sectors as has been demonstrated in this literature review. There are many areas of importance that come across. This thesis chooses to take a systems approach and adapt a WHO framework for climate resilience health services to focus on 4 objectives as outlined in Chapter 1. These are: O1 *Assess policy prioritization and governance, O2 evaluate the trends and modelling for extreme heat, O3 develop new technologies to reduce risk to heat and O4 consider the communication of heat risks and impacts within wider culture.*

3. Methodology

Across the thesis a mixed-methods approach is taken. This is the chosen approach given the interdisciplinary research carried out in this thesis and the intersection of extreme heat across sectors (as shown in Chapter 2). All technical research was carried out in the programming languages of python and R.

3.1 Open Science, Software and Research

All the methods and data chosen used across this thesis are in keeping with open science, software and research. Open science is where the research results are reproducible and transparent (Armeni et al., 2021). Open software is where developed code is made available to the research community, in this case the heat stress research community. Then, collaboration and contributions from the community are encouraged allowing for transparency in how methods are calculated (Currion et al., 2007; Li et al., 2013). This is important because it allows for the opportunity for the results produced in this thesis to be reproduced and allows for better comparison.

3.2 ERA5 Reanalysis dataset

The ERA5 Reanalysis Dataset is used throughout this thesis. A reanalysis dataset combines a range of observations (i.e. satellite data and weather station data) with numerical weather prediction data via data assimilation (Hersbach et al., 2020).Limitations to Reanalysis datasets do exist it is known there is a reduction in accuracy around the coast and at higher elevations. Reanalysis historically do not take into account land cover, and therefore do not include the urban heat island effect (Hersbach et al., 2020).

The 2 main reasons for using ERA5 are because this is a state-of-the-art dataset that provides global gridded data every 1 hour at a 0.25x0.25° grid scale, providing data for regions where observations are sparse (Hersbach et al., 2020). The second, is because although there are a number of reanalysis datasets available as listed in Table 3.1, ERA5 is the only product that provides data for Mean Radiant Temperature and the thermal comfort index, the Universal Thermal Climate Index (UTCI) as part of ERA5-HEAT(Di Napoli et al., 2021).

Table 3.1 available reanalysis datasets

Reanalysis Dataset	Provider	DOI
ERA5	ECMWF	doi:10.24381/cds.e2161bac

MERRA-2	NASA	doi: 10.5067/VJAFPLI1CSIV
JRA-55	Japanese Meteorological Agency	doi:10.2151/jmsj.2015-001
CFSR	NOAA	doi:10.1175/2010BAMS3001.1

3.3 Heat Stress Indices Calculations

Here the equations and methods to calculate thermal comfort indices are outlined. All the thermal comfort indices and supporting methods discussed below are featured as part of the *thermofeel* python package developed as an output of this project in collaboration with ECMWF and part of the EU Horizon 2020 Hidalgo project (Brimicombe, et al., 2021, 2022).

The cosine of the solar zenith angle (cossza) is the angle between the sun's rays and the vertical (Aktaş & Kirçiçek, 2021). It can be calculated using instant cossza which is the simplest approach to calculating a cossza, it is calculated using equation 3.1 and 3.2 (Hogan & Hirahara, 2015, 2016). It involves the solar declination angle which is the angle between the equator and the center of the earth the center of the sun. In addition, it involves the local solar time.

$$\mu_0 = \sin\delta\sin\phi + \cos\delta\cos\phi\cos h$$

[3.1]

δ is the solar declination angle and ϕ is latitude, h is the local hour angle.

$$h = T + \lambda + \pi$$

[3.2]

T is local solar time and λ is longitude.

The mean radiant temperature can be defined as the incidence of radiation on a body. For a numerical weather prediction service, it requires 5 input radiations (surface-solar-radiation-downwards, surface net solar radiation, total sky direct solar radiation at surface, surface thermal radiation downwards, surface net thermal radiation) in addition to the cosine of the solar zenith angle (cossza). The full methodology for mean radiant temperature is available in Di Napoli et al., 2020 and is summarized in table 3.1 and equations 3.3 and 3.4.

$$\mathrm{MRT}^* = \frac{1}{\sigma}\left\{\mathrm{f_a}\ \mathrm{L_{surf}^{dn}} + \mathrm{f_a}\ \mathrm{L_{surf}^{up}}\left[\frac{\mathrm{a_{ir}}}{\varepsilon_\mathrm{p}} + \left(\mathrm{f_a}\ \mathrm{S_{surf}^{dn,diffuse}} + \mathrm{f_a}\ \mathrm{S_{surf}^{up}} + \mathrm{f_p}\ \mathrm{I}^*\right)\right]\right\}^{0.25}$$

[3.3]

$$\mathrm{f}_p = 0.308\cos\left(\gamma\left(\frac{0.998-\gamma^2}{50000}\right)\right)$$

[3.4]

Table 3.1: The radiation variables that are used in the calculation of the MRT in Equations 3.3 and 3.4. Table 1 from Di Napoli et al., 2020

Name	Symbol/Equation
Surface solar radiation downwards	Sdnsurf=Sdn,directsurf+Sdn,diffusesurfSsurfdn=Ssurfdn,direct+Ssurfdn,diffuse
Surface net solar radiation	Snetsurf = Sdnsurf − SupsurfSsurfnet=Ssurfdn−Ssurfup
Direct solar radiation at the surface	Sdn,directsurfSsurfdn,direct
Surface thermal radiation downwards	Ldnsurf Lsurfdn
Surface net thermal radiation	Lnetsurf=Ldnsurf−Lupsurf

The universal thermal climate index (UTCI) is a bioclimatological model of an average human body's response to different thermal conditions where the subject is not acclimatised to the climate and is outdoors, doing minimal work (Fiala et al., 2012; Di Napoli et al., 2018). It was developed as part of the COST European Cooperation in Scientific and Technical Research action 370 in the early 2000s.

The original Fiala model of the UTCI is computationally complex, featuring 12 symmetric compartments and 187 nodes (Fiala et al., 2012). This encompasses key heat transfer systems within the body, including the central nervous system and modelling the reaction of processes to external climate factors which include long-wave and short-wave radiation, ambient temperature, convection and evaporation. The basic human heat/energy balance equations, and the UTCI scale are described more fully in Fiala, et al., (2012).

The UTCI is the thermal comfort index explored the most as part of this thesis. This is because it is new in comparison to many heat stress and thermal comfort indices (Blazejczyk et al., 2012; Jendritzky et al., 2012; Zare et al., 2019). Other evidence for exploring the UTCI is for example, Zare et al., (2019) demonstrate that the UTCI and Wet bulb dry temperature have a strong correlation and should be explored further for the mining sector, whilst Jendritzky et al., (2012) outlines the full background of the usefulness of the UTCI to standardize heat stress cross sectors and further Blazejczyk et al., (2012) claim that the UTCI on a micro-climate scale outperforms a number of heat stress indices such as WBGT, Effective temperature and Heat Index. It is also the only one that is commonly found in research to contain a body model. This body model can be a considered a more robust way to try and capture a body response to the thermal environment (Blazejczyk et al., 2012; Jendritzky et al., 2012). The UTCI method currently in use by most research is a 6-order polynomial approximation of the more complex body model a schematic can be seen in figure 3.1.

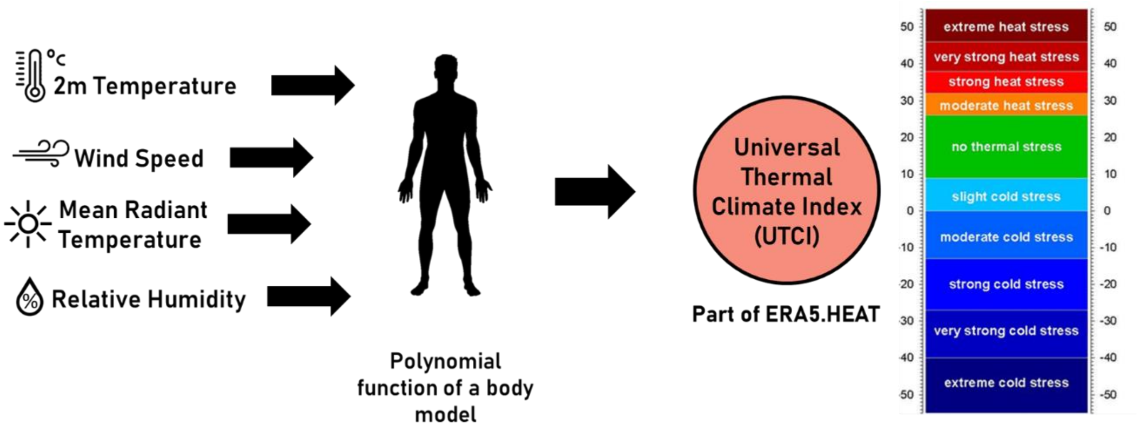

Figure 3.1: a schematic of the UTCI, adapted from Brode et al., (2012)

The polynomial approximations significantly reduces run-time and the computer capacity needed to run the original model whilst having a small 1.1°C Root Mean Square Error and is summarised by equations 3.5 and 3.6 (Bröde et al., 2012; Fiala et al., 2012; Jendritzky et al., 2012).

$$UTCI(Ta, Tr, Va, Pa) = Ta + Offset(Ta, Tr, Va, Pa)$$

where Ta is air temperature, Tr is mean radiant temperature, Va is wind speed Pa is water vapour pressure and the Offset is the 6-order polynomial. *Pa* is determined from saturation vapour pressure (*Ps*) and relative humidity percent (φ)

[3.5]

$$Pa = Ps \times \frac{\varphi}{100}$$

[3.6]

The most widely used heat index is the wet bulb globe temperature (WBGT) (Blazejczyk et al., 2012; World Meteorological Organization, 2018a). It was developed in the US by the navy to account for heat stress cases as a result of training (Blazejczyk et al., 2012; Budd, 2008). However, it has been established as an environmental index, which means the index does not take into account biological or behavioural responses by individuals to extreme temperatures (Budd, 2008). WBGT combines measurements from a natural wet-bulb temperature (which is an indication of evaporation levels), a globe temperature (which with a dry-bulb temperature measures the effect of radiant heat), air temperature and wind speed. WGBT is defined by equation 3.7.

$$WBGT = 0.7T_w + 0.2T_g + 0.1T_d$$

where T_w is Natural wet-bulb temperature, T_g is Globe Temperature and T_d is Dry bulb temperature.

[3.7]

The instrumentation that is used to take the temperatures combined into the WGBT are not standardly used, and this leads to calibration errors and some omitting the Globe Temperature element from WGBT. It is also concluded by Budd, (2008), that it is only a representation of the likelihood of adverse effects of heat.

The Heat Index takes into account air temperature and relative humidity to be an indication of how hot it feels and as such is another example of an environmental index (Blazejczyk et al., 2012). The method combines multiple regression analysis and another index, Apparent Temperature's use of relative humidity. The simplified version of the Heat Index can be seen in equation 3.8 where T is in °C (Blazejczyk et al., 2012), whilst the version of the Heat Index used by the National Weather Service in the US can be seen in equations 3.9 and 3.10 where T is in °F (National Weather Service, 2022) .

$$HI = -8.784695 + 1.61139411 \cdot T + 2.338549 \cdot RH - 0.14611605 \cdot T \cdot R$$
$$-1.2308094 \cdot 10^{-2} \cdot RH^2 + 2.211732 \cdot 10^{-3} \cdot T^2 \cdot RH + 7.2546 \cdot 10^{-4} \cdot T \cdot RH^2 - 3.58 \cdot 10^{-6} \cdot T^2 \cdot RH^2$$

[3.8]

HI = −42.379+2.04901523 T+10.14333127 R−0.22475541 TR−0.00683783 T^2−0.05481717 R^2+0.00122874 T^2*R+0.00085282 T*R−0.00000199 T^2*R^2+ADJ

[3.9]

Where, ADJ=0 unless (1) R<13% and T is between 80 and 112◦F, then ADJ=−[(13−R)/4]∗SQRT([17−ABS×(T−95.)]/17); or (2) if R>85% and T is between80 and 87◦F, then ADJ=[(R−85)/10]∗[(87−T)/5]

[3.10]

Humidex aims to describe how hot and humid weather feels to an average person, and was developed by the Canadian meteorological service (Smoyer-Tomic & Rainham, 2001). Similarly to WGBT and Heat Index, it is an environmental index, where air temperature and air vapour pressure are used as an indication of perceived temperature (Blazejczyk et al., 2012). The equation for humidex and for how air vapour pressure are calculated can be seen in equation 3.11 and 3.12.

$$Humidex = T + 0.5555 \cdot (vp - 10)$$

[3.11]

$$vp = 6.11 \cdot e^{5417.753 \cdot \left(\frac{1}{273.16}\right) \cdot \left(\frac{1}{273.16+td}\right)} \ where\ td\ is\ dew\ point\ temperature.$$

[3.12]

Normal effective temperature (NET) links effective temperature which indicates the effects on comfort through air temperature and relative humidity and an organism's thermoregulatory capacity. This can be seen in equation 3.13.

$$NET = 37 - \frac{37 - T}{0.68 - 0.0014 \cdot RH + \frac{1}{1.76 + 1.4 \cdot v^{0.75}}} - 0.29 \cdot T \cdot (1 - 0.01 \cdot RH)$$

where v is wind speed for 1.2m above the ground.

[3.13]

NET has been adapted for use by many countries meteorological services, including Hong Kong and Poland. Interestingly in Germany it is extended further and used for medical check-ups for workers who could be vulnerable to heat.

Apparent Temperature was developed by Steadman, (1984) to describe the thermal comfort/resistance of an average adult walking when they are exposed to certain combination of temperatures, relative humidity's and wind speed. It is an environmental index and it is calculated using equation 3.14.

$$AT = T + 0.33 \times RH - 0.7 \times V - 4$$

[3.14]

Wind Chill is an indication of cold thermal conditions. Originally developed by Siple & Passel, (1945) and updated by the Canadian Meteorological Service in 2001, it is a cold stress index and it is calculated using equation 3.15 .

$$WCT = 13.12+0.6215 \cdot T-11.37 \cdot v10^{0.16}+0.3965 \cdot T \cdot v10^{0.16}$$

[3.15]

3.4 Quantitative Analysis

A range of quantitative analysis techniques are used in this thesis to answer the key aim and objectives More detail can be found in each Chapter of this thesis.

A principal component analysis (PCA) was carried out. This is a popular type of multi-variance analysis that can be used to assess how input variables correlate with the outputted variable as well as, providing an overview of how much of the output variance (the variability of a variable from its mean) (Abdi & Williams, 2010; Yarnal, 1994). Whilst linear interdependencies between variables can affect the performance of a PCA, it is a valuable method in any case to demonstrate the make-up of variance, reducing the dimensions and space of variables.

The method used to carry out the analysis is a probabilistic principal component analysis, which uses likelihoods to determine the most probable make-up of the components as described in the method set out by (Tipping and Bishop, 1999). In addition, this approach applies Singular Value Decomposition which projects values into simpler dimensions of space. It uses a type of orthogonal matrix which is created during the method that can be described as rotation (Pedregosa et al., 2011). First, the input variables were standardized to remove the units, because PCA responds to dimensionality and then a principal component analysis carried out making use of the *scikit-learn* python library (Pedregosa et al., 2011).It should be noted that this methodology is not carried out over a spatial domain as would be the case in an empirical orthogonal function (EOF) analysis, the focus is on the individual variables variance in the UTCI not their spatial composition. There are many studies that use this method these include pre-processing for detection of breast cancer, use in heart failure detection and classifying forum questions (Ibrahim et al., 2021; Reham et al., 2020; Fong et al., 2015).

Multiple linear regression is another method used. Assumptions made are it can only be robust when most input variables are demonstrated to have at least a small degree of linear correlation with the outputted variable. In addition to any linear interdependencies between variables meaning that the trend of the UTCI could not accurately be captured by this technique (Schneider, et al., 2010). The *scikit-learn python* library was used, specifically its *linear regression* function. Further, to assess the linear relationship between variables, scatterplots, also known as correlation plots, are created. To explore the sensitivity of input variables with an outputted thermal comfort method a Spearman's rank correlation is also used (de Winter et al., 2016).

Spatial anomaly plots are used to demonstrate a range of differences. These include the difference in methods for the calculation thermal comfort indexes and the anomaly of heat indices compared to climate (1991 to 2020) values. In addition, mean absolute errors (MAE) are also used to make comparisons between different methods.

Heat stress area is evaluated in three ways. The first makes use of the 26°C UTCI threshold, which, once exceeded, indicates thermal levels at which an individual would experience heat stress, ranging from moderate (26°C to 32°C UTCI) to extreme (above 46°C UTCI). The second uses values above a 5°C UTCI anomaly compared to the heat stress climatology for August from 1981 to 2010. The third, uses a monthly 90th percentile threshold. In all cases, we use gridded spatial data to create binary maps with grid cells over the threshold set equal to 1, 0 otherwise (Vitolo et al., 2019) .

As exposure to heatwaves is known to be greater in more populated areas (Chambers, 2020; Watts et al., 2017), the gridded data is first masked to land area, excluding Antarctica, and then also masked to populated land area using grid cells with a population count of over 0 from the Land Scan dataset for 2000 to 2019 provided by the Oak Ridge National Laboratory (Dobson et al., 2000; Vijayaraj et al., 2007), with 2020 being masked to 2019 population count.

3.5 Qualitative Analysis

A range of qualitative analysis is used in addition to the quantitative analysis carried out in this thesis. We analyse the international natural disaster database EM-DAT. Emergency Events Database (EM-DAT) is a leading international disaster database run by the Centre on the Epidemiology of Disasters (CRED) since 1988 (CRED, 2020a) and data is used in reports by the UN (Cullmann et al., 2020; World Meteorological Organization, 2019). A disaster is included in EM-DAT if it meets this definition *'as a situation or event which overwhelms local capacity, necessitating a request to the national or international level for external assistance, or is recognised as such by a multilateral agency or by at least two sources, such as national, regional or international assistance groups and the media'* (CRED, 2020b) . Furthermore, a disaster is included if it is reported to kill more than 10 people or/and 100 or more people are affected or/and call for international assistance/declaration of a state of emergency (CRED, 2020b).

We investigate how the August 2003, 2010 and 2020 heatwaves were reported in 3 major international climate reports by meteorological organisations. These reports inform on trends and extremes of the global or European climate on an annual basis. They are the American Meteorological Society State of the Climate reports (Achberger et al., 2011; American Meteorological Society, 2004), World Meteorological Organisation reports (World Meteorological Organization 2011, 2004) and the Copernicus State of the Climate for Europe (Copernicus Climate Change Service, 2021).

Another method is a systematic literature review. These offer an effective, transparent, accountable, and reproducible method for identifying, analysing and synthesising large amounts of published research (Ford *et al.* 2011). This was used to provide an understanding of how

UK heatwave research has developed over the last twenty years, and to assess the main drivers, barriers and recommendations for future policy. Web of Science, and Scopus, two of the largest and most comprehensive publication index databases, were used to perform a keyword search for peer-reviewed research published between 1st January 2000 and 31st December 2019. Research published prior to 2000 was excluded because the UK's ten hottest years on record have happened in the last two decades and the frequency, intensity and duration of UK heatwaves have also increased since that point (McCarthy et al., 2019).

Another method is an advanced Google search was carried out for the period 1st January 2017 to the 1st January 2022. The individual search selection was for all news articles in the period containing the keyword flood, heat wave, wildfire, storm and drought and then the search was carried out again this time including climate change as a keyword (cf. Brimicombe et al., 2021). Each hazard was evaluated separately, and their results compared, with duplicated results not included.

Further another method is a framework is applied to mainstream media. One way to frame perceptions is in the form of Douglas's Cultural Theory of Risk framework which comes from a social anthropology background (Douglas, 1966, 2002; Douglas & Wildavsky, 1982). Cultural theory of risk identifies 4 categories on a grid-group continuum these are: Egalitarian, Individualist, Hierarchical and Fatalists (Figure 3.1).

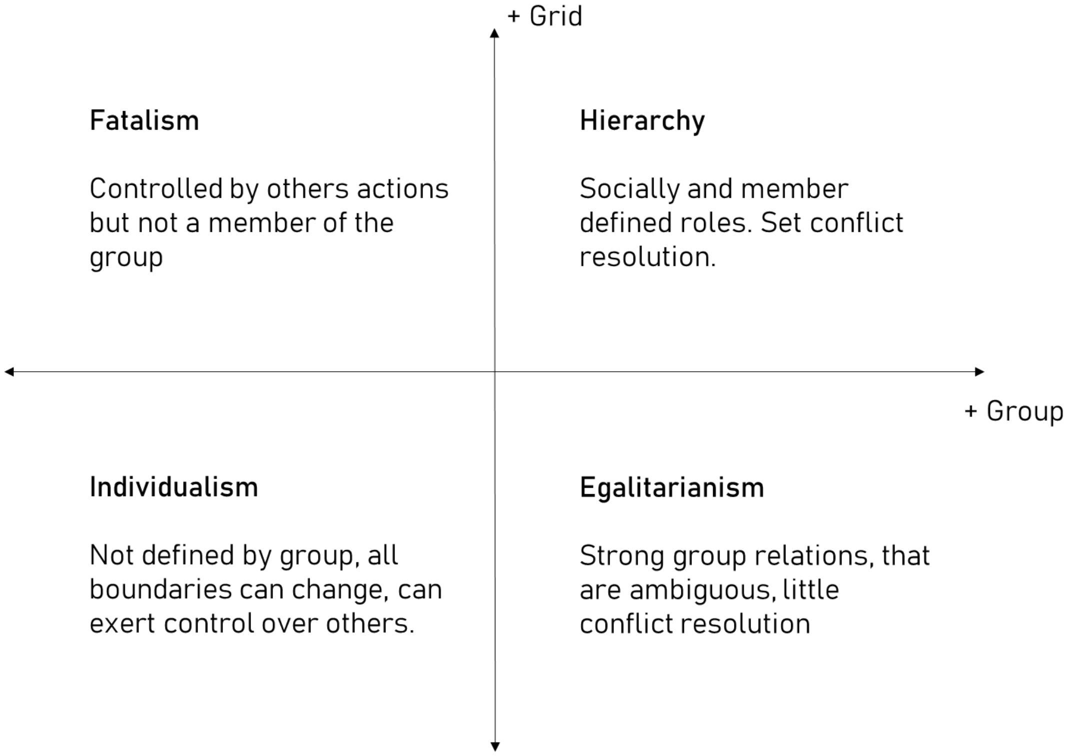

Figure 3.1 an adapted schematic based on Thompson et al., (1990) *to demonstrate the continuum of the 4 different categories from the Cultural Theory of Risk framework.*

Cultural Theory of risk has been used as a framework to explore barriers to climate change adaptation and when used as a tool to frame communication these local barriers can be broken, increasing adaptive capacity with case studies focusing on the US, Canada and Tuvalu (McNeeley & Lazrus, 2014). In addition, it has also been demonstrated that grid-group typology is a more powerful way to explore whether someone will support climate policy and climate adaptation in the US than their political stance (Leiserowitz, 2006). Further, it has been found that when policy and communication of climate change is framed to fit the groups of Egalitarian, Individualist, Hierarchical and Fatalists that there is better engagement with adaptation than using one method of communication (Thompson, 2003).

Overall a wide range of research methods are employed in this thesis to provide answers for the aim*: to investigate the impact of extreme heat and policy measures and to explore the development of a global heat hazard early warning system.* Full methods are discussed in detail in the relevant chapters throughout the thesis.

4. Borderless heat hazards with bordered impacts

Commentary: The motivation of this chapter and paper came from my first-hand experience of seeing how the impacts of the August 2020 heatwave were reported, this led to the discovery of long-term under reporting by meteorological organisations that did not match the growing heat stress trends. Chapter 4 has been published in the Journal Earth's Future under the reference:

Brimicombe, C., Napoli, C. Di, Cornforth, R., Pappenberger, F., Petty, C., & Cloke, H. L. (2021). Borderless Heat Hazards With Bordered Impacts. Earth's Future, 9(9), e2021EF002064. https://doi.org/10.1029/2021EF002064

This research has had success being presented in some form at a number of conferences, being presented to the media and won me the European Meteorological Society Tromp foundation conference award to young scientists in 2021. However, in hindsight I would change the methodology as Chapter 6 in this thesis and use percentiles instead of a fixed anomaly, which would be more in keeping with literature presented in Chapter 2. In addition, this methodology would be advantageous for other months than just August but was not the scope of this chapter.

This research fits within component 1 Mobilization and Governance, because it presents evidence towards the objective assess policy prioritization and governance for extreme heat, by showing there is a lack of prioritization of reporting impacts by international meteorological organisation.

Key Points of Research:

- **In the Northern Hemisphere, heat stress during the month of August is growing in area and is larger during a heatwave.**
- **Heat stress area increase is greater over the populated land surface than the total land surface during August.**
- **Impacts of heatwaves are not sufficiency captured by international meteorological organisation reports and the Emergency Events Database EM-DAT.**

Abstract:

Heatwaves are increasing in frequency, duration, and intensity due to climate change. They are associated with high mortality rates and cross-sectional impacts including a reduction in crop yield and power outages. Here we demonstrate that there are large deficiencies in reporting of heatwave impacts in international disasters databases, international organisation reports and climate bulletins. We characterise the distribution of heat stress across the world focusing on August In the Northern Hemisphere, when notably heatwaves have taken place (i.e. 2003,2010 and 2020) for the last 20 years using the ERA5-HEAT reanalysis of the Universal Thermal Comfort Index (UTCI) and establish heat stress has grown larger in extent, more so during a heatwave. Comparison of heat stress against the Emergency Events impacts database (EM-DAT) and climate reports reveals underreporting of heatwave-related impacts. This work suggests an internationally agreed protocol should be put in place for impact reporting by organisations and national government, facilitating implementation of preparedness measures and early warning systems.

Plain Text Summary:

Heat extremes are increasing in frequency, duration and intensity due to climate change. Their impacts include a rise in death rates, a decrease in how much of a crop is produced and power outages. Here we show that there is a lack of reporting of impacts in international organisation reports, international disaster databases. Further, heat stress, an impact of heat extremes is characterised using an index that is human-centric. With a focus on August and the Northern Hemisphere, we show that heat stress has grown in extent and is presenting a growing risk to more of the population over this millennium. This work suggests that organisations and national governments should come together to agree a protocol for how to best report heat impacts, so that we can be better prepared for them.

4.1 Introduction

Heatwaves are increasing in frequency, duration and intensity due to climate change (Perkins-Kirkpatrick & Gibson, 2017; Russo et al., 2017b; Vogel et al., 2019), and they occur over large areas often coinciding with other natural hazards such as wildfires and droughts (Sutanto et al., 2020; Vogel et al., 2019). Heatwaves are as impactful as other hazards, such as floods, but reporting their characteristics and impacts, as well as understand their risk is challenging because they are an invisible physical phenomenon (Brimicombe, Porter, et al., 2021). They are also considered to be widely underreported in official databases, reports and in news media (Harrington & Otto, 2020; Khare et al., 2015). However, robust reporting is essential not only for communicating the risk of heatwaves, but also to develop effective policy and action (Harrington & Otto, 2020; Howarth et al., 2019; Kitzinger, 1999).

Heatwaves can be considered the most deadly meteorological hazard (World Meteorological Organization, 2019), responsible for the death of more than 70,000 and 55,000 people globally in 2003 and 2010 respectively (Robine et al., 2008; Schubert et al., 2011). Heatwaves have other health risks such as increased morbidity (Watts et al., 2019). In addition, they also cause cross-sectional risks including decreasing crop yields (Abass et al., 2018; Vercillo et al., 2020), putting a strain on power grids (Larcom et al., 2019), reducing productivity of labourers (Oppermann et al., 2017) and impacting economic activity (Kotz et al., 2021).

Heatwave morbidity and mortality arise due to heat stress on the human body (Campbell et al., 2018), which can be defined as "*the build-up of body heat generated either internally by muscle use or externally by the environment*" (McGregor & Vanos, 2018). There is currently a lack of understanding of the exact nature of heat stress from a human thermal comfort perspective during heatwaves, how this has changed through time and how exposure to heat stress conditions might be changing. Existing heatwave research at a international level focuses only on temperature(Perkins-Kirkpatrick & Gibson, 2017; Vogel et al., 2019) and does not provide the necessary analysis on heat stress thus failing to answer recent calls for inclusion of physiological responses when assessing heat exposure and vulnerability (Nazarian & Lee, 2020a; Vanos et al., 2020).

In this study we provide quantitative evidence of the areas of the world that are exposed to heat stress with a focus on the Northern Hemisphere. We use the ERA5-HEAT reanalysis (Di Napoli, Barnard, et al., 2020) of the Universal Thermal Climate Index (UTCI)(Di Napoli et al., 2018b, 2019) . We analyse the change in heat stress extent for the month of August, a notable month for heatwaves since 2000 for both total land area and populated land area as well as consider to what extent exposure to heat stress conditions is growing. We compare these measures of heat stress to reported heatwave impacts to assess deficiencies in the reporting of these natural hazards. Using the heatwaves of August 2003, 2010 and 2020 notable for their intensity and impacts (Robine et al., 2008; Schubert et al., 2011), we compare ERA5-HEAT UTCI to heatwave impacts reported in the emergency events database (EM-DAT) international disasters database, international organisation reports and climate bulletins (Achberger et al., 2011; Copernicus Climate Change Service, 2021; CRED, 2020a; World Meteorological Organization, 2021).

We consider heatwaves to be borderless, unconstrained by the geography of the physical and human landscape. However, disaster reporting is severely constrained by national and institutional geographic boundaries. This work aims to demonstrate the extent of heat stress from heatwaves, to what extent heat stress is becoming an increasing hazard and demonstrate whether impacts are captured in reporting. Such evidence can be used to establish an internationally agreed protocol in order to provide robust global heat impact reporting by organisations and national governments. This in turn will provide the evidence to facilitate the implementation of preparedness measures and early warning systems for heat on a global scale.

4.2 Methods

4.2.1 ERA5-HEAT Universal Thermal Climate Index (UTCI) reanalysis

Heat stress is assessed using the ERA5-HEAT reanalysis (https://doi.org/10.24381/cds.553b7518) which is freely accessible on the Copernicus Climate Data Store (Di Napoli, Barnard, et al., 2020). We use the 0.25° x 0.25° gridded Universal Thermal Climate Index (UTCI) from ERA5-HEAT at an hourly time step. The UTCI is shown to be a useful indicator of heatwaves and heat stress by studies in many countries (Guigma et al., 2020; Di Napoli et al., 2018b; Pappenberger et al., 2015; Urban et al., 2021) and models the response of the human body to the outside thermal environment in terms of 2m air temperature, mean radiant temperature, relative humidity and 10m wind speed (Bröde et al., 2012; Di Napoli, Barnard, et al., 2020). It is worth noting that although the UTCI has the units °C, it is not the same as temperature and provides an indication of the average human body response to different thermal environments (Jendritzky et al., 2012).

We calculate the monthly mean of the daily maximum UTCI for August 2003, 2010 and 2020 as well as the climatological of this for the UTCI for the 1981-2010 period. The latter is then used to calculate anomalies of the UTCI (°C) for the aforementioned months. Further, number of exposure hours to heat stress above 26°C is additionally calculated for the months (Nazarian & Lee, 2021). We focus on the Northern Hemisphere, the region with the largest area of land mass and the largest proportion of the global population (Chambers, 2020) and August was chosen because it historically has experienced notable heatwaves in both the Northern Hemisphere during the summer and the tropics where heat extremes do occur throughout the year (Perkins-Kirkpatrick & Gibson, 2017; Russo et al., 2016).

4.2.2 Reporting Global Heatwaves

We undertake a two-part review of reported heatwave information. First, we analyse the international natural disaster database EM-DAT for the August 2003, 2010 and 2020 heatwaves. Emergency Events Database (EM-DAT) is a leading international disaster database run by the Centre on the Epidemiology of Disasters (CRED) since 1988 (CRED, 2020a) and data is used in reports by the UN (Cullmann et al., 2020; World Meteorological Organization, 2019). A disaster is included in EM-DAT if it meets this definition *'as a situation or event which overwhelms local capacity, necessitating a request to the national or international level for external assistance, or is recognised as such by a multilateral agency or by at least two sources, such as national, regional or international assistance groups and the media'* (CRED, 2020b) . Furthermore, a disaster is included if it is reported to kill more than 10 people or/and 100 or more people are affected or/and call for international assistance/declaration of a state of emergency (CRED, 2020b).

Secondly, we investigate how the August 2003, 2010 and 2020 heatwaves were reported in 3 major international climate reports by meteorological organisations, these reports inform on trends and extremes of the global or European climate on an annual basis. These are the American Meteorological Society State of the Climate reports (Achberger et al., 2011; American Meteorological Society, 2004), World Meteorological Organisation reports (World Meteorological Organization 2011, 2004) and the Copernicus State of the Climate for Europe (Copernicus Climate Change Service, 2021).Other international reports are not included as they are written for a different year, for example The State of the Climate in Africa is only for 2019 (World Meteorological Organization, 2020). In addition, they are not included if they do not specifically mention heatwaves (i.e. National Centers for Environmental Information 2020).

4.2.3 Heat Stress Area

We assess heat stress area in two ways. The first makes use of the 26°C UTCI threshold, which, once exceeded, indicates thermal levels at which an individual would experience heat stress, ranging from moderate (26°C to 32°C UTCI) to extreme (above 46°C UTCI). The second uses values above a 5°C UTCI anomaly compared to the heat stress climatology for August from 1981 to 2010. In both cases, we use gridded spatial data to create binary maps approach is used (Vitolo et al., 2019) with grid cells over the threshold set equal to 1, 0 otherwise.

As exposure to heatwaves is known to be greater in more populated areas (Chambers, 2020; Watts et al., 2017), the gridded data is first masked to land area, excluding Antarctica, and then also masked to populated land area using grid cells with a population count of over 0 from the Land Scan dataset for 2000 to 2019 provided by the Oak Ridge National Laboratory (Dobson et al., 2000; Vijayaraj et al., 2007), with 2020 being masked to 2019 population count. All grid cells are then summed, allowing for proportions to be calculated. All calculations are carried out using Rstudio.

4.3 Results

4.3.1 International heat stress characteristics from ERA5-HEAT

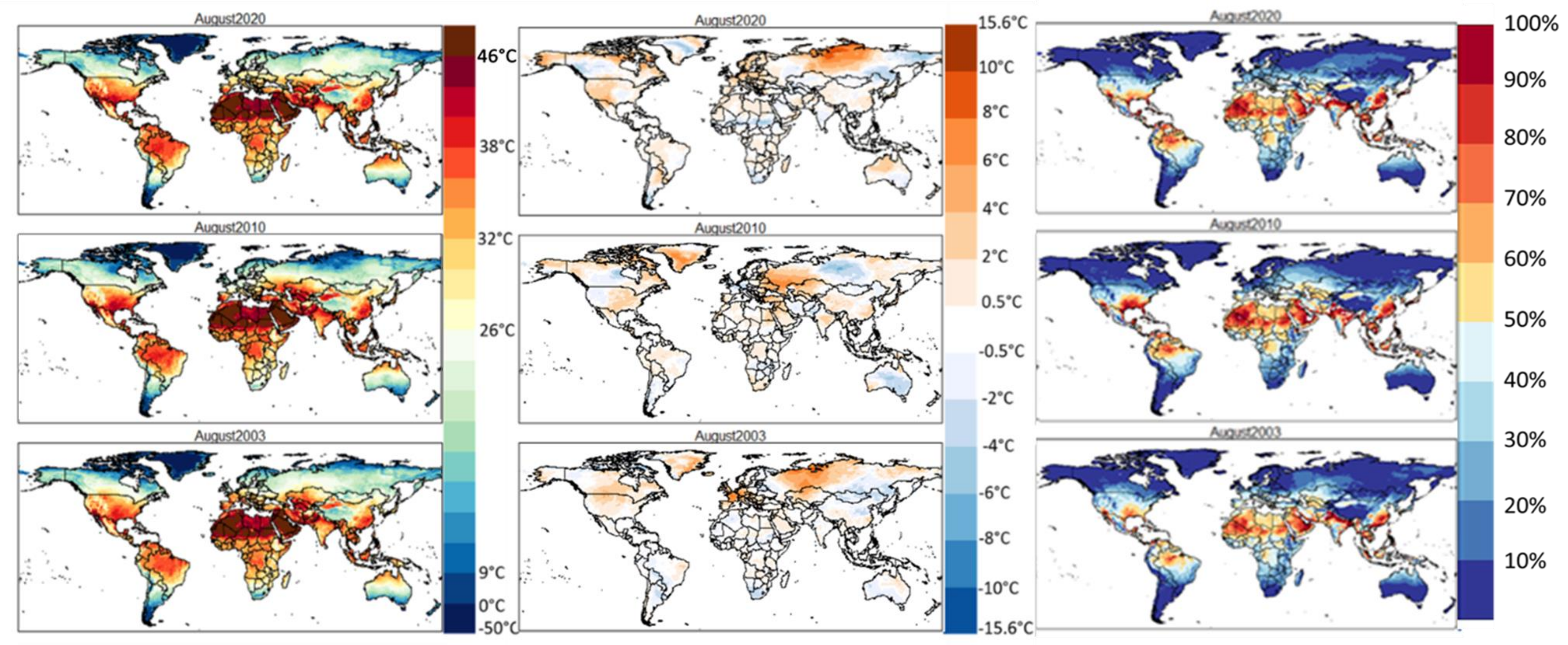

Figure 4.1: UTCI monthly mean of the daily maxima (left), corresponding anomalies with respect to climatology (centre),percentage time that hourly UTCI is over heat stress threshold (26°C)(right) from August 2020, 2010 and 2003 heatwaves.

In each of the heatwave events considered in this study heat stress occurs between the latitudes of 50 degrees north and 40 degrees south (*Figure 4.1, left panels*). The maximum value for heat stress occurs in the Sahara and Arabian Peninsula, where the UTCI reaches a maximum value of 54°C which exceeds the extreme heat stress threshold of 46°C UTCI. Countries impacted include Algeria, Tunisia and Mauritania in North Africa and Oman, United Arab Emirates and Saudi Arabia on the Arabian Peninsula. Further, there are high levels of heat stress in the average maximum values for August extending over much of the globe. This is across Europe including Spain, Croatia and Germany; parts of Asia including Bangladesh, Vietnam, parts of India and China; the Americas including parts of North America, Brazil and Ecuador; and Northern Australia.

The anomaly of the UTCI with respect to the 1981-2010 climatology locates the centres of heat stress for August 2020, 2010 and 2003 (*Figure 4.1, central panels*). For August 2003 and 2020 above-average heat is centred on Russia and Siberia. During August 2010 the main heat stress hotspot is situated over Russia. In all 3 heatwaves, hotspots are also evident in the USA and Europe, but the anomalies are spatially different for these regions in each event. For example, in 2010 in the USA the hotspot is the east coast, during 2003 it is central and during 2020 it is the west coast.

In addition, the regions that are experiencing the highest intensity heat stress (*Figure 4.1, left panels*) are also experiencing the longest exposure time to above heat stress values (*Figure 4.1, right panels)*. For example, North West Africa is experiencing exposure times of at least 80% in all 3 heatwaves. Europe sees a lower exposure time of up to 20% during all 3 heatwaves, but a larger heat stress anomaly (*Figure 4.1, central panels*).

4.3.2 Changes in heat stress during August

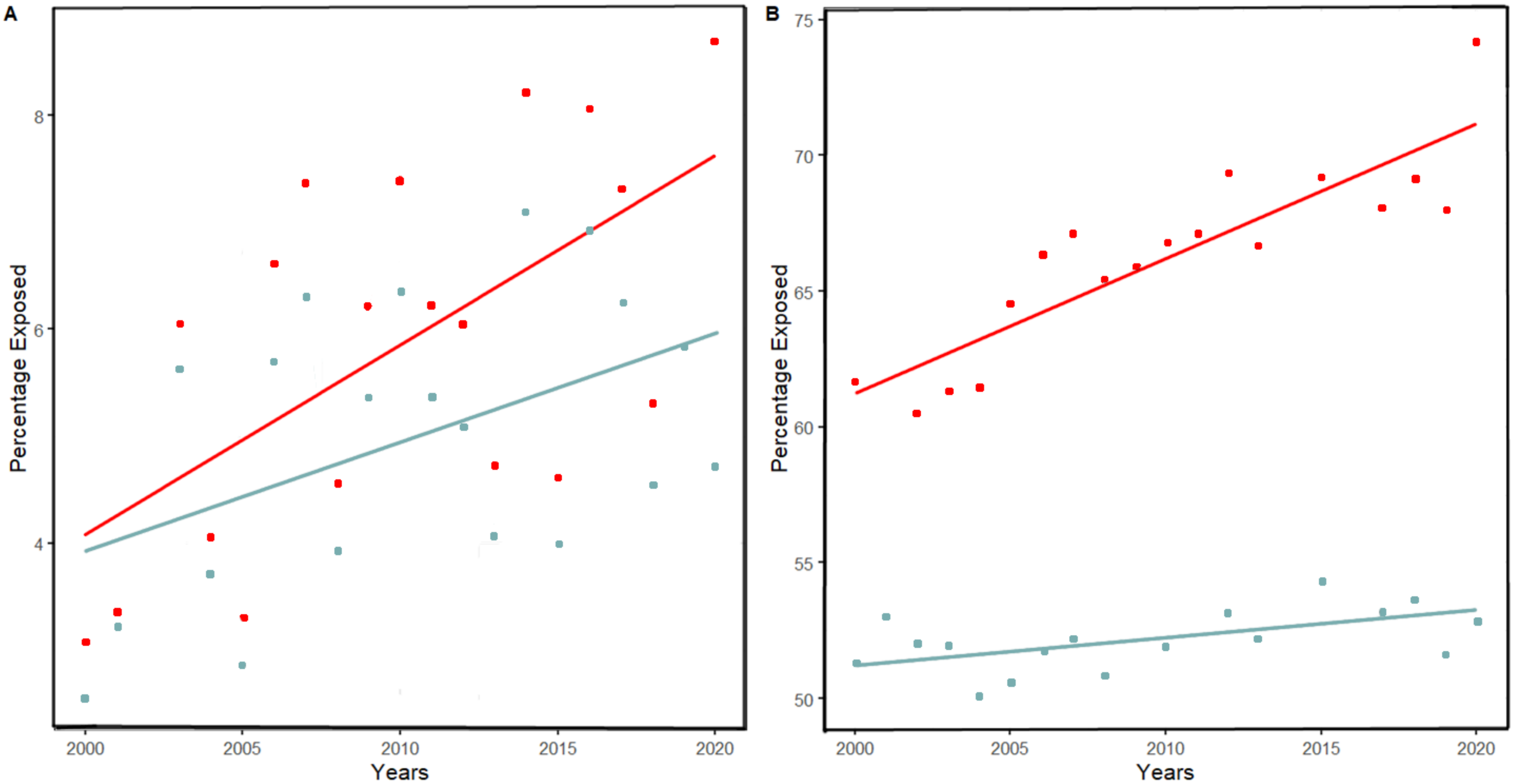

Figure 4.2: Percentage of land area exposed to heat stress values from 2000 to 2020, Red/Top: Proportion of Populated Land Area as defined by LandScanTM (2000 to 2019) (Dobson et al., 2000; Vijayaraj et al., 2007), *Blue/Bottom: Proportion of total land mass. A: uses values over a 5°C anomaly compared to August 1981 to 2020, B: uses maximum values over the 26°C UTCI heat stress threshold.*

Populated areas have greater exposure to maxima in heat stress than the total global land mass (*Figure 4.2*). Over half of the populated land area has been exposed to heat stress levels in the month of August, every year since 2000. 74% of the populated land area of the world was exposed to heat stress levels above 26°C UTCI in 2020 (*Figure 8.2b*). Peaks in data over the heat threshold are consistent with heatwave years. They are also consistent with El Niño years (e.g. 2003, 2006, 2007, 2013, 2018 and 2020). This suggests that heat stress area is larger during heatwaves.

There is an increasing trend in UTCI maxima anomalies of more than 5°C UTCI when compared to the 1981-2010 climatology *(panel a)* and maxima UTCI over the heat stress threshold of 26°C UTCI (*panel b*). The trend is stronger for the populated land area than for the overall land area, showing that the increase in heat stress is greater in areas which are populated. Peaks in the UTCI maximum anomalies are also consistent with years where a heatwave is also occurring (e.g. 2003, 2006, 2010, 2013, 2016, 2019 and 2020), but capture slightly different years to the above threshold method.

4.3.3 Evaluating deficiencies in heatwave impact reporting

The meteorological organisation reports, and EM-DAT do not capture the impacts to the extent we see heat stress *(Figure 4.1)*. Notable differences can be seen for parts of North Africa including Tunisia and Mauritania; Asia including Vietnam and the Americas including Brazil and Ecuador.

During August 2020, a heatwave had the largest extent on record, covering 74% of the populated land surface, and extreme heat stress conditions are observed in the African Sahel and Arabian Peninsula with parts of Europe, Asia, the Americas and Northern Australia experiencing moderate to high heat stress levels *(Figure 4.2, panel b)*. Evidence of heatwaves for 2020 in EM-DAT is limited with only Belgium, France, the Netherlands and the UK included. Our research shows a discrepancy between reports and countries experiencing heat stress.

The World Meteorology Organization *State of the Climate* report for 2020 discusses heatwaves in a section with droughts and wildfires. It simply lists temperature records from heatwaves and mentions the regions of Europe, the US and some of Asia (Japan and Hong Kong)(World Meteorological Organization, 2021). The *European State of the Climate* has a specific session for heat stress despite showing evidence of heat stress they consider the overall summer not 'unusually warm', with no long lived heatwaves and only short ones which broke a few temperature records (Copernicus Climate Change Service, 2021). In another section they state how it 'wasn't remarkable' despite stating the 'length of the period of with tropical temperatures was exceptional' stretching over a large area (Copernicus Climate Change Service, 2021). Figure 4.1 demonstrates how the exposure time to heat stress is similar in Europe for August 2020 in comparison to August 2003, whilst the anomalies in heat stress are slightly lower. In addition, Figure 4.1 shows many countries from North Africa (e.g. Morocco) and the African Sahel (e.g. Mauritania and Chad), as well as the West Coast of America, experiencing heat stress but these do not feature in English Language reports. In both the international meteorological organisation reports currently available no impacts are reported.

The comparison between our heat stress data and reports allows us to show what the real life impacts of heat stress are. However, it is limited with no English language reports for Algeria, Tunisia in North Africa and Mauritania in the African Sahel and Oman and Saudi Arabia on the Arabian Peninsula and the Americas including parts of North America, Brazil and Ecuador, despite these areas experiencing high levels of heat stress in August 2020 (*Figure 4.1)* and is indicative of under-reporting.

In August 2010, 67% of the populated land surface was exposed to heat stress levels (F*igure 4.2, panel b).* Extreme heat was experienced again in the African Sahel and Arabian Peninsula. With parts of Europe, Asia, the Americas and Northern Australia experiencing moderate to high heat stress levels (*Figure 4.1*). The evidence is stark for 2010 from EM-DAT, with only Brazil, India, Japan and Russia listed as experiencing heatwaves (CRED, 2020a). Our results show during 2010 countries exposed to heat stress also included many North African countries (e.g. Tunisia, Algeria and Libya), the Central USA and the Middle East (e.g. Jordan and Israel). The American Meteorological Society *The State of the Climate* (Achberger et al., 2011) and the World Meteorological Organization *The State of the Global Climate* (World Meteorological Organization, 2011) reports only make reference to heatwaves condition and excess mortality in Europe for 2010.

There are overall less reported impacts for 2010 in comparison to 2020. We again see a discrepancy from different reporting sources, there were no English language reports indicating heat stress impacts for North Africa, the Middle East or Latin America that were found in our systematic search.

A similar picture to that of August 2020 and 2010 is observed for August 2003. In August 2003, 62% of the populated land surface was exposed to heat stress levels (F*igure 4.2, panel b).* Extreme heat was experienced again in the Sahara and Arabian Peninsula with parts of

Europe, Asia, the Americas and Northern Australia experiencing moderate to high heat stress levels (*Figure 4.1*). For EM-DAT anytime in 2003 the only countries listed are 15 in Europe, 4 countries of Bangladesh, India, Japan and Pakistan in Asia and only Algeria in Africa (CRED, 2020a). Our results show (*Figure* 4.*1*) countries experiencing heat stress during 2003 included many countries in North Africa (e.g. Morocco, Tunisia and Libya) during 2003, as well as Canada and the Eastern US and Asia and the Middle East (e.g. UAE, China and Japan)

The American Meteorological Society *State of the Climate* reports(American Meteorological Society, 2004) and the World Meteorological Organization *The State of the Global Climate* (World Meteorological Organization, 2004) reports only make reference to heatwaves and excess mortality in only Europe, India and Pakistan for 2003.

Overall, reports allow us to observe what the impacts of high, moderate and extreme heat stress are. But there is a huge discrepancy between regions experiencing heat stress and reporting impacts, leading to a lack of evidence of the impacts of heatwaves and heat stress.

4.4 Discussion

4.4.1 Heat Stress expanding is exposing a larger proportion of the population to a risk.

Our results demonstrate that heat stress is borderless, covering a large proportion of the total land mass during an August heatwave. In addition, during a heatwave the population exposed to the risk of heat stress is increasing and as such populations are experiencing a rise in baseline levels of mortality and morbidity more often during August. Moreover, with an increase in nations with an aging population this risk is greater, as those over 65 are especially vulnerable to heat illnesses and mortality (Arbuthnott & Hajat, 2017; Chambers, 2020; Kovats & Hajat, 2008; WMO & WHO, 2015). We also show how regions with the highest heat stress levels also have the highest exposure time which is an important element when considering heat morbidity and indicates less time to recover from heat exposure(Chambers, 2020; WMO & WHO, 2015).

In addition, this study presents evidence that heat stress area has grown since the millennium in the month of August (*Figure* 4.2), which is consistent with trends seen in temperature and extreme heat by other studies (Chambers, 2020; Perkins-Kirkpatrick & Gibson, 2017; Vogel et al., 2019; Watts et al., 2018). This provides evidence for the need of a global heat hazard alert system, as heat is not simply impacting one area at a time but many regions simultaneously, even when only considering August as we present here. However, we note that above the 26°C UTCI heat stress threshold is not experienced the same everywhere due to climate and acclimatization, which should be explored further and is only an indication of when one could start experiencing heat stress (Nazarin and Lee, 2021; Di Napoli 2018).

4.4.2 Europe receives the most attention

Furthermore, the results of this study show that when a heatwave exposes a large proportion of the total land mass to heat stress conditions, Europe is the focus of attention. For EM-DAT 20 out of the 28 countries featured are in Europe. Europe is also the most mentioned continent for international meteorological reports, featuring for all the heatwaves considered. Interestingly for Europe in 2020 there is a slight contradiction between sources the *European State of the Climate* (Copernicus Climate Change Service, 2021) isn't considering this as long lived or remarkable, whereas the World Meteorological Organisation *State of the Climate* (World Meteorological Organization, 2021) consider it for this region as 'significant'. This demonstrates the need even in regions with the most attention the need for an international heatwave reporting protocol, which would prevent this confusing situation from occurring.

We provide evidence of the scale of the discrepancies in reporting of heatwaves with no reports considered mentioning Latin America and at most two mentioning Africa. These regions are in part in the tropics where heatwaves can occur all year. One reason is because the main language spoken in these areas is often not English. Other reasons behind areas globally where heatwaves are not reported can be complex, and includes the country is in a state of conflict, there is not the political will or there is not the funding for this to take place, e.g. the political economy of hazards and disasters (Fankhauser & McDermott, 2014; Neumayer et al., 2014). This has led to a lack of evidence of what the impact of heatwaves and heat stress are, further supporting the need for a heatwave reporting protocol.

4.4.3 Influential Data

In comparison, EM-DAT is an influential database, being used by the UN in not only World Meteorological Organisation reports(World Meteorological Organization, 2004, 2011) but also in Disaster Risk Management reports (Cullmann et al., 2020). In literature it is often presented that EM-DAT has a bias on what disasters are recorded (Ceola et al., 2014; Fankhauser & McDermott, 2014; Gall et al., 2009). In reality, EM-DAT is the most reliable source of information on disasters (Cullmann et al., 2020) but is subject to the same challenges that are faced by all in recording and assessing heatwave impacts, where there is huge discrepancies between countries reporting (CRED, 2020c). In addition, because of the lack of attention and evidence heatwaves often are not perceived as a risk by international agencies and national governments leading to impacts going unknown and in some regions the situation is such that resources to report do not exist (Brimicombe, Porter, et al., 2021; Harrington & Otto, 2020). Through the availability bias we are more likely to recognise a heatwave as a risk if it has previously been presented as such (Wolf et al., 2010). EM-DAT are aware of these discrepancies and are making good progress in addressing these(CRED, 2020c).

4.5 Conclusion

In summary, this study shows for the first time with a focus on notable August heatwaves and the Northern Hemisphere that heat stress is growing in area and is larger during the month of August. It also demonstrates how heatwaves are borderless not constrained by political boundaries and that impacts are not adequately reported - a deficiency in risk reporting. To start solving the discrepancies presented here between heat stress exposure and impact reports we offer three suggestions to address these aimed at building the evidence base that is currently lacking and putting in place the robust adaptation measures needed.

These are: *Firstly, the establishment of an international protocol for reporting heatwave impacts for international organisations and national governments.* This will allow us to build an evidence base of ongoing heat impacts so that the right adaptation measures can be put in place, building resilience to heat in our changing climate. *Secondly, improve recording in EM-DAT and make it clear in all reports that it has discrepancies being addressed.* This will prevent the potential perception amongst those that work in natural hazards that heatwaves present less of a risk than other hazards such as storms and flooding. It in addition will support the first suggestion, by building an evidence base. *Thirdly, implement a Global Heat Hazard Alert System*. This would follow guidelines set out in the joint report by the World Health Organisation and World Meteorological Organisation(WMO & WHO, 2015). This should be similar to GloFAS implemented and maintained by ECMWF for flooding(Alfieri et al., 2013; Emerton et al., 2016) and would inform countries when the risk to heat stress is highest. As well as, indicating when a country and international organisation should be putting extra preparedness measures in place, but also when to expect an increase in impacts. In addition, we suggest that it should in some way include acclimatization which was not the focus here and is an important aspect that needs further research. By investing in such measures, we can improve resilience to heatwaves which are increasing in frequency, duration, intensity and area as a result of climate change.

Open Data Section:

ERA5-HEAT, provided by ECMWF is freely accessible here: https://doi.org/10.24381/cds.553b7518 [Di Napoli et al. 2020]. The Oak Ridge National Laboratory LandScanTM population count dataset from 2000 to 2019, is freely available to those in educational organisations or the US Federal Government [Dobson et al. 2000; Vijayaraj et al. 2007].

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5. Heatwaves: An invisible risk in UK policy and research

Commentary: The motivation of this chapter was to understand the policy landscape of my own country before exploring it for other nations or internationally. Chapter 5 has been published in the Journal of Environmental Science and Policy under the reference:

Brimicombe, C., Porter, J. J., Di Napoli, C., Pappenberger, F., Cornforth, R., Petty, C., & Cloke, H. L. (2021). Heatwaves: An invisible risk in UK policy and research. Environmental Science & Policy, 116, 1–7. https://doi.org/10.1016/j.envsci.2020.10.021

This research has been most successful, it was the subject of a number of news articles that were distributed on a global scale. In addition, it has been incorporated in a number of policy briefs including a POSTnote in 2021 that advised the UK government on heatwaves in the UK as part of a brief on extreme weather in the face of climate change. It may even be considered that this research led to some of the changes that have been seen in heatwave policy, for example with the incorporation of heatwaves into the Met Office severe weather warnings. Despite advancements I would still consider heatwaves an invisible risk in the UK, because there have been no legislative changes in policy yet for overheating yet and still discrepancies for other sectors, I hope to see changes as part of the National Adaptation Plan within the next year.

This research fits within component 1 Mobilization and Governance, because it presents evidence towards the objective assess policy prioritization and governance for extreme heat, by showing there is a lack of prioritization of policy and governance for extreme heat in the UK, going as far as demonstrating it is an invisible risk.

Keywords: Heatwave; UK; Policy; Health; Building; Risk

Abstract:

In 2019, a heatwave – an unusual extended period of hot weather – broke the UK's highest recorded temperature of 38.7°C set in 2003. Of concern is that for summer 2019, this resulted in 892 excess deaths. With the intensity and frequency of UK heatwaves projected to increase, and summer temperatures predicted to be 5°C hotter by 2070, urgent action is needed to prepare for, and adapt to, the changes now and to come. Yet it remains unclear what actions are needed and by whom. In response, a systematic literature review of UK heatwaves peer-reviewed publications, inclusive of keyword criteria (total papers returned =183), was conducted to understand what lessons have been learnt and what needs to happen next. Our research shows that heatwaves remain largely an invisible risk in the UK. Communication over what UK residents should do, the support needed to make changes, and their capacity to enact those changes, is often lacking. In turn, there is an inherent bias where research focuses too narrowly on the health and building sectors over other critical sectors, such as agriculture. An increased amount of action and leadership is therefore necessary from the UK government to address this.

5.1 Introduction

In 2019, a heatwave broke the UK's highest ever recorded temperature of 38.7°C set in 2003. Over 2 heatwaves 892 excess deaths were recorded (Public Health England, 2019). Of concern here is that the intensity, frequency, and duration of UK heatwaves are all projected to increase, and summer temperatures are predicted to be 5°C hotter by 2070 (Lowe *et al.* 2018) yet the UK Government's efforts to prepare for, and adapt to, these risks has been heavily criticised for leaving the UK 'woefully unprepared' (Carrington 2018; Committee on Climate Change 2017; Environment Audit Committee 2018; Howarth *et al.* 2019).

Too often the problems of heatwaves are narrowly defined as one concerned with public health alone. To date, the only tangible heatwave plan in the UK is led by the Department of Health and Social Care and is aimed primarily at healthcare service providers (Public Health England 2018). Yet heatwaves can have other negative impacts too. For instance, they can affect 'critical national infrastructure such as transport, digital systems and water supply...' cause 'railway tracks [to buckle which] are costly to repair' and in 2010 led to economic losses of £770 million related to lost staff days (Environmental Audit Committee, 2018: 4). The risks posed by heatwaves are, importantly, not confined to a single sector but cut across different sectors in both predictable and unpredictable ways (Howarth *et al.* 2019). Such 'silo thinking', where an issue is only dealt with by individual sectors with little or no communication between affected sectors (c.f. Pregernig, 2014; Rogers-Hayden et al., 2011), has become politically ingrained in how the UK approaches the management of heatwaves.

In turn, the UK's research and forecasting arrangements for heatwaves are institutionally fragmented. The UK Met Office is responsible for providing meteorological and climatological data and advice to policymakers and the public nationwide. In partnership with Public Health England, the Met Office runs an early warning system for heatwaves from 1st June to 15th September each year (Met Office, 2020a). Yet this service only covers England. Scotland, Wales and Northern Ireland receive no official warnings, and it is unclear to what extent they are covered by the National Severe Weather Warnings system (Met Office, 2020b). Institutional peculiarities are found in the evidence base used to inform government policy too. As part of the UK's 2008 Climate Change Act, a risk assessment must be conducted every five years to identify which climate risks the UK faces, and therein, inform a National Adaptation Programme to tackle these risks. Whilst the first and second Climate Change Risk Assessments called for urgent action to address heatwaves (Committee on Climate Change 2017; DEFRA 2018), the problem of overheating – whereby a building becomes too hot reducing comfort and productivity for those using that space – will only be addressed from 2023, too late to cover new homes built to meet the Government's housing targets of 1.5 million by 2022 (Committee on Climate Change, 2020).

Another challenge here is that there is no universal definition for what a 'heatwave' is. For instance, the World Meteorological Organization (2018: 4) defines a heatwaves as, 'A period of marked unusual hot weather (maximum, minimum and daily average temperature) over a region persisting at least three consecutive days during the warm period of the year based on local (station-based) climatological conditions, with thermal conditions recorded above given thresholds'. The UK Met Office, by contrast, defines a heatwave as a point 'when a location records a period of at least three consecutive days with maximum temperatures meeting or exceeding a heatwave temperature threshold' (McCarthy et al., 2019). Although subtle these definitions reveal competing criteria for what constitutes a heatwave: the uniqueness of the event itself vs. exceedance of a predetermined temperature threshold, which only adds to confusion when planning to manage the impact of heatwaves, especially when mortality rates can also increase from above average temperatures not just from a heatwave (Abeling 2015). For this study, a heatwave will be defined as an unusual period of extended hot weather.

At present, research suggests that the problem faced by the UK in managing heatwaves is a political one (Environmental Audit Committee 2018; Howarth *et al.* 2019). Either there is insufficient political appetite, patchiness in provision of forecasting services, or a lack of capacity to implement policies. Yet such reading pays little attention to what 'research' is being used to inform heatwave policy in the UK and why silo-thinking has taken root. To better understand how UK heatwave research has developed over the last twenty years, and importantly to assess what are the drivers, barriers and recommendations for future heatwave policy, a systematic literature review was conducted. This research seeks to pinpoint where the problem of inaction comes from and what could be done in response. To do this, the data and methods used to conduct the systematic literature review are explained in the next section, followed by the key findings, and a discussion of what those findings mean and why they are important.

5.2 Data and Methods

To understand how UK heatwave research has developed over the last twenty years, and to assess the main drivers, barriers and recommendations for future policy, a systematic literature review was conducted (cf. Berrang-Ford *et al.* 2011; Porter *et al.* 2014; Porter & Birdi 2018). Web of Science, and Scopus, two of the largest and most comprehensive publication index databases, were used to perform a keyword search for peer-reviewed research published between 1st January 2000 and 31st December 2019. Research published prior to 2000 was excluded because the UK's ten hottest years on record have happened in the last two decades and the frequency, intensity and duration of UK heatwaves have also increased since that point (McCarthy et al., 2019).

Systematic literature reviews offer an effective, transparent, accountable, and reproducible method for identifying, analysing and synthesising large amounts of published research (Ford *et al.* 2011). By making both the selection criteria and the analytical framework used explicit from the outset, biases can be reduced and more reliable conclusions reached. As noted earlier, the term 'heatwave' is understood and enacted differently across disciplines – hot spells, extreme weather events, severe heat – and therefore different keyword combinations were used to ensure the topic was comprehensively searched (see Supplementary Materials). In total, 33 keywords were used across 3 categories: (i) *topic*: heatwave identifying characteristics; (ii) *purpose*: policy and research domains; and (iii) *place*: countries within the United Kingdom. 183 publications were returned. After importing the publications to an MS Excel spreadsheet, inclusion and exclusion criterion were applied.

Only empirical, peer-reviewed, publications written in English and focusing on UK heatwave policy were analysed. Impact studies that only focused on modelling future mortality rates or temperature projections, for instance, and papers concerned with detection and attribution, were excluded. Publications that failed to address the main drivers, barriers, and recommendations for formulating and/or implementing UK heatwave policy, were also excluded. 52 journal articles fulfilled the inclusion criteria.

To ensure consistency, a qualitative scorecard was created to record key details about the retained journal articles including funding sources, disciplinary orientation, research focus, and methods used. This data helped to build a picture on 'what' research was being done, and in 'which' sector, so that linkages and gaps could be identified. A thematic analysis of the dataset was then performed whereby a ranking criterion was developed to differentiate between the high-quality, empirically robust, publications and the less rigorous studies using a grading system from one to five. A five-star paper used method(s) highly appropriate for the research question(s), included a large sample size (e.g. >200 survey subjects or 50 interview participants), and were critically and reflexively analysed. By contrast, a two-star paper or below was more exploratory in nature, with lower data points (e.g. <50 survey respondents or <10 interview participants), and the findings were more speculative (see Supplementary Materials).

20 journal articles (38.5% of the retained search) scored three-stars or above and were analysed. Of these, different research designs were used such as quantitative (n=7), qualitative (n=7), and mixed methods (n=6), and the sectors covered focused on: health (n=8), building/infrastructure (n=6) and behaviour/adaptation (n=6).

5.3 Results

To date, the UK's most prominent heatwave policy is the 'Heatwave Plan for England' (see Supplementary Materials for full details). It covers England only, however (n=9/20 – number of papers out of total that mentioned this policy) (Public Health England, 2018). Under the plan, responsibilities are divided between the Department of Health and Social Care, which takes the lead role in coordinating heatwaves responses across the National Health Service (NHS) and community health services, and the UK Met Office, which forecasts heatwaves and issues warnings to healthcare practitioners and Local Government (Met Office, 2020a).

Our review suggests that questions remain over the effectiveness of the interventions proposed by the Heatwave Plan for England, whether these interventions are aimed at the right people, and if sufficient efforts are being made to manage heat risk in sectors beyond health. Many studies praised the Heatwave Plan, for putting in place reactive measures, which are reviewed annually (Abeling, 2015; Abrahamson and Raine, 2009; Khare et al., 2015; Page et al., 2012). However, these studies also raised challenges the Heatwave Plan doesn't address, for instance, Abeling (2015: 7) suggested that the plan failed to 'consider social, environmental and technical risk dimensions', which is due to the reactive nature of the plan. Whilst Page et al. (2012) argued that the heatwave plan does not address the risks posed to mental health patients, especially those based in the community.

Several studies (n=3/20) also referred to the important role that national climate change policies can play such as the UK's latest Climate Change Risk Assessment, which identified heatwaves and building overheating as 'high risk' (Committee on Climate Change, 2017), and the National Adaptation Plan, which seeks to address these risks (DEFRA, 2018). Of interest here is the Climate Change Risk Assessment considers the level of heat risk to be the same for all parts of the UK. Our review, however, found that the evidence base for heatwave research varies geographically as 94% (n=172/183) of the returned results for the original Scopus search focused on England, and only fraction considered Wales (n=10/183) and Scotland (n=1/183), with Northern Ireland absent altogether (n=0/183).

In terms of the building sector, which is responsible for designing and building new homes, office space, schools, and other properties; there is no official Government policy and/or legislation that requires overheating to be factored into new builds. Rather 'best practice' involves following the Chartered Institution of Building Services Engineers (CIBSE) thermal comfort guidance (CIBSE 2013; 2015; 2017). Yet two-thirds of the overheating studies reviewed suggest that upwards of 20% UK buildings exceed the maximum thermal comfort limit for a normal UK summer, without additional extreme heat, or the projected higher summer temperatures from climate change (Baborska-Narożny et al., 2017; Vellei et al., 2017).

5.3.1 What are the main drivers for formulating and/or implementing UK heatwave policy?

Of the 20 papers reviewed, the main drivers that influence the formulation and/or implementation of UK heatwave policy were: (i) the occurrence of a heatwave event(s); (ii) concerns about the frequency, severity and duration of heatwaves increasing due to climate change; and (iii) growing recognition of the wide range of vulnerabilities exposed by heatwaves. The vast majority of papers (80%, n=16/20) found that heatwaves, such as the 2003 European heatwave, were instrumental in the development of new policies and/or plans as well as research into warning systems and coping strategies.

Nearly half of the papers (40%, n= 8/20) agreed that the growing scientific infrastructure around heatwave forecasting, particularly in relation to climate change risk assessments and projections, was also a driving force in the formulation and implementation of UK heatwave planning. It was noted that as the frequency, severity and duration of heatwaves increase, if the UK does not adapt fully and soon key sectors, including healthcare and agriculture, could fail (Committee on Climate Change, 2017). Indeed, the UK's 2019 climate projections suggest that the 2003 heatwave will become a normal event for UK summers by 2040 (Murphy et al., 2019).

Over a third of the papers (35%, n=7/20) agreed that the growing recognition of vulnerabilities exposed by heatwaves played an important role in driving UK heatwave policy and/or plans. The Intergovernmental Panel on Climate Change, for instance, defines 'vulnerability' as 'the propensity or predisposition to be adversely affected' and it 'encompasses a variety of concepts and elements including sensitivity or susceptibility to harm and lack of capacity to cope and adapt' (IPCC, 2013, p. 128). How vulnerability is defined depends, however, on the sector. Healthcare studies (n=9/20) identified vulnerable groups as those above the age of 65 and/or those with pre-existing medical conditions such as respiratory diseases (Abrahamson and Raine, 2009; Page et al., 2012). Infrastructure studies (n=6/20), by contrast, focus on vulnerable as the capacity for buildings or equipment to cope with excess temperatures such as the failure of signals for the railway network (Ferranti et al., 2016, 2018; Larcom et al., 2019).

5.3.2 What barriers were identified to the formation and/or implementation of UK heatwave policy?

14 barriers were identified to the formulation and/or implementation of UK heatwave policy or plans. As shown in Figure 5.1, the most frequent barrier cited was the perception that heatwaves are not a risk (n=10/20). Prior to 2003, heatwaves in the UK were fairly uncommon occurring in 1976 and 1995 (see Figure 5.2). This may help clarify why, as Wolf et al. (2010: 47) explains, 'long term and anticipatory responses to heat [are] perceived as largely unnecessary because of a belief that heat waves are and will remain rather uncommon in the UK'.

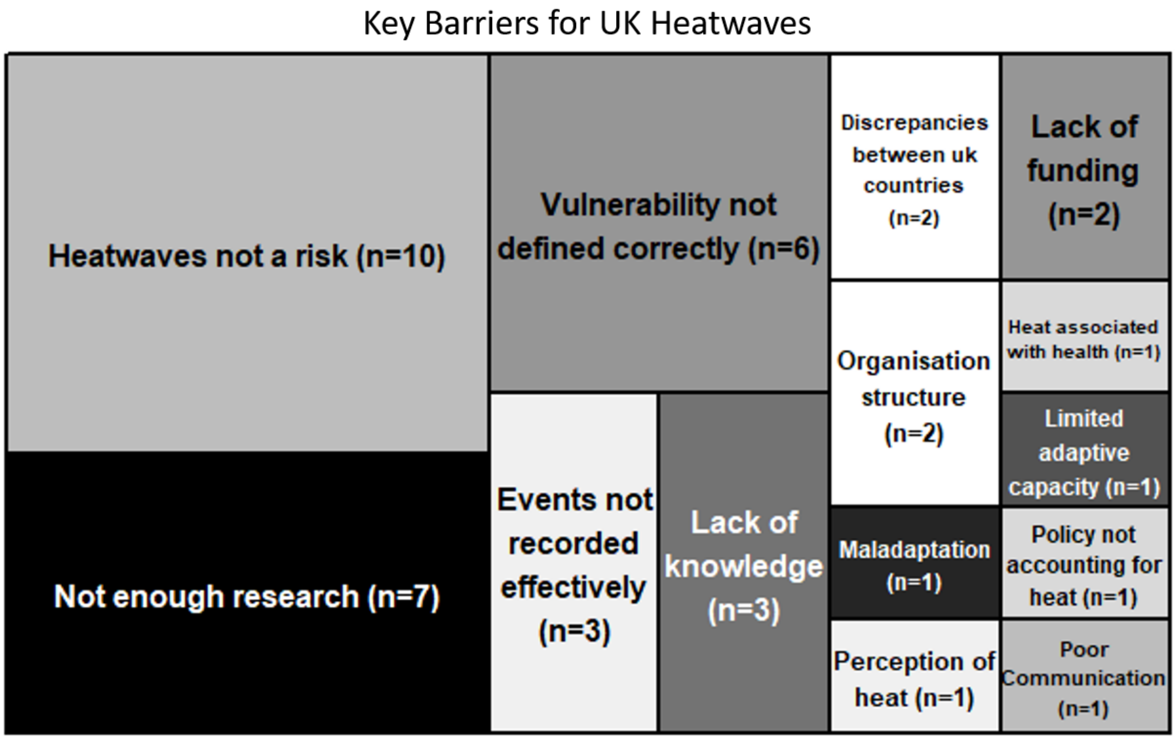

Figure 5.1: Treemap visualisation of all 14 barriers identified in the dataset. The different size boxes represent the level of agreement within the dataset.

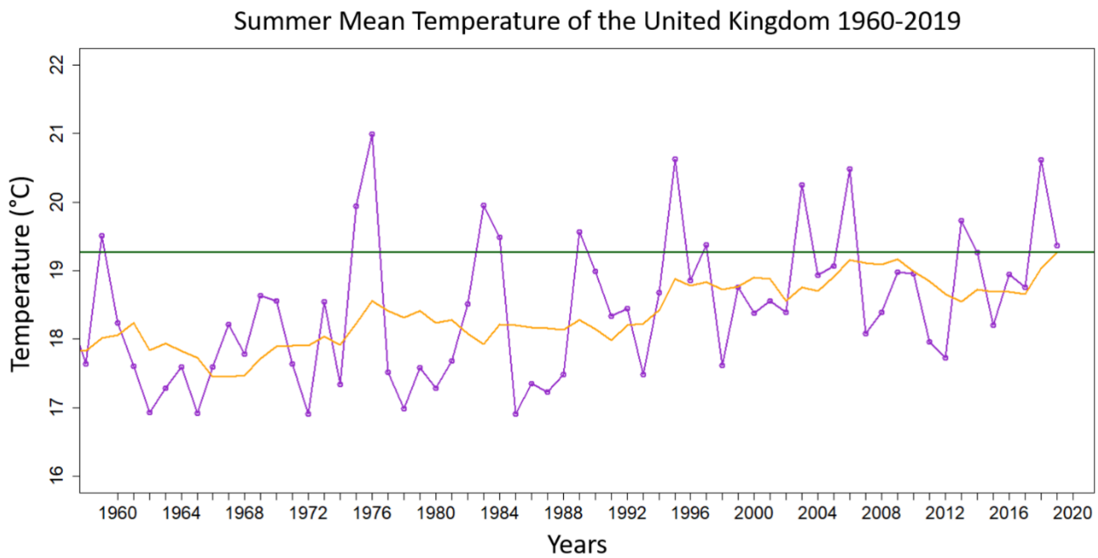

Figure 5.2: Summer Mean Temperature for the UK 1960-2018. The purple line represents the trend of the summer mean temperatures from 1960 to 2019; the orange line depicts a smoothed rolling mean line of the summer mean temperatures; and the green line shows the 90th Percentile of summer mean temperatures from 1960 to 2019, purple values above this line indicate heatwaves.

A quarter of the studies (25%, n=5/20) also commented on how UK heatwaves are 'invisible' in comparison to other extreme meteorological events (Abeling, 2015; de Bruin et al., 2016; Ferranti et al., 2018; Murtagh et al., 2019; Taylor et al., 2014). As Murtagh et al. (2019) suggests, the visual impact and newsworthiness of flood events captures public attention far more than heatwaves, in part because newspaper coverage tends to link hot weather with barbeques and other positive outdoor pursuits as opposed to there being a risk. Indeed, Taylor et al. (2014) found that UK residents believe that floods are more likely to increase due to climate change than heatwaves. Adapting our original search in Scopus to account for floods instead of heatwaves, returned 1,766 results for the keyword flood compared to 68 results for the keyword heatwave, which suggests that difference in public perceptions may also be related to a research bias in favour of flood risk studies over heatwave research.

A lack of research into different areas impacted by heatwaves was also identified by a third of the studies (35%, n=7/20) as a barrier. Although the 2003 European heatwave has served to generate more research in the healthcare and building sectors, other at-risk sectors including transport, energy, water and food are largely ignored. Even when research is happening the focus can be somewhat narrow. For instance, much of the research from the building sector concentrates on homes, with research on other building types such as schools and offices having to play catch up (Montazami and Nicol, 2013). In turn, behaviour studies suggest that building research rarely considers the motivation and capacity of users to tackle concerns with overheating risks or the role played by mental health and pro-environmental values (Khare et al., 2015; Murtagh et al., 2019; Page et al., 2012).

The barriers outlined in this section can hinder the uptake of heatwave research in policy decision-making. A research bias in favour of floods, for instance, serves to keep heatwaves as an 'invisible' risk whilst the amount of research conducted on some sectors (e.g. healthcare, building) can skew which risks are identified and who should be responsible for dealing with them so that a form of silo thinking develops in policy debates. Indeed, the UK's latest National Adaptation Plan uses the word 'heat*' 70 times compared to 251 times for 'flood*' (DEFRA, 2018).

5.3.3 What solutions were proposed to improve the formulation and/or implementation of UK heatwave policy?

Just under half of the studies reviewed (40%, n=8/20) agreed that a key solution to managing heatwaves is through 'targeted action'. For example, where a railway signal is at-risk of failing in a heatwave, a 'targeted action' would be to replace it before this occurred (Ferranti et al., 2016, 2018). Targeted action, therefore, involves identifying, assessing, and proactively intervening in current systems to reduce, or avoid, the negative impacts associated with a heatwave. For the healthcare plan, this could involve a shift away from concentrating responsibilities in a single Government department and redistributing those responsibilities according to where heat presents a risk across Government as a whole (Oven et al., 2012).

Another main solution discussed was how to better communicate heat risks using different strategies, across different geographical scales, and aimed at different actors. This was identified through 3 separate themes/scales: nationwide engagement with the population (n=4/20), community-based engagement (n=4/20) and the use of media (n=3/20). Most communication solutions were proposed by research participants who were surveyed or interviewed through the studies. Abrahamson, et al., (2008), for instance, reported that respondents suggested heatwaves should be incorporated in television or radio storylines, as a creative way to present the risk to a large proportion of the population. Whilst others have called on the Met Office to give heatwaves names similar to winter storms to help persuade the media, and by extension the public, of the serious risks heatwaves pose (Ward 2019).

Furthermore, the papers reviewed agreed that more research could hold the answer to identify which sectors are at-risk, where targeted action is needed, and provide a richer and more robust evidence base to inform policymaking. One concern raised is that the UK's National Adaptation Plan seeks to empower the public to make decisions in their own interest to reduce their exposure to heat risks (Abeling, 2015; DEFRA, 2018). Yet the studies analysed suggest that the evidence base for heatwaves lacks sufficient depth to be able to inform policy on how to help people improve their adaptive capacity, drill down into the important role that social networks play in building up their resilience (Abrahamson, et al., 2008; Wolf et al., 2010); or how the difference between a tenant and homeowner can limit adaptive capacities. More research was called for to better understand what solutions can be offered, and if these solutions are context specific (Baborska-Narożny et al., 2017; Murtagh et al., 2019).

5.4 Discussion

A major challenge faced by nation-states as well as international bodies over how best to manage heatwaves relates to a lack of evidence and inconsistencies within the evidence base that is available (e.g. geographical, sectoral). In the UK, silo thinking has taken root in the policy arena as the healthcare sector and building/infrastructure sector have been proactive in developing policies, plans and guidance, whilst other at-risk sectors are largely ignored. In turn, the research community has produced evidence to support these policy domains but again largely ignored the challenges faced by other sectors and an imbalance between heatwave and flood risk research has emerged. As a result, UK policy and research on heatwaves have worked together to produce this 'invisible risk'.

5.4.1 Why are there discrepancies in the reporting and analysis of extreme weather events?

Arguably the imbalance in research between floods and heatwaves is borne out of a legacy, where triggering events motivate research and policy changes, which historically has favoured the higher frequency of flood events in the UK (Met Office, 2019). With more research written about UK flooding than heatwaves, an 'availability effect' has developed. That is, the importance of something is directly related to how prevalent it is and/or how it is perceived (Khare et al., 2015). Media reporting of extreme weather events has contributed to the 'availability effect' by framing floods as a risk, and heatwaves as an opportunity (Wolf et al. 2010).

Of interest here, is that discrepancies between extreme weather events is not unique to the UK. In 2017, the European Environment Agency released its report on 'Climate Change Adaptation and Disaster Risk Reduction'. A keyword search of the document for 'flood*' and 'heat*', returned 446 and 186 mentions respectively (European Environment Agency, 2017). Despite the European Union funding research projects on extreme heat, an imbalance exists in which extreme weather events are given top billing. At the international level, reports by the OECD (Organisation for Economic Co-operation and Development) and the WMO (World Meteorological Organisation), on Climate Change Adaptation and services the word 'flood*' appears at least twice as often as the word 'heat*' (GFCS, 2016; OECD, 2018). Yet for health and climate change reports by WHO (World Health Organisation), 'heat*' does appear more frequently than 'flood*', but suggests that extreme heat remains an 'invisible risk' outside of the health sector (WHO, 2019; 2018).

5.4.2 Are heatwaves an 'invisible risk'?

Our review shows that, outside of a select few policy domains, yes heatwaves remain an 'invisible risk' in the UK. However, a growing body of literature is seeking to change this by broadening the scope of research into other at-risk sectors. The grey literature may offer a template for the research community to follow here. The Joseph Rowntree Foundation, for instance, has commissioned several studies on heat risks that capture the experiences of practitioners and stakeholders working and living in exposed sectors, and found that the Heatwave Plan for England is too reactive in that it focuses on coping rather than building adaptive capacity within communities (Benzie et al. 2011). Likewise, the UK's second Climate Change Risk Assessment brought together insights from researchers and practitioners to review how heat risk had been discussed across different sectors, with the findings aimed at policymakers across the full breadth of Government (Committee on Climate Change, 2017). Such efforts reveal how the profile of heat risks can be increased via more interdisciplinary and collaborative projects, and why future research should focus on mining the grey literature to see how to accelerate the changes it calls for in both policy and research too.

5.4.3 Why is defining heat-related vulnerability key?

Vulnerability was a central theme throughout the reviewed papers. Heatwaves events served to reveal where social inequalities exist in the capacity of people, buildings/infrastructure, and sectors to respond effectively. Yet it is important to remember that vulnerability is not static but dynamic. Different studies, and different sectors, conceptualised and enacted the discourse on vulnerability differently. Whereas for healthcare professionals 'vulnerability' concerns the ability of 'people' to adapt and respond, for building/infrastructure researchers 'vulnerability' concerns the 'physical apparatus' that allows everyday life to function (Curtis et al., 2017; Larcom et al., 2019; Murtagh et al., 2019; Page et al., 2012; Wolf, and McGregor, 2013). One solution made in the review was that the Health and Social Care Act 2012 could be updated to include consideration for climate change, and particularly heat risk, as this would help mainstream the need to address vulnerabilities across all policy areas in Government (Rauken et al., 2015). This has also been highlighted in the grey literature (see Benzie et al., 2011; Royal Society 2014).

5.4.4 What action is needed on overheating in buildings and at work?

To date, the vast majority of the research into building overheating has focused on homes. Despite research suggesting that up to 20% of homes currently experience overheating problems during an average UK summer, new houses built in line with Government housing plans do not have to factor overheating into their designs (Peacock et al., 2010; Wilson and Barton, 2018). Moreover, the UK Government's own research has already found that new homes do overheat, but no policy action has been taken (MHCLG, 2019). New legislation on building standards is needed as 'best practice' guidance is not working (CIBSE 2013; 2015; 2017).

It is also surprising the main research has been on homes given that – outside of a global pandemic – people come into contact with a wide variety of building types in their everyday lives. A growing body of literature is seeking to addresses the problem of overheating in other buildings such as hospitals, schools and offices (Committee on Climate Change, 2017; Montazami and Nicol, 2013). But there is currently no 'maximum' safe working temperature under the UK's Workplace (Health, Safety and Welfare) Regulations 1992, despite there being a 'minimum' safe working temperature. This needs to be urgently addressed as exposure to extreme heat can be a contributory factor to a range of health conditions (Glaser et al., 2016) as well as impact upon productivity.

5.4.5 Is there a geography to UK heatwave research?

Yes, not only does a discrepancy exist in the amount of heatwave research conducted in different regions of the UK but this discrepancy is also mirrored in the formulation and/or implementation of official Government policies and plans (Khare et al., 2015). England is the only region of the UK that has a heatwave plan, and it focuses only on health (The Met Office, 2020a). Despite the UK's latest climate projections showing that heatwave will increase in frequency, severity and duration across all UK regions, the level of research and policy development does not follow these concerns. No research met our criteria for heatwaves policy and management in Northern Ireland. This is concerning because without an evidential base for policy at best the urgency of the problem will remain low and at worst it will remain an 'invisible risk'.

This result may be related to legacy as heatwave events have historically been rare in the UK and institutional fragmentation introduced through devolution – where each country controls how they are governed and the policy they prioritise – has impeded centralised planning and action This is important because heatwaves do not observe administrative boundaries: they are borderless. Yet the creation of the Heatwave Health Plan for England speaks to this inconsistency as only some sectors, and some places, prepare for and adapt to heat risks. Historically heatwaves spread across wide areas, for example the European Heatwave in 2003, and the Russian Heatwave in 2010. But it is key that all guidance on heat is developed to avoid patchiness in provision and response (e.g. WMO and WHO, 2015).

5.5 Conclusion

Despite scholars highlighting the importance of planning for, and adapting to, the impacts of heatwaves in the UK (Environmental Audit Committee 2018; Howarth et al. 2019; Public Health England 2014), our research shows that the evidence base available to decision-makers is limited. Where evidence does exist, it is accompanied by a research bias. That is, the vast majority of studies focus on health risks or infrastructure. Other at-risk sectors, such as transport, energy, water and food, which are just as important to the functioning of our everyday lives receive considerably less attention. Risks posed by heatwaves are rarely limited to a single sector but cut across different sectors in both predictable and unpredictable ways. Efforts to formulate, and in turn, implement heatwave policies can encounter problems as Government departments have different mandates, priorities, and influence, and as a result, institutional responsibilities become fragmented and/or deferred (Environmental Audit Committee 2018).

Our research also found that the heatwave evidence base varies geographically. Nearly all the studies focus on England, with Scotland and Wales receiving only a small amount of attention and Northern Ireland ignored altogether. Likewise, the official Government policy and/or plan for managing heatwaves focuses on just England. Yet heatwaves do not observe administrative boundaries. Without a rich, robust and diverse evidence base, the risk of maladaptation and poor coping strategies could increase on a regional basis. A major concern, therefore, is that heatwaves become an 'invisible risk' for policymakers. A lack of evidence, and inconsistencies within that evidence base, can serve to deprioritise the seriousness of heatwave risks and the urgency of policy action. For instance, 892 excess deaths were attributed to the UK's 2019 heatwaves whereas 11 deaths were ascribed to floods in the same year yet the evidence base and managerial resources for heatwaves is tiny in comparison to flood risk.

Unless the problem of 'silo thinking' in the way in which Government policy is formulated and/or implemented is urgently addressed, and the research community broadens the scope of studies to consider other at-risk sectors, the connections between those sectors, and actively seeks to fill gaps in the knowledge base between regions, then heatwaves will remain at worst an 'invisible risk' amongst policymakers or at best a niche debate between healthcare and building professionals. Answers on how to tackle these challenges may already exist but require more interdisciplinary thinking and commitment. Future research should focus on bringing insights from practitioners, local communities, and the grey literature together with scholarly research to provide a fully rounded picture on heatwave research so that policymakers can be better informed and supported when making decisions.

5.6 Supplementary Material

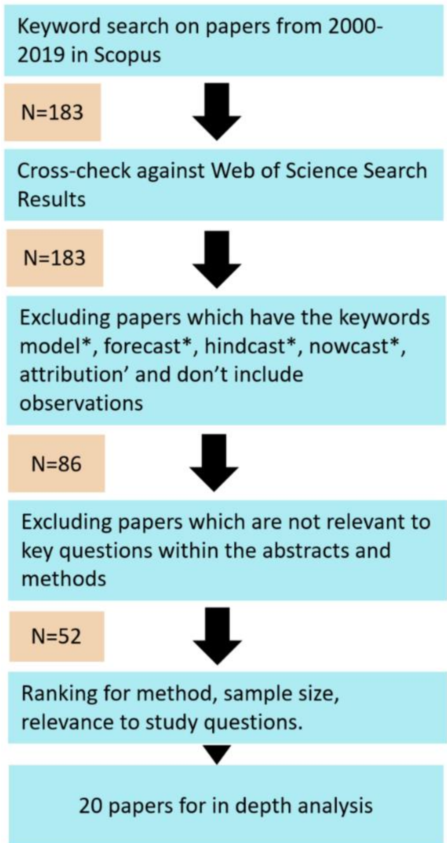

Figure S9.1: a simple schematic of the search criteria.

In-depth methods included in the schematic.

Keyword Search Criteria for Scopus, cross-checked against Web of Science:

ONE OF THE FOLLOWING KEYWORDS

Level 1: Heatwave; Heat-wave; Extreme temperature; Warm*

PLUS ONE OF THE FOLLOWING KEYWORDS

Level 2: Capacity; adapt*; alert; warning; mortality; risk; vulnerability; exposure; policy; hazard; morbidity; elderly; infants; workers; stress; management; overheating; health; buildings; climate; hot spell; period; season;

PLUS ONE OF THE FOLLOWING KEYWORDS

Level 3: UK, United Kingdom, England, Scotland, Wales, Northern Ireland, Britain

Inclusion criteria	**Exclusion criteria**
• Empirical publications (e.g. data, evidence-based, findings); • Peer-reviewed publications; • Match the keyword searches; • English language; • 1st January 2000 to 31st December 2019; • Indexed in ISI Web of Science and Scopus;	• Non-English Language; • Pre-2000 and after 1st January 2020; • Neither indexed nor available from ISI Web of Science and Scopus; • Other types of publications (editorials, reviews, books, chapters, conference proceedings etc); • Conceptual or modelled/forecasted studies;

(This returned 183 papers)

After applying the exclusion criteria using a key work search, removing papers that have key words that contain 'model*, forecast*, hindcast*, nowcast*, attribution' the number of papers left is 83.

The methods and abstract were reviewed for relevance and this left 52.

Ranking that was carried out on the 52 papers.

Ranking Criteria:

Was it quantative /qualitative research?

How big was that sample of the research?

How relevant is the research to this study's key questions?

5* Papers (n=4)

Papers where the sample size is of a large size, the way the data is analysed provides key information about heatwaves in UK policy. Strong empirical aspect to the paper.

Author(s)	**Article Title**	**Score**

de Bruin W.B., Lefevre C.E., Taylor A.L., Dessai S., Fischhoff B., Kovats S.	Promoting protection against a threat that evokes positive affect: The case of heat waves in the United Kingdom	5*
Ferranti E., Chapman L., Lee S., Jaroszweski D., Lowe C., McCulloch S., Quinn A.	The hottest July day on the railway network: insights and thoughts for the future	5*
Khare S., Hajat S., Kovats S., Lefevre C.E., De Bruin W.B., Dessai S., Bone A.	Heat protection behaviour in the UK: Results of an online survey after the 2013 heatwave	5*
Murtagh N., Gatersleben B., Fife-Schaw C.	Occupants' motivation to protect residential building stock from climate-related overheating: A study in southern England	5*

4* Papers (n=8)

Papers where the empirical analysis is strong and the sample size is larger than that seen with the 3* papers. Often the findings were better supported by the paper's evidence.

Author(s)	**Article Title**	**Score**
Abrahamson V., Raine R.	Health and social care responses to the Department of Health Heatwave Plan	4*
Abrahamson V., Wolf J., Lorenzoni I., Fenn B., Kovats S., Wilkinson P., Adger W.N., Raine R.	Perceptions of heatwave risks to health: Interview-based study of older people in London and Norwich, UK	4*

Ferranti E., Chapman L., Lowe C., McCulloch S., Jaroszweski D., Quinn A.	Heat-related failures on southeast England's railway network: Insights and implications for heat risk management	4*
Kovats R.S., Hajat S., Wilkinson P.	Contrasting patterns of mortality and hospital admissions during hot weather and heat waves in Greater London, UK	4*
Larcom S., She P.-W., van Gevelt T.	The UK summer heatwave of 2018 and public concern over energy security	4*
Lefevre C.E., Bruine de Bruin W., Taylor A.L., Dessai S., Kovats S., Fischhoff B.	Heat protection behaviours and positive affect about heat during the 2013 heat wave in the United Kingdom	4*
Vellei M., Ramallo-González A.P., Coley D., Lee J., Gabe-Thomas E., Lovett T., Natarajan S.	Overheating in vulnerable and non-vulnerable households	4*

3* Papers (n=9)

Papers where, there is enough empirical evidence to support findings, but where the sample size is sometimes small or not as much of a focus on heatwaves from the sample.

Author(s)	Article Title	Score
Abeling T.	According to plan? disaster risk knowledge and organizational responses to heat wave risk in London, uk	3*
Baborska-Narony M., Stevenson F., Grudziska M.	Overheating in retrofitted flats: occupant practices, learning and interventions	3*
Elliot A.J., Bone A., Morbey R., Hughes H.E., Harcourt S., Smith S., Loveridge P., Green H.K., Pebody R., Andrews N., Murray V.,	Using real-time syndromic surveillance to assess the health impact of the 2013 heatwave in England	3*

Catchpole M., Bickler G., McCloskey B., Smith G.		
Wolf J., Adger W.N., Lorenzoni I., Abrahamson V., Raine R.	Social capital, individual responses to heat waves and climate change adaptation: An empirical study of two UK cities	3*
Wolf T., McGregor G.	The development of a heat wave vulnerability index for London, United Kingdom	3*
Page L.A., Hajat S., Sari Kovats R., Howard L.M.	Temperature-related deaths in people with psychosis, dementia and substance misuse	3*
Taylor A., De Bruin W.B., Dessai S.	Climate Change Beliefs and Perceptions of Weather-Related Changes in the United Kingdom	3*
Tomlinson C.J., Chapman L., Thornes J.E., Baker C.J.	Including the urban heat island in spatial heat health risk assessment strategies: A case study for Birmingham, UK	3*
Kovats R.S., Johnson H., Griffith C.	Mortality in southern England during the 2003 heat wave by place of death.	3*

2* Papers (n=20)

Papers where, the level of empirical research is higher than seen in 1* papers, but the research outcomes in some cases remain irrelevant for providing information for the systematic review. Some of the sample sizes are also not clear or small.

Author(s)	Article Title	Score
Bennett J.E., Blangiardo M., Fecht D., Elliott P., Ezzati M.	Vulnerability to the mortality effects of warm temperature in the districts of England and Wales	2*

Boyson C., Taylor S., Page L.	The National Heatwave Plan - A Brief Evaluation of Issues for Frontline Health Staff	2*
Crichton B.	Keep in a cool place: Exposure of medicines to high temperatures in general practice during a British heatwave	2*
Dobney K., Baker C.J., Quinn A.D., Chapman L.	Quantifying the effects of high summer temperatures due to climate change on buckling and rail related delays in south-east United Kingdom	2*
Fagan-Watson B., Burchell K.	Heatwave planning: community involvement in co-producing resilience	2*
Green H.K., Edeghere O., Elliot A.J., Cox I.J., Morbey R., Pebody R., Bone A., McKendry R.A., Smith G.E.	Google search patterns monitoring the daily health impact of heatwaves in England: How do the findings compare to established syndromic surveillance systems from 2013 to 2017?	2*
Hajat S., Kovats R.S., Atkinson R.W., Haines A.	Impact of hot temperatures on death in London: A time series approach	2*
Hill D.L., Wall E.	Weather influences feed intake and feed efficiency in a temperate climate	2*
Hill D.L., Wall E.	Dairy cattle in a temperate climate: The effects of weather on milk yield and composition depend on management	2*
Leonardi G.S., Hajat S., Kovats R.S., Smith G.E., Cooper D., Gerard E.	Syndromic surveillance use to detect the early effects of heat-waves: An analysis of NHS direct data in England	2*

Oven K.J., Curtis S.E., Reaney S., Riva M., Stewart M.G., Ohlemüller R., Dunn C.E., Nodwell S., Dominelli L., Holden R.	Climate change and health and social care: Defining future hazard, vulnerability and risk for infrastructure systems supporting older people's health care in England	2*
Page L.A., Hajat S., Kovats R.S.	Relationship between daily suicide counts and temperature in England and Wales	2*
Short C.A., Renganathan G., Lomas K.J.	A medium-rise 1970s maternity hospital in the east of England: Resilience and adaptation to climate change	2*
Smith S., Elliot A.J., Hajat S., Bone A., Bates C., Smith G.E., Kovats S.	The impact of heatwaves on community morbidity and healthcare usage: A retrospective observational study using real-time syndromic surveillance	2*
Taleghani M., Marshall A., Fitton R., Swan W.	Renaturing a microclimate: The impact of greening a neighbourhood on indoor thermal comfort during a heatwave in Manchester, UK	2*
Thornes J.E., Fisher P.A., Rayment-Bishop T., Smith C.	Ambulance call-outs and response times in Birmingham and the impact of extreme weather and climate change	2*
Wolf T., McGregor G., Analitis A.	Performance assessment of a heat wave vulnerability index for Greater London, United Kingdom	2*
Wreford A., Neil Adger W.	Adaptation in agriculture: Historic effects of heat waves and droughts on UK agriculture	2*

Wright A.J., Young A.N., Natarajan S.	Dwelling temperatures and comfort during the August 2003 heat wave	2*
Zhang Y., Peng M., Wang L., Yu C.	Association of diurnal temperature range with daily mortality in England and Wales: A nationwide time-series study	2*

1* Papers (n=11)

Where Papers, do not contain enough empirical research to back up findings, or the research focuses on a small study sample. In addition, sometimes the structure of the research and outcomes are not relevant to assist with providing information for this systematic review.

Brown S., Walker G.	Understanding heat wave vulnerability in nursing and residential homes	1*
Gough H., Faulknall-Mills S., King M.-F., Luo Z.	Assessment of overheating risk in gynaecology scanning rooms during near-heatwave conditions: A case study of the royal Berkshire hospital in the UK	1*
Hulme M.	'Telling a different tale': Literary, historical and meteorological readings of a Norfolk heatwave	1*
Johnson H., Kovats R.S., McGregor G., Stedman J., Gibbs M., Walton H., Cook L., Black E.	The impact of the 2003 heat wave on mortality and hospital admissions in England.	1*
Lomas K.J., Ji Y.	Resilience of naturally ventilated buildings to climate change: Advanced natural ventilation and hospital wards	1*
McLafferty E.	Prevention and management of hyperthermia during a heatwave.	1*

Nobert S., Pelling M.	What can adaptation to climate-related hazards tell us about the politics of time making? Exploring durations and temporal disjunctures through the 2013 London heat wave	1*
Stedman J.R.	The predicted number of air pollution related deaths in the UK during the August 2003 heatwave	1*
Tang C., Rundblad G.	The potential impact of directionality, colour perceptions and cultural associations on disaster messages during heatwaves in the UK	1*
Taylor J., Wilkinson P., Davies M., Armstrong B., Chalabi Z., Mavrogianni A., Symonds P., Oikonomou E., Bohnenstengel S.I.	Mapping the effects of urban heat island, housing, and age on excess heat-related mortality in London	1*
Zaidi R.Z., Pelling M.	Institutionally configured risk: Assessing urban resilience and disaster risk reduction to heat wave risk in London	1*

Table S9.1: 20 Papers, which ranked highest against the criteria, and their keywords.

Publications	**Keyword(s)**	**Journal**	**Ranking**
Abeling, (2015)	Adaptation and Health	Ecosystem Health and Sustainability	3*
Abrahamson and Raine, (2009)	Health	Journal of Public Health	4*
Abrahamson, *et al.*, (2008)	Health	Journal of Public Health	4*
Baborska-Narożny *et al.*, (2017)	Building and Infrastructure	Building Research and Information	3*

de Bruin *et al.*, (2016)	Behaviour	Journal of Experimental Psychology: Applied	5*
Elliot *et al.*, (2014)	Health	Environmental Research	3*
Ferranti *et al.*,(2018)	Railway and Infrastructure	Meteorological Applications	5*
Ferranti *et al.*, (2016)	Railway and Infrastructure	Weather, Climate, and Society	4*
Khare *et al.*, (2015)	Behaviour	BMC Public Health	5*
Kovats, *et al.*, (2004)	Health	Occupational and Environmental Medicine	4*
Kovats, *et al.*, (2006)	Health	Health statistics quarterly / Office for National Statistics	3*
Larcom *et al.*, (2019)	Behaviour and Infrastructure	Nature Climate Change	4*
Lefevre *et al.*, (2015)	Behaviour	Social Science and Medicine	4*
Murtagh *et al.*, (2019)	Behaviour and Building	Journal of Cleaner Production	5*
Page *et al.*, (2012)	Health	British Journal of Psychiatry	3*
Taylor *et al.*, (2014)	Behaviour	Risk Analysis	3*
Tomlinson *et al.*, (2011)	Health	International Journal of Health Geographic's	3*
Vellei *et al.*, (2017)	Building	Building Research and Information	4*
Wolf, *et al.*, (2010)	Behaviour and Adaptation	Global Environmental Change	3*
Wolf, and McGregor,(2013)	Adaptation	Weather and Climate Extremes	3*

Table S9.2: UK Departments and Guidance, Policy and Reports on Heatwaves.

Organisation/Public Body and the Legislation/Policy/Guidance	***Definition***	***Reference***
Committee on Climate Change	*Independent body, which provide the UK Government and the constituents of the UK with Climate change guidance.*	

Climate Change Risk Assessment 2017	*Latest Risk Assessment, feeds into the National Adaptation Plan.*	*(The Committee on Climate Change, 2017)*
UK Government		
Climate Change Act,2008	*Main policy document for the UK, for climate change, sets out key actions. For example the creation of the Committee on Climate Change, came as part of this policy.*	*(HM UK Parliament, 2008)*
The National Risk Register	*Guidance document which lists the main risks to the UK, and key advice on how to respond.*	*(The UK Cabinet Office, 2017)*
Environmental Audit Committee	*Is a cross-party group of members of parliament, which review Environmental Issues and how the UK Government has responded.*	
Heatwaves: adapting to climate change Ninth Report of Session 2017-19 Report,	*Report in which the Committee set out that the UK Governments policy and guidance on heatwaves is inadequate.*	*(Environmental Audit Committee, 2018)*
Met Office	*The Met Agency in the UK, are themselves a public body, provide key weather and climate data to other organisations and public bodies.*	
UKCP18 Climate Projections	*The Latest climate change projections for different scenarios for the UK region. Provided by the HADCM3*	*(The Met Office Hadley Centre, 2018)*
National Severe Weather Warning system	*Warning systems for different meteorological conditions for the whole of the UK.*	*(Met Office, 2020)*
Department of Health and Social Care	***(Lead Department in heatwave response)*** *Department which oversees the National Health Service and*	

	community care in the form of Social Care.	
Health and Social Care Act (2012)	*Policy which sets out how the NHS and Social Care is run within the UK. For example, setting out Accident and Emergency wait times.*	*(Abeling, 2015)*
Department for Environment, Food and Rural Affairs.	*Department which manages climate change policy related to the Environment. Also oversees agriculture.*	
National Adaptation Plan (NAP) 2018-2023	*Is a policy which sets out measures that the UK will aim to put into place as a result of the Climate Change Risk Assessment.*	*(Department for Environment Food and Rural Affairs (Defra), 2018)*
Department for Education	*Department for the whole education system within the UK*	
Guidelines on ventilation, thermal comfort and indoor air quality in schools.	*Guidance for those within the sector on thermal comfort in schools.*	*(Department of Education, 2016)*
Ministry of housing, Communities and Local Government.	*Department for housing and the community. Overseeing local authorities.*	
Research into overheating in new homes: Phase 1 report.	*Research report into how overheating is effecting new homes.*	*(MHCLG, 2019)*
Public Health England	*Health body only for England, has devolved powers from the department of health and social care.*	
Heatwave Health Plan England	*Updated every year by public health England, Meteorology data and forecasting provided by Met Office. Aims to reduce mortality and morbidity rates due to heat.*	*(Public Health England, 2018)*
Syndromic Surveillance	*A computer system that Public Health England, runs to flag key health issues, which could cause*	*(Public Health England, 2019)*

	capacity problems, including heat conditions.	
Welsh Assembly	*Devolved power for Wales from the UK Government, have some jurisdiction over policy areas including health.*	
Scottish Government	*Devolved power for Scotland, have the most control over own powers of any region of the UK, including health and climate change.*	
Northern Ireland Assembly	*Devolved power for Northern Ireland, from the UK Government, have some jurisdiction over policy areas including health.*	
Chartered Institution of Building Services Engineers	*Professional body for Building Services Engineers.*	
Thermal Comfort Guidance	*Guidance on the International and European Standards that buildings should meet.*	*(Baborska-Narożny et al., 2017; Murtagh et al., 2019)*
National Rail	*Organisation which oversees railway stations and track/track side infrastructure in the UK.*	
Weather Resilience and Climate Change Adaptation Plans	*Guidance that national rail has to adapt to meteorological hazards and climate change.*	*(Ferranti et al., 2018, 2016)*

6. Heat Stress trends in Africa

Commentary: at the original conception of this paper, there was a lack of evidence for heatwave and heat stress trends across the African continent. This was despite evidence demonstrating that this was a region that was at a large risk to extreme heat. This research originally won me the AGU student travel award in December 2020.

I consistently faced setbacks with this research, to start with predominantly because of difficulties explaining the Universal Thermal Climate Index. After, it got a commission by a popular science outlet, but eventually was rejected by the second journal. Since then I have carried out new research based on the methodology of Chapter 4 of the thesis and restructured it. In addition, the pre-print of the paper from the second journal has been used in at least one other piece of research and cited as such.

This chapter fits within component 2: Health Information Systems because it provides evidence towards the objective Evaluating trends and modelling of extreme heat, by demonstrating trends of heat stress over Africa for over the last 30 years.

Abstract:

Extreme heat has increased on a global scale with global heating. Africa is a region known to be at a greater risk to the impacts of climate change because of its limited adaptative capacity. However, on a continental scale little research has been carried out on heat stress. Here we show that the area exposed to heat stress has significantly increased since 2000 with the use of the Universal Thermal Climate Index (UTCI). In addition, a larger proportion of the African population is being exposed to heat stress for a longer duration. Our findings highlight the urgent need for mitigation and adaptation to extreme heat in African Nations.

6.1 Introduction

Africa is being significantly impacted by climate change and the multiple natural hazards it has been exacerbating (IPCC et al., 2021). One such hazard is extreme heat which has been increasing in frequency, duration and intensity in step with global heating across the continent and the globe (Ceccherini et al., 2017; Perkins-Kirkpatrick & Lewis, 2020; Russo et al., 2014, 2017). Previous research has shown that heat stress has been increasing in frequency for certain regions of Africa (Ahmadalipour & Moradkhani, 2018; Guigma et al., 2020; Parkes et al., 2019), as well as demonstrating an increase in the number and intensity of heatwaves for parts of the continent (Dosio, 2017; Fontaine et al., 2013; Hao et al., 2018; Ringard et al., 2016). However, on a continental scale it remains unclear how heat stress has increased in duration, intensity and area (Russo et al., 2016; van der Walt & Fitchett, 2021). Exploring this is vital to improve our understanding of how extreme heat is impacting African nations to assess neccesary mitigations and adaptations.

There are calls by many for the international community to come to a consensus and face the risk posed by heat globally and in Africa (Harrington and Otto 2020, Russo *et al* 2016, Global Commission on Adaptation 2020, World Meteorological Organization 2018). This would be welcomed by many in the humanitarian community who are working on the frontline of the climate emergency: *"An understanding of how temperatures have impacted people in Africa during past extreme heat events is critical to building public consensus on the issue and moving us toward action.*" (Roop Singh, Climate Risk Adviser for the Red Cross Climate Centre, pers comm).

The Universal Thermal Climate Index (UTCI) is part of the reanalysis dataset ERA5-HEAT, and is a robust thermal comfort index for evaluating heat stress for the continent of Africa (Guigma et al., 2020; Di Napoli et al., 2021). The UTCI models heat stress by making use of 2 metre temperature, dew point temperature, mean radiant temperature and wind speed in combination with a bespoke body model giving a highly accurate indication of heat stress (Bröde et al., 2012). Previous research has demonstrated the forecasting capabilities of the UTCI, as well as its valuable use in heat and cold mortality modelling (Di Napoli et al., 2018; Pappenberger et al., 2015; Urban et al., 2021).

First, we investigate how the number of days with the daily maximum UTCI (indicating the highest heat stress level achieved in daytime) has changed since 1980 for two different ways of indicating heat stress above the 90^{th} percentile and above 32°C, i.e. the strong heat stress threshold. Then, we assess how the proportion of the land area and the populated area exposed to heat stress has changed since 2000. Next, we consider how the intensity of heat stress has shifted on average across the continent since 1980. Finally, we consider the sensitivity of heat stress during 2 heatwaves case studies for the continent. This allows us to investigate how the characteristics of heat stress have been changing across the African Continent.

6.2 Method

6.2.1 Universal Thermal Climate Index (UTCI) reanalysis data

Heat stress is assessed using the UTCI from the ERA5-HEAT reanalysis (https://doi.org/10.24381/cds.553b7518) which is freely accessible on the Copernicus Climate Data Store on a 0.25° x 0.25° grid at an hourly time step (Di Napoli et al., 2021). The UTCI is a thermal index indicative of the risk of an individual experiencing heat or cold stress. It makes use of the meteorological parameters of 2m temperature, water vapour pressure, 10m wind speed and mean radiant temperature, and a human body thermophysiological model (Jendritzky et al., 2012). It has been compared to many other thermal indices such as apparent temperature and heat index, and captures well an average body response to the thermal environment (Blazejczyk et al., 2012; Zare et al., 2018). In addition, the UTCI has also been used as a thermal index to forecast heatwaves internationally (Pappenberger et al., 2015) and accurately indicate extreme heat for Africa (Guigma et al., 2020).

6.2.2 Defining a Heatwave

As there is no universal definition of heatwaves, a heatwave is defined in this paper using an adaptation of the World Meteorological Organisation (WMO) guideline definition for the Universal Thermal Climate Index (UTCI) i.e., *"A period of marked unusual hot weather (maximum, minimum and daily average temperature) over a region persisting at least three consecutive days during the warm period of the year based on local (station-based) climatological conditions, with thermal conditions recorded above given thresholds"* (World Meteorological Organization, 2018). In this paper, a term for human heat stress is included when the mean UTCI exceeds the 90th percentile of the daily mean for a region. This threshold is 26.1°C UTCI for the country of South Africa (based on the 90th percentile of the daily means for December and January 1991 to 2020), and 28.2°C UTCI for the country of Morocco (based on the 90th percentile of the daily means for July and August 1991 to 2020).

6.2.3 Heat Stress Exposure and Intensity

We calculate the heat stress exposure in 2 ways. First, by considering the number of days where the daily maximum UTCI is above the strong heat stress threshold of 32°C and second above the monthly 90th percentile climatology (1991 to 2020) (Guigma et al., 2020; Di Napoli et al., 2021). This value is presented as a proportion of time in percent. We calculate heat stress intensity as the decadal or annual mean of the monthly mean of the daily maximum values of the UTCI.

6.2.4 Heat Stress Area

We use gridded spatial data to create binary maps (Brimicombe et al., 2021; Vitolo et al., 2019) with grid cells over the threshold for more than 50% of the time set equal to 1, otherwise 0. We assess heat stress across both for the total land area and the populated area for the continent of Africa. Land area is masked using the *Rworldmap* Africa shape. Populated land area is masked using grid cells with a population count of over 0 from the Land Scan dataset for 2000 to 2019 provided by the Oak Ridge National Laboratory (Dobson et al., 2000; Vijayaraj et al., 2007), All grid cells are then summed, allowing for proportions to be calculated. To assess the significance and the linear correlation of duration, intensity, and area an R^2 and p-values are also calculated.

6.2.5 Historical Heatwave Analysis

In this section of the paper, an analysis of two heatwaves is conducted based on seasonal-mean anomalies of the key variables that are frequently used to identify and characterise heatwaves (Guigma et al., 2020; Oueslati et al., 2017). The two case studies included: the South Africa 2015/16 heatwave and the Morocco 2000 heatwave. These were chosen because they occurred in different regions of the continent, exhibited different heat characteristics, notably their spatial extent and their impacts were reported in the EM-DAT international disaster database (CRED, 2020) (see section 6.3.1). In addition, South Africa 2015/16 is a compound or sequential heatwave event, adding to its interest (Bevacqua, et al., 2021).

The heatwave characteristics selected came from the ERA5 reanalysis dataset and are: 2m air temperature, the UTCI and the geopotential height at 500hpa (z500) and 850hpa (z850) (Hersbach et al., 2020; Di Napoli et al., 2021). Geopotential height at 500hpa is frequently used to identify and characterise blocking high pressure systems (high surface pressure and high surface temperature), whilst geopotential height at 850hpa is a useful diagnostic for identifying heat lows such as the Saharan Heat Low (low surface pressure and high surface temperature) (Lavaysse et al., 2016).

Anomalies were calculated based on the difference of the mean of each variable for the duration of the heatwave, from its climatological means over the period from 1991 to 2020 for the months in which the heatwave occurred. These were December-January for the South Africa 2015/2016 heatwave, and July-August for the Morocco 2000 heatwave. The anomalies for the week before, and the week after the heatwave were also calculated to provide a picture of the meteorological characteristics that started and ended the two heatwaves. In addition, the visual trends in a scatter plot matrix are evaluated for the input variables in comparison to the outputted UTCI heat stress values for each heatwave (c.f. Pappenberger et al., 2015). All calculations were carried out using Rstudio.

6.3 Results

6.3.1 Difference in exposure times between heat stress thresholds

There is a difference in exposure times when you use a 90th percentile climatology in comparion to a 32°C threshold. The number of days where the daily maximum is above the 90th percentile threshold has been increasing since the 1980s (Figure 6.1, middle). By the 2010s the area between 20°N and 20°S had a daily maximum above the 90th percentile climatological threshold up to 90% of the time In comparison, in this region since 1980 above 32°C regularly has been experienced up to 90% of the time (Figure 6.1, bottom). The area between 20°N and 20°S experienced at least 50% more days above 32 °C in comparison to days above the 90th percentile (Figure 6.1,top). Valley regions such as the Ethiopian highlands appear to not be experiencing as much heat stress exposure as other regions in the percentage of days above 32°C but more in days above 90th percentile (Figure 6.1, middle and bottom).

6.3.2 Increasing heat stress duration and area

The total land area has a significant increase in number of days where the daily maximum is experiencing heat stress for more than 50% of the time (Figure 6.2,a). The increase is marked and is about 20% more from 2000 to 2019. A greater area is experiencing heat stress for more of the time above a 32°C threshold. However, the increase is faster above the 90th percentile. The year experiencing the greatest area exposed to heat stress is 2013 for above the 90th percentile and 2019 for above 32°C. In comparison, for populated areas the 90th percentile threshold has more days where the daily maximum for more than 50% of the time is above a heat stress threshold than the 32°C threshold by up to 10% (Figure 6.2,b). In addition, the populated area exposure trend is less significant (R^2 0.10 and p-value < 1) than the total land area trend (R^2 0.40 and P value < 0.001). The populated area exposed and land area exposed for above 32°C are very similar at between between 55% to 80%. The increase in land area being exposed to heat stress is more significant (R^2 0.51 and 0.40,P value < 0.001) than the increase in number of days where the daily maximum is above a heat stress threshold (R^2 0.39 and 0.14, p-value <0.1 and < 1) (Figure 6.2). This suggests that a larger proportion of the land area is being exposed to heat stress for a greater amount of time.

6.3.3 Intense heat stress

The most intense values of heat stress are in desert regions (Figure 6.3, a). There is an increase in the decadal mean of daily maximum between 1980 and 2010 of up to 6°C in some parts of Africa (Figure 6.3,b). The greatest increase is in desert regions (up to 6°C) and the smallest increase in valley regions (up to 2°C). On average, across the African continent there has been a significant increase in the intensity of heat stress (R^2 0.61, p value < 0.001) (Figure 6.3,c). Overall, a significantly larger proportion of populated regions are being exposed to higher intensity heat stress values for a greater amount of time by the end of the 2010 decade in comparison to the year 2000 (Figure 6.2 and 6.3)

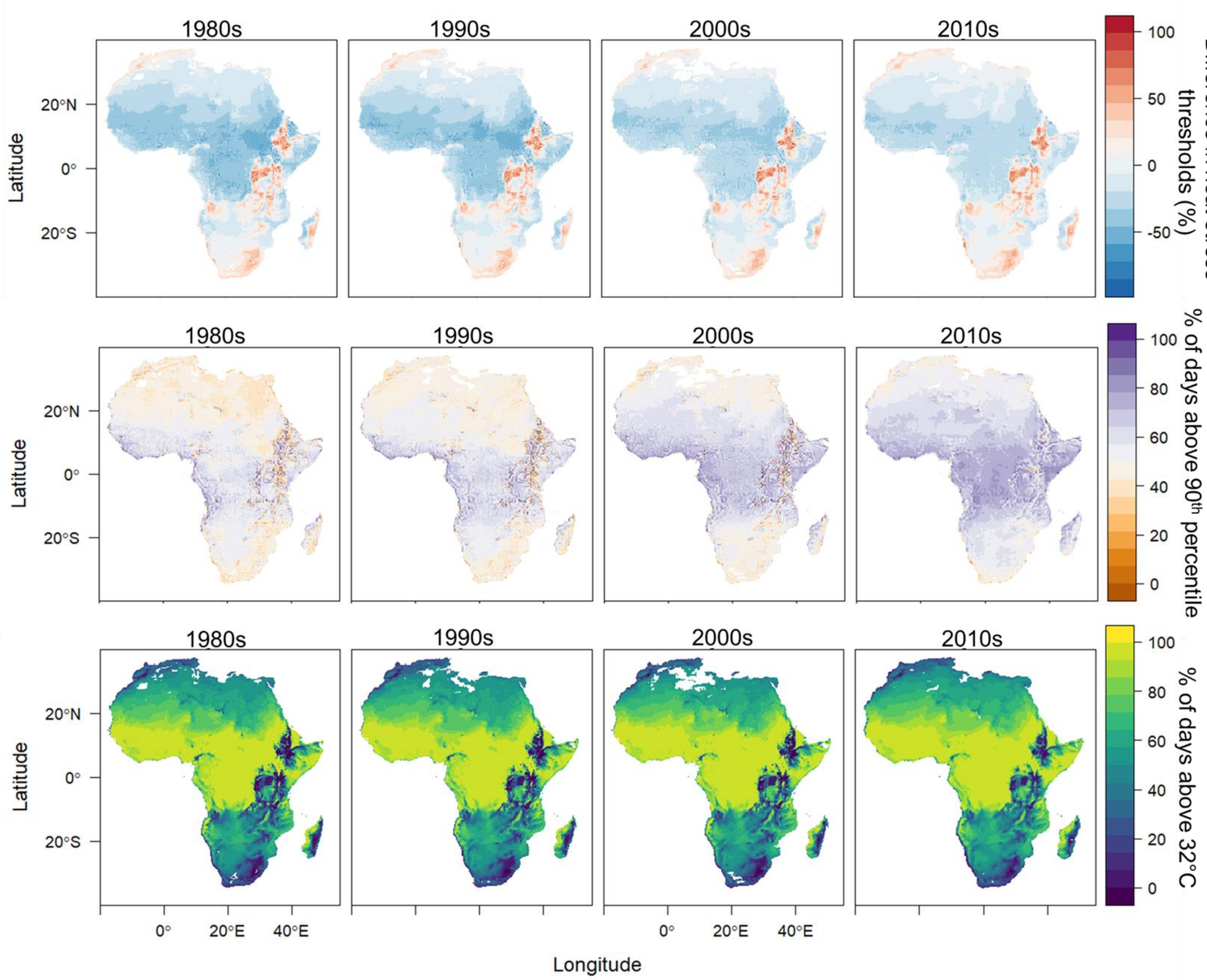

Figure 6.1: The decadal mean of the daily maximum for each decade of the UTCI since 1980 where top row: the difference between where number of days of daily max above 90th percentile indicative of a heatwave (middle row) and above 32°C (strong heat stress threshold) (bottom row)

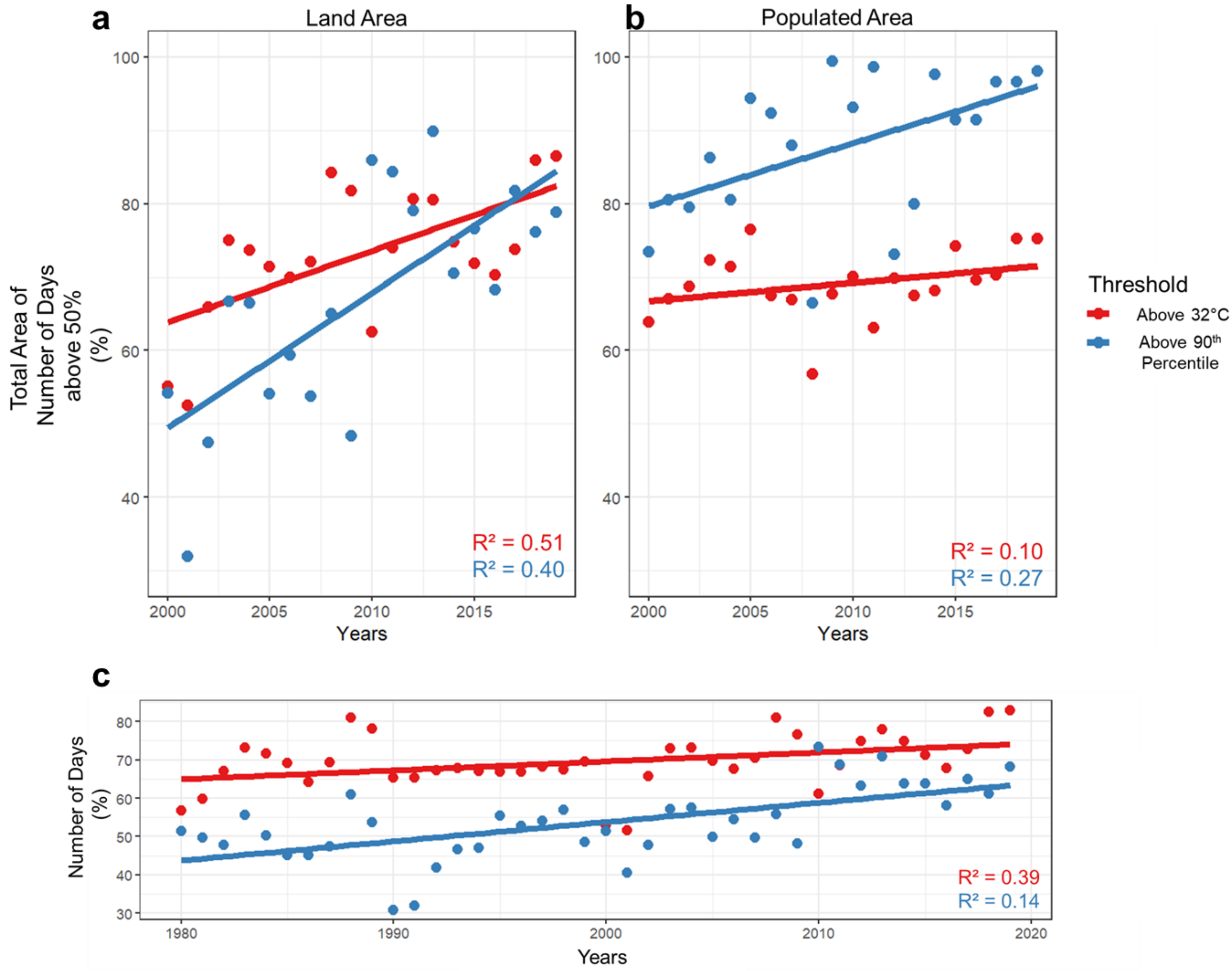

Figure 6.2: The annual mean of the daily maximum for 2000 to 2019 of the UTCI where a) is total land area as grid points experiencing heat stress on average for more than 50% of the time, b) total populated area as grid points experiencing heat stress on average for more than 50% of the time and c) total number of days above a heat stress threshold. Red is above 32°C (strong heat stress threshold) and blue is above the 90th percentile.

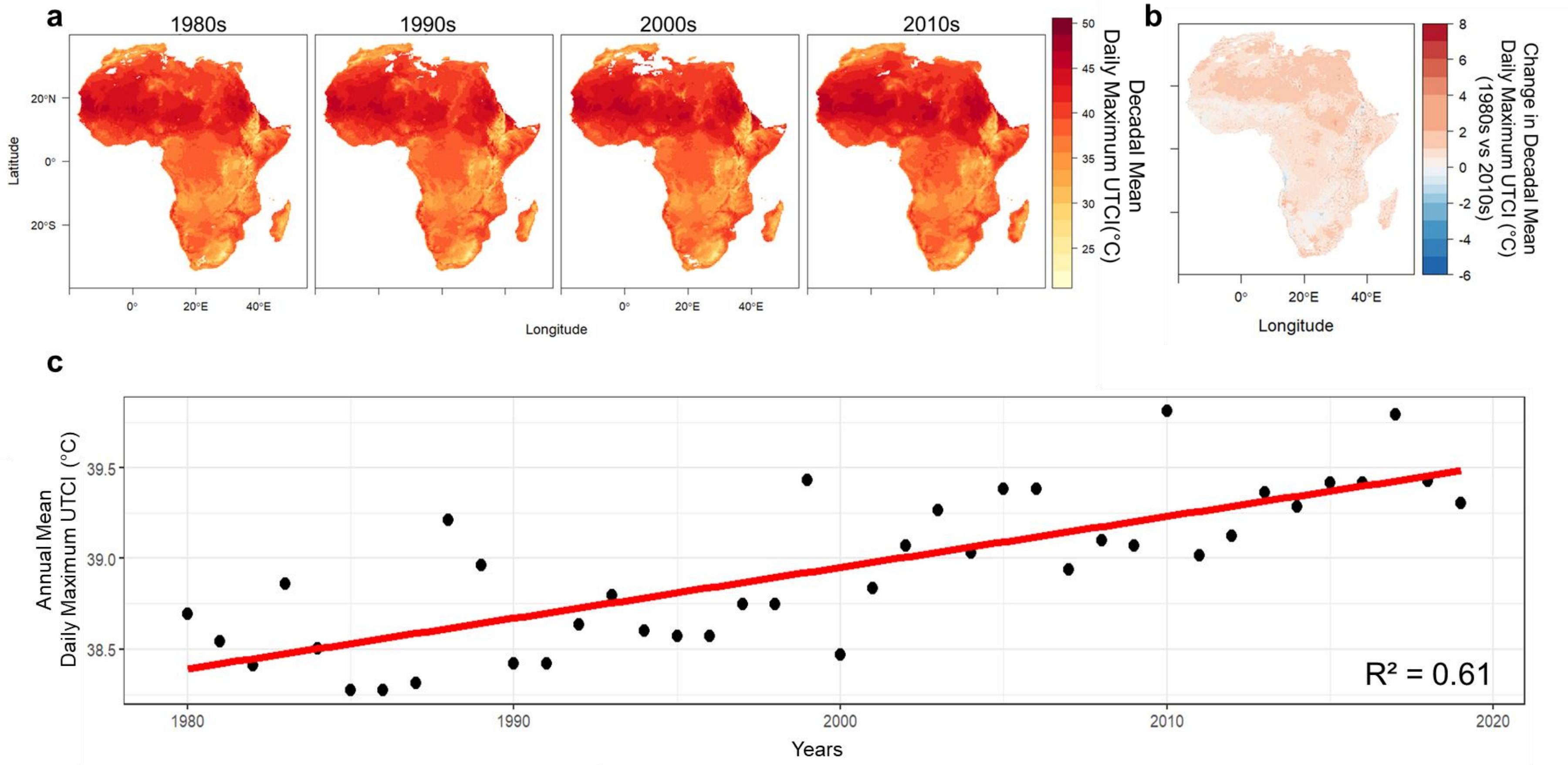

Figure 6.3: The average maximum intensity of the UTCI where a) is the decadal average daily maximum UTCI, b) is the change in decadal daily maximum UTCI between the 1980s and 2010s and c) is the average annual daily maximum UTCI from 1980 to 2019.

6.3.4 The South Africa 2015/16 Heatwave

The South Africa heatwave occurred in the period from 30 December 2015- 6 January 2016. It was selected for analysis as this heatwave is one of the most widely reported African heatwaves in the peer-reviewed literature. Furthermore, it has very interesting characteristics.

8 days (22-29 December 2015) prior to the heatwave, there are positive anomalies for the mean UTCI, z850 and z500 in South Africa and indeed in much of the southern part of the continent compared with the 1991 to 2020 climatology (Figure 6.4, A). However, there is a large negative anomaly in z500 and z850 off the coast of South Africa during this period, and the UTCI is anomalously cooler than climatology (1991 to 2020) by up to -5°C in the western part of South Africa. The 2m air temperature though is similar to the average climate for most of South Africa.

In contrast, during the 8 days of the South African heatwave, all variables have positive anomalies in the vicinity of South Africa (see Figure 6.4, B), with warm 2m air temperature anomalies of up to +10°C and higher UTCI anomalies of up to +6°C, coupled with anomalous high pressure. Focusing on the region of South Africa where Pretoria and Johannesburg are located, there are also warm 2m air temperature anomalies of +5°C and higher UTCI anomalies of +5°C. In addition, much of the southern part of the continent has positive anomalies in 2m air temperature, the UTCI, z850 and z500.

In the 8 days (7^{th} to 15^{th} January) after the heatwave, there is a return to the negative anomalies in the z500 and z850 extending off the east coast of South Africa, together with the strengthening of area of low pressure over the continent (Figure 6.4, C). It can be inferred that this low-pressure system helps to reduce 2m air temperatures and the UTCI as indicated from the negative anomalies in Figure 6.4 following the warm anomalies associated with the heatwave.

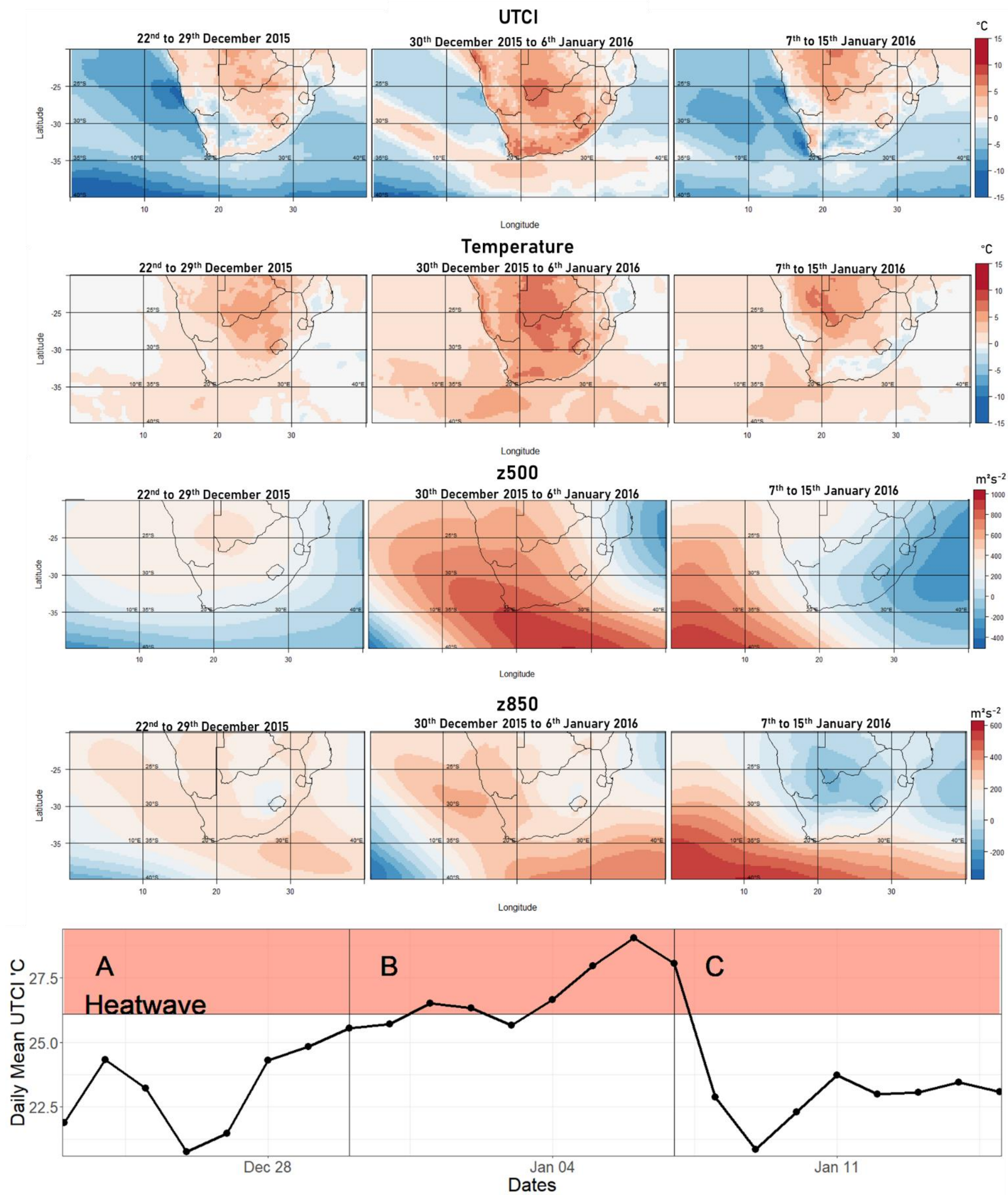

Figure 6.4: The South Africa 2015/2016 heatwave gridded anomalies of the UTCI, temperature, z500 and z850. (A) Before the heatwave, 22–29 December 2015; (B) during the heatwave, 30 December 2015 – 6 January 2016; (C) After the heatwave, 7–15 January 2016; (bottom panel) The mean areal averaged UTCI temporal trend for the period (black trend line) and the 90th percentile of the 1991-2020 UTCI climatology for South Africa (black horizontal line). A heatwave is indicated when the mean UTCI trend (black line) is above the 90th percentile of the climatology (red area).

6.3.5 The Morocco August 2000 Heatwave

The Morocco heatwave occurred between 30 July - 3 August 2000. It was selected for analysis as it was the only heatwave with an associated economic impact that was reported in detail. It also has contrasting characteristics to the South Africa heatwave.

In the 5 days (25th to the 29th July) prior to the heatwave, there were warm anomalies in the area compared with the 1991 to 2020 climatology for the 2m air temperature and the UTCI though the z500 and z850 geopotential heights are similar to the climatological means (see Figure 6.5, A). In comparison, the rest of the northern part of the continent has negative anomalies in temperature and UTCI reaching -4°C and -6°C respectively.

During the 5 days of the heatwave there are significant warm anomalies in Morocco in both the UTCI (up to 15°C) and temperature (up to 10°C) (Figure 6.5, B). In addition, the z500 and z850 both showed positive anomalies linked to a high-pressure system. Interestingly, the area of high warm anomalies is limited to Morocco. The air temperature of Morocco is highly influenced by winds from the Sahara Desert. These winds are, in turn, partly influenced by the Saharan Heat Low, a synoptic weather system which migrates from West Africa to the Sahara at the same time as the migration of the West African Monsoon and the Libyan High Pressure System (Filahi et al., 2015; Lavaysse et al., 2016).

In the 5 days after the heatwave (4- 9 July) the warm anomalies for both 2m air temperature and UTCI dissipate, being at most 2°C and 1°C respectively (Figure 6.5, C). The strengthening negative anomalies in z500 and z850 to the south of Morocco are associated with the mesoscale convective system that became Hurricane Alberto which tracked across Africa, forming in the Ethiopian highlands on the 28th July (Berry & Thorncroft, 2005; Hill & Lin, 2003).

During the period of the Moroccan heatwave, the spatial extent of the UTCI and the 2m air temperature anomalies are similar for both the Morocco 2000 and South Africa 2015/16 heatwaves in comparison to the preceding period. However, this is where the similarities end. The duration of the Morocco heatwave was shorter than the South African heatwave (5 days compared with 8 days respectively). Furthermore, the rate at which the anomalies developed was faster for Morocco, increasing by 6°C in the daily mean UTCI in 5 days. However, the anomalies for the South Africa heatwave increased by about 4°C in the daily mean UTCI in 8 days. These rates of change in the daily mean UTCI are similarly mirrored for the time when the maximum value in UTCI was reached and subsequently declined.

Finally, it is clear that the areal extent of a heatwave can be quite different. For example, warm anomalies in the UTCI and temperature spread into neighbouring countries for South Africa but were limited to Morocco in July and August 2000. In both cases however, the high pressure indicated by the positive geopotential anomalies in the z500 and z850 dominated the affected areas, with a transition to low pressure systems as the heatwave dissipated.

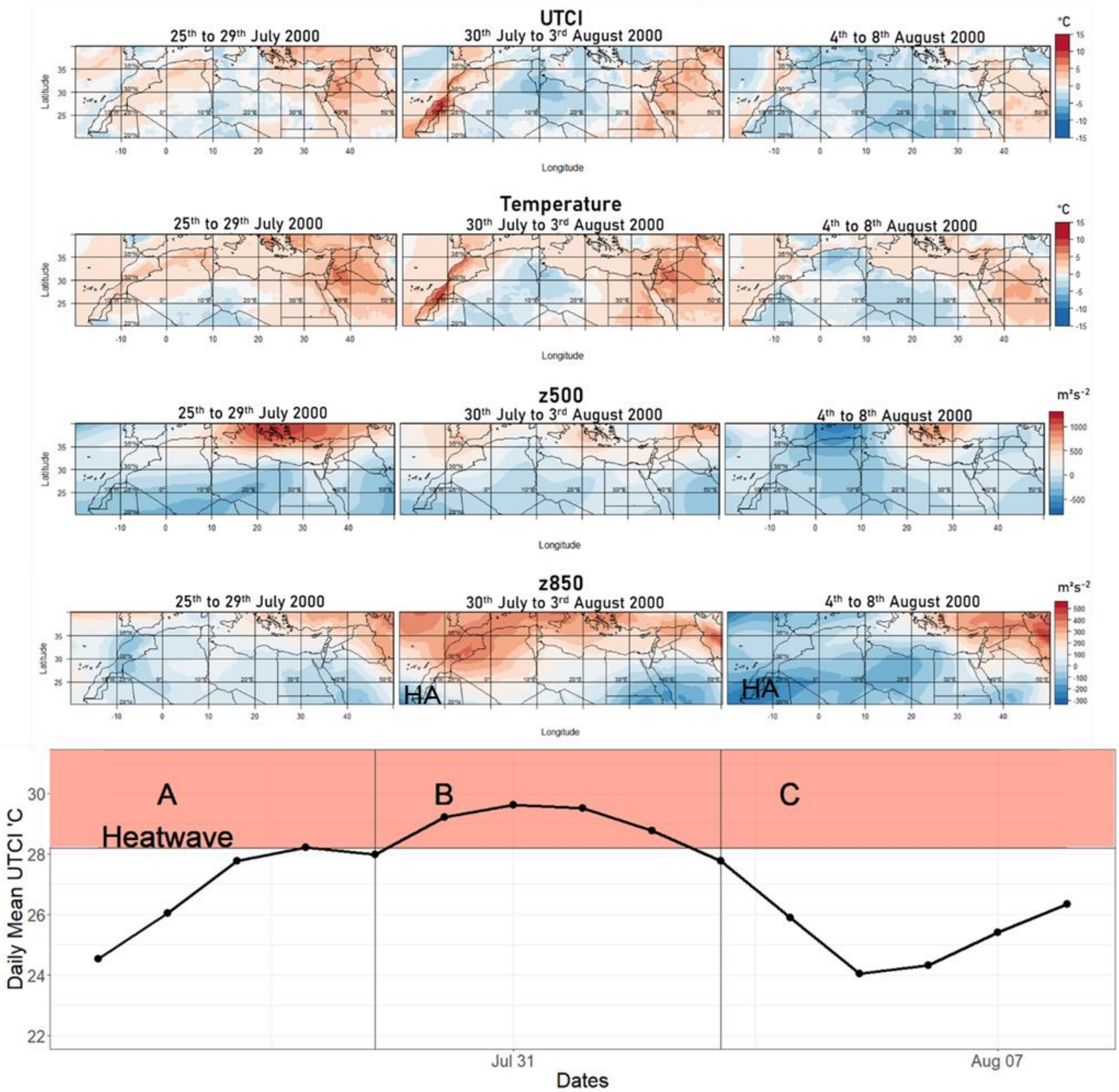

Figure 6.5: The Morocco 2000 heatwave gridded anomalies of the UTCI, temperature, z500 and z850. (A) Before the heatwave, 25–29 July; (B) during the heatwave, 30 July – 3 August; (C) After the heatwave, 4–8 August; (bottom panel) The mean areal averaged UTCI temporal trend for the period (black trend line) and the 90th percentile of the 1991-2020 UTCI climatology for Morocco (black horizontal line). A heatwave is indicated when the mean UTCI trend (black line) is above the 90th percentile of the climatology (red area). HA indicates the position of Hurricane Alberto.

6.3.6 UTCI heatwave sensitivity analysis

To look in greater detail at how a high UTCI value is arrived at, a sensitivity analysis is carried out (Figure 6.6). For the South Africa heatwave, the strongest linear trend is observed between the UTCI and Mean Radiant Temperature, with 2m temperature also having a linear trend with the UTCI. There is clustering of 2m dew point temperature with high UTCI values. There is the least clear trend with wind speed, however it can be suggested that slightly lower values of wind speed contribute to a higher UTCI.

Overall, high incidence of radiation, high temperatures, higher humidity considering the relationship between temperature and dew point temperature and low to moderate wind speeds caused the high heat stress values of the South African Heatwave. This can be seen to be similar in the Morocco heatwave, however there is less clustering of dew point temperature towards a higher UTCI value.

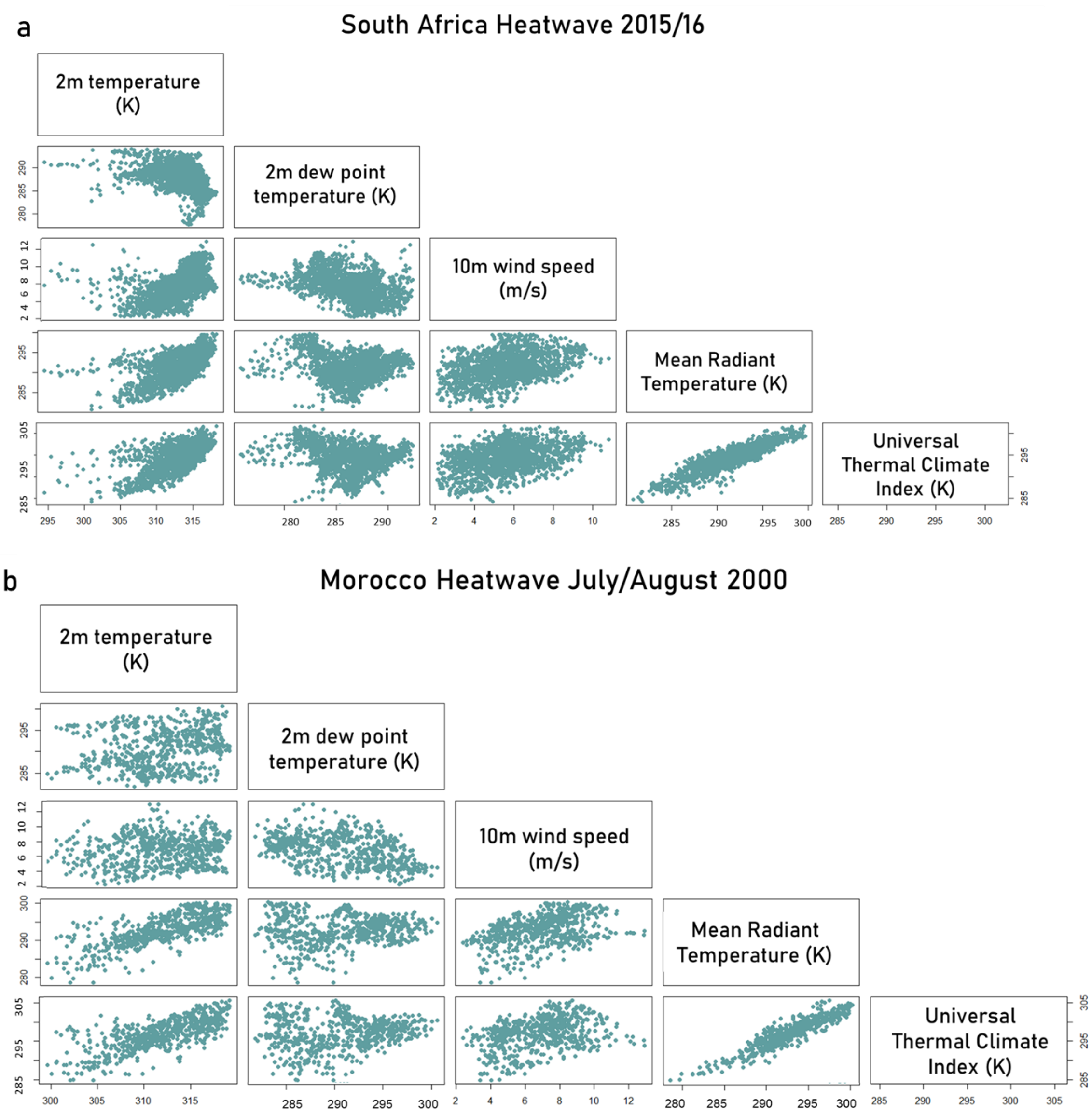

Figure 6.6 The sensitivity analysis of the UTCI and it's input variables for a) the South Africa heatwave (30 December 2015 – 6 January 2016) and b) the Morocco heatwave (30 July – 3 August).

6.4 Discussion

We explored the changes in heat stress area, duration and intensity over time for the continent of Africa, in addition to 2 heatwave case studies. We compared 2 indications of heat stress for the UTCI using the daily maximum UTCI above 32°C (strong heat stress category) threshold and above the climatological 90th percentile. Both indicators significantly demonstrate that a larger proportion of both the populated and land area of Africa is being exposed to more intense values of heat stress for longer in 2019 than in 2000. However, there are differences in the level of signifcance and the characteristics of trends for area exposed and the duration of heat stress between heat stress indicators (Zare et al., 2019). Impact studies for Africa would help to demonstrate which threshold is most appropriate, for example a comparison of each heat stress threshold indicator in contrast to mortality rates similar to studies at a global scale and for Europe (Di Napoli et al., 2019; Urban et al., 2021; Vicedo-Cabrera et al., 2021; Zhao et al., 2021).

Our research also supports findings that the duration and intensity of heatwaves and extreme heat has increased across the African continent (Ceccherini et al., 2017; Fontaine et al., 2013; Ringard et al., 2016; Russo et al., 2016, Misganaw Engdaw et al., 2021). It also demonstrates that the area exposed to heat stress has also increased for the continent supporting population weighted (Tusholke et al. 2021 and Rodgers 2021). Previous research had evidenced that on a global scale heat stress was growing in area during the month of August and was greater during a heatwave (Brimicombe et al., 2021) in addition to the UTCI mirroring trends in temperature for heatwaves (Thompson et al., 2022). Further, the duration of time where Africa is exposed to heat stress values is significantly increasing, demonstrating that heat stress values are higher than even an optimistic acclimatization level (Nazarian & Lee, 2020).

In addition, the case studies for Morocco 2000 and South Africa 2015/16 focused on examining the associated pressure systems, temperature regimes and biothermal conditions that occurred prior to, during and post the heatwaves to identify their characteristics and potential triggers. This suggests a possible approach for both anticipating and formally identifying heatwaves and thus the basis for more robust heat hazard reporting in African nations and elsewhere.

Another important finding is the differing areal extents of the heat stress and temperature anomalies between the South Africa and Morocco heatwaves. Similarities exist however, in the nature of the positive geopotential anomalies at z500 and z850. In contrast, the main driver in z500 of the South Africa is advection and subsequently subsistence blocking high consistent with other studies e.g. (Guigma et al., 2020; Suarez-Gutierrez et al., 2020). But, for Morocco, advection is more so present, given that temperature changes in the country are influenced by the Harmattan wind off the Saharan desert (Filahi et al., 2015; Lavaysse et al., 2016). Z500 remains a useful marker for the onset of a heatwave in regions outside of the tropics.

It can be suggested that, drivers of heatwaves are closely linked to the arrival of synoptic systems as well as the large-scale shifts in the background environment (e.g. El Nino events) for both of the heatwave examples (Hu et al., 2019; Russo et al., 2016, Meque, et al., 2022). It is shown in a study by Meque, et al., (2022), that different modes of El Nino lead to an intensification and probability of heatwaves occurring in the Southern region of Africa. Synoptic systems are prominent for the Moroccan heatwave with changes in the placement of the Libyan High Pressure present, due to the migration and development of Hurricane Alberto as it travels from the Ethiopian highlands to the Atlantic Ocean, having an influencing factor on the direction of the Harmattan winds and therefore advection in the region (Filahi et al., 2015; Lavaysse et al., 2016).

A more detailed dynamical analysis is now required to elucidate the onset and cessation mechanisms and explore the extreme heat impacts. It would, for example, be beneficial to investigate other heatwave events to continue to build dynamical understanding of heatwaves and to be able to catalogue key markers to inform their forecasting and identification in different countries across Africa. This in turn enables better preparedness for heatwaves (see e.g. Guigma et al. 2021) and hopefully, the reduction of their negative impacts. Strengthening local meteorological services alongside health services remains a key element towards such improvements and improved climate change preparedness plans. In addition, public health policies that address morbidity and mortality linked to heat stress in Sub-Saharan Africa are also required (Amegah *et al* 2016, Nunfam *et al* 2019, Hussey and Arku 2020,van Loenhout *et al* 2021). Heatwave warning systems, such as those in Tunisia and Egypt, are an important contribution to such preparedness efforts and allow early decisions to be made to mitigate the worst effects of an upcoming heatwave, through for example, issuing warnings to media outlets and readying health services (Boubaker, 2010; Hafez & Almazroui, 2016).

The South Africa heatwave led to 11 deaths and 20 injuries (CRED,2020).Previous literature has documented a 1.64% increase per 1°C in excess mortality rates in South Africa above a 2m air temperature threshold of 19°C (Scovronick & Armstrong, 2012). Given this analysis shows warm anomalies in air temperature and higher heat stress, indicated by the UTCI, of up to 6°C in both case studies, it suggests that the impacts of the South Africa heatwave were under-reported at an international level. For the Morocco heatwave, the deaths of 4 million chickens were reported leading to up to 809,000 USD of damages (CRED, 2020). Interestingly, this is the only heatwave with an economic loss associated with it and reported in the EM-DAT international database. This perhaps highlights the added difficulty of assessing related loss and damages, and suggests the need to strengthen research on heat-related impacts (Campbell et al., 2018). Expanding such research, and increasing in-situ observations of heatwaves informed by this research, will begin to address the current under-reporting (Harrington & Otto, 2020; Vicedo-Cabrera et al., 2021).

6.5 Conclusion

This study provides evidence on the scale and characteristics of extreme heat risk in Africa at a time where such research is sparse and yet the loss and damages from heatwaves are increasing. The main findings are that reports of heatwaves in Africa are absent from international databases, and that local climate and geography are influential in controlling the range of characteristics of the heatwaves that occur.

Our results also demonstrated the increasing risk to a larger proportion of the population of African nation posed by more intense heat stress. National weather services and other agencies have a mandate for heat risk and public health require specialist information to anticipate and prepare for heatwaves. This is the first time that the Universal Thermal Climate Index has been used at a continental scale to assess heat stress during a heatwave in Africa.

In the short term, national understanding of heatwaves could be improved through this research. In addition, the methods can be adapted and applied to climate projections to look into future risks. Finally, policymakers and authorities should urgently adapt to address extreme heat as a growing risk for their countries. Our results demonstrate that heat is not just a future risk but a clear current risk and one with devastating impacts on people's livelihoods.

7. thermofeel: a python thermal comfort indices library

Commentary:

I developed *thermofeel* in collaboration with the Development Section at ECMWF as an analyst on the EU Horizon's 2020 project Hidalgo. Given that this is an interdisciplinary thesis this chapter can be characterised into an intersection of the field of applied Computer Science and Environmental Science. My motivation for creating *thermofeel* is outlined in Chapter 2. It was unclear which thermal comfort index could be assumed as the 'gold' standard for a global early warning system. ECMWF already had the implementation of Mean Radiant Temperature and the Universal Thermal Comfort Index (UTCI) in both reanalysis and in pre-operations for forecasting (but lacked the remaining indexes). However, that system was based on legacy software not easily extended to other Thermal Comfort Indices. This opened an opportunity to develop a new system, more flexible, adopting open development (via GitHub) that would enable closer interaction between scientists and faster transition Research-to-Operations (R2O). I was part of a small team of 3, put together to achieve this, where I was given the role of implementing the thermodynamical models of a representation of a human body in space.

This led to the development of *thermofeel* as a scientific python library. The library provides scientific advances made are in multiple ways:

- It extends the number of thermal comfort indices available in pre-operational forecasts at ECMWF from 2 to 10 and includes multiple supporting methods such as the cosine of the solar zenith angle discussed in chapter.
- In Computer Science terms, it is an advancement as it is designed in a way to be independent of user-defined data structures. This allows the code to be more reusable in different contexts and by different analysis tools. This means that a single thermodynamic function can be used with Python arrays, scalar quantities, XArrays or even tensors. This is achieved by only depending on one other python library (numpy) and allows for users to apply methods to any type of data (i.e., scalar or vector) as long as it can be wrapped in (or viewed as) a numpy array.
- The previous feature also implies that the same functions can be used for both observational data (irrespective of data structure) and gridded data. This opens the door

for better validation and comparison tools.

- *thermofeel* also introduces an important advancement by bringing in Just-In-Time (JIT) compilation of the thermodynamic functions. Using the *numba* framework, this allows the algorithms in python to be converted in real-time to high-performance and high optimised C language that speeds up the run time of all of the thermal comfort algorithms, reducing the overall computational cost.
- Finally, the computational design of thermofeel is known as *pure function design.* This means that its functions do not store internal state and are free of side-effects. This enables the library functions to be more easily parallelisable and integrated into concurrent computational environments (such as Dask). Moreover, it helps with increasing the software longevity because it can be more easily maintained and extended in the future.

All the above characteristics combine together to allow member states, partners and scientists in the Environment community to access and make use of the same code as ECMWF uses for high-performance generation of products, thus promoting open science and reproducibility of research and close feedback to operations.

Chapter 7 has been published in the Software X Journal under the reference:

Brimicombe, C., Di Napoli, C., Quintino, T., Pappenberger, F., Cornforth, R., & Cloke, H. L. (2022). Thermofeel: A python thermal comfort indices library. *SoftwareX*, *18*, 101005. https://doi.org/10.1016/J.SOFTX.2022.101005

Since release in June 2021 (three months after development started by my work) and publication of the supporting paper in February 2022, *thermofeel* has been well received by the research community included being cited in a nature publication and the reviewers of the EU project Hidalgo. *thermofeel* was one of the reasons I was given the RMetS Malcolm Walker award for an outstanding early career researcher. I've presented *thermofeel* at the AGU, AMS and EGU international conferences and had good feedback about the usefulness of the library for the community. *thermofeel* is going on to be the basis of a global heat health early warning system at ECMWF, as part of their ongoing research in the area.

This chapter fits within component 2: Health Information Systems because it provides evidence towards the objective Evaluating trends and modelling of extreme heat, by providing thermodynamical models of heat stress.

Abstract:

Here the development of the python library *thermofeel* is described. *thermofeel* was developed so that prominent internationally used thermal indices (i.e. Universal Thermal Climate Index and Wet Bulb Globe Temperature) could be implemented into operational weather forecasting systems (i.e. the European Centre for Medium Range Weather Forecasts) whilst also adhering to open research practices. This library will be of benefit to many sectors including meteorology, sport, health and social care, hygiene, agriculture and building. In addition, it could be used in heat early warning systems which, with the right preparedness measures, has the potential to save lives from thermal extremes.

Keywords:

Heat, Cold, Thermal Comfort, Weather Forecasting, Python

Current code version 1.1.3

Table 7.1 – Code metadata (mandatory)

Nr	**Code metadata description**	***Please fill in this column***
C1	Current code version	*1.2.0*
C2	Permanent link to code/repository used of this code version	*https://github.com/ecmwf-projects/thermofeel*
C4	Legal Code License	*Apache License version 2*
C5	Code versioning system used	*Git*
C6	Software code languages, tools, and services used	*Python*
C7	Compilation requirements, operating environments & dependencies	*Linux and IOS operating systems for some methods indicated in documentation*
C8	If available Link to developer documentation/manual	*https://thermofeel.readthedocs.io/en/latest/?*
C9	Support email for questions	servicedesk@ecmwf.int

Nomenclature

t2m: 2m temperature (K)

td: dew point temperature (K)

va: wind speed at 10 meters height (m/s)

rh: relative humidity (%)

svp/e_hPa: saturation vapour pressure (hPa)

mrt: mean radiant temperature (K)

mrtw: mean radiant temperature from wet bulb globe temperature (K)

ssrd: surface solar radiation downwards ($J/\ m^2$)

ssr: surface net solar radiation (J/m^2)

fdir: total sky direct solar radiation (J/m^2)

strd: surface thermal radiation downwards (J/m^2)

strr: surface net thermal radiation (J/m^2)

lat: latitude

lon: longitude

y: year

m: month

d: day

h: hour

tbegin: time step beginning

tend: time step end

cossza: cosine of the solar zenith angle (°)

utci: universal thermal climate index (°C)

wbt: wet bulb temperature(°C)

bgt: globe temperature(°C)

wbgt: wet bulb globe temperature (°C)

wbgts: wet bulb globe temperature simple/approximation (°C)

hi: heat index (°C)

net: normal effective temperature (°C)

C: Celsius

K: Kelvin

m: metres

J :Joules

Pa: pascal

7.1 Motivation and Significance

Extreme heat is an increasing killer hazard and research around heatwaves and heat stress is growing (Harrington & Otto, 2020; Mora, Counsell, et al., 2017; Perkins-Kirkpatrick & Lewis, 2020; Russo et al., 2017b). However, there is not a universal definition of heatwaves and this has led to the use of many different heat indices by studies globally (Campbell et al., 2018). In addition, cold weather continues to cause excess mortality and causes challenges for infrastructure for example Winter in Texas 2021 (Doss-Gollin et al., 2021). Key indices include wet bulb globe temperature(Budd, 2008b; Lemke & Kjellstrom, 2012) and the biometerological method of the Universal Thermal Climate Index (UTCI) which brings together meteorological parameters and a body model providing a human centric heat index (Bröde et al., 2012; Di Napoli et al., 2021).

To date there is no comprehensive library that brings together the most prominent thermal indices, with only pythermalcomfort (Tartarini & Schiavon, 2020) existing for a small selection of indoor thermal comfort indexes, comfort (Huang, 2020) not being maintained and undocumented and ladybug-comfort (Ladybug, 2020) which is not developed specifically for numerical weather prediction and does not provide the same methods as *thermofeel.* This makes it difficult to incorporate thermal comfort indices into numerical weather prediction services as well as to adhere to open science best practices, such as reproducibility and transparency, that are widely being adopted (Nosek et al., 2015).

The development of thermofeel as a python library was chosen due to the popularity of the language for scientific applications, usually with faster run-time on a given system than that of R, a comparable language (Ozgur et al., 2021). It also has a range of free learning courses associated with it, making it easier to learn than other common scientific languages such as C, C++ or Fortran (Bogdanchikov et al., 2013). In addition, it has a constantly growing catalogue of libraries that aid testing and documentation but complement the methods presented in *thermofeel* (Kramer & Srinath, 2017).

thermofeel allows the user to reproduce the methods used in the development of the ERA-5 HEAT dataset which provides historical world-wide data records for mean radiant temperature and universal thermal climate index (Di Napoli et al., 2021). In addition, it extends this dataset by giving users methods to easily calculate the most prominent heat indexes, with a current focus on outdoor thermal comfort. Users can use the methods on a range of different data types by making use of existing python libraries.

Most notably this library presents the first operational method of calculating the wet bulb globe temperature from mean radiant temperature (De Dear, 1987; Guo et al., 2018). Furthermore, *thermofeel* is developed by the European Centre for Medium Range Weather Forecasts (ECMWF) following well established development procedures for time-critical operational software and contains methods that are currently being tested and integrated into ECMWF's weather forecasting product generation systems.

7.2 Software Description

7.2.1 Software Architecture

The library thermofeel contains a main module with the calculation methods and a helper module which is called in the background for auxiliary functions. The functional design of this library allows for easier maintenance and, since each calculation method is implemented as a *pure function* guaranteeing no side-effects, the library can be easily used in parallel and concurrent environments such as Dask (Sievert et al., 2019). Moreover, this also allows each calculation method to simultaneously support scalars and numpy arrays as input, performing the calculations elementwise where appropriate and thus returning a compatible result (scalar or arrays) as output. This design was intentional to ease the integration with ECMWF's parallel computing environment. This library was developed and tested on the Linux and Mac OSX operating systems, and we believe it is fully compatible with any POSIX system supporting Python 3.

7.2.2 Software Functionalities

thermofeel provides methods to calculate the most prominent indices which currently focuses on outdoor thermal comfort. Ahead we discuss the methods and present some of the relevant literature describing them in more detail, with more depth provided in the *thermofeel* documentation (https://thermofeel.readthedocs.io/en/latest/?). Table 7.1 shows the different thermofeel index calculation methods

Table 7.1 showing thermofeel index calculation methods

Name	Function	Description	Reference
Solar Declination Angle	solar_declination_angle(jd,h)	returns declination angle in degrees and time correction in hours	
Relative Humidity	calculate_relative_humidity_percent(t2m,td)	returns relative humidity as a percentage	
Saturation Vapour Pressure	calculate_saturation_vapour_pressure(t2m)	returns relative humidity as water vapour pressure units hPa	
Cosine of the Solar Zenith Angle Instant	calculate_cos_solar_zenith_angle(lat,lon,y,m,d,h)	returns the cosine of the solar zenith angle which is used to calculate mean radiant temperature	(Hogan & Hirahara, 2016)
Cosine of the Solar Zenith Angle Integrated	calculate_cos_solar_zenith_angle_integrated(lat,lon,y,m,d,h,tbegin,tendintervals_per_hour=1, integration_order=3,):	returns the cosine of the solar zenith angle which is needed to calculate mean radiant temperature from solar radiation, based upon an integration over forecast steps	(Hogan & Hirahara, 2016)
Mean Radiant Temperature	calculate_mean_radiant_temperature(ssrd, ssr, fdir, strd, strr, cossza)	returns mean radiant temperature (mrt) in kelvin, incidence of radiation on the body which is used in the utci and wbgt calculations	(Di Napoli, Hogan, et al., 2020b)
Universal Thermal Climate Index (UTCI)	calculate_utci(t2m, va, mrt, e_hPa)	returns the biometeorology index the universal thermal climate index (utci) in °C	(Bröde et al., 2012; Di Napoli et al., 2021)

Wet Bulb Globe Temperature Simple	calculate_wbgts(t2m)	returns an approximation of wet bulb globe temperature known as wet bulb globe temperature simple in this library °C	(American college of sports medicine, 1987)
Wet Bulb Temperature	calculate_wbt(t2m,rh)	returns wet bulb temperature calculated using an empirical expression from temperature and relative humidity percent	(Stull, 2011)
Globe Temperature	calculate_bgt(t2m, mrt, va)	returns globe temperature calculated from temperature mean radiant temperature and 10 meter wind speed in °C (Method not tested for windows operating system)	(De Dear, 1987; Guo et al., 2018)
Wet Bulb Globe Temperature	calculate_wbgt(t2m,mrt,va,td)	returns wbgt using the wet bulb temperature and globe temperature methods as components into the wbgt equation	(Minard, 1961)
Mean Radiant Temperature from Globe Temperature	calculate_mrt_from_bgt(t2m, bgt, va)	returns mean radiant temperature using the inverse method to calculate_bgt in °C	(De Dear, 1987; Guo et al., 2018)
Humidex	calculate_humidex(t2m, td)	returns humidex a heat index that incorporates	(Masterson

		relative humidity with temperature in °C	& Richardson, 1979)
Normal Effective Temperature (NET)	calculate_net_effective_temperature(t2m, rh, va)	returns normal effective temperature (NET) which is a model of how a human responds to meteorological parameters in °C	(Li & Chan, 2000)
Apparent Temperature	calculate_apparent_temperature(t2m,rh,va):	returns apparent temperature a heat index modelled on wet bulb globe temperature in °C	(Steadman, 1984)
Wind Chill	calculate_wind_chill(t2m,rh,va)	returns wind chill is designed to emulate how cold it feels in a very windy environment in °C	(Siple & Passel, 1945)
Heat Index Simplified	calculate_heat_index_simplified(t2m, rh=None)	returns heat index simplified the original method for heat index in °C	(Blazejczyk et al., 2012)
Heat Index Adjusted	calculate_heat_index_adjusted (t2m, td)	returns heat index that is adjusted between different thresholds to be more accurate in the tropics in °C	(Blazejczyk et al., 2012)

7.2.3 Software Exceptions and Validation

We filter the data as is indicated by the original method documentation where appropriate. For example, the UTCI is set to -9999 when its input parameters – temperature, wind speed, relative humidity and mean radiant temperature – fall outside specific validity ranges (Di Napoli et al., 2021). In addition, adjustments are calculated for set thresholds for solar zenith angle integrated and heat index adjusted.

7.2.4 Software Validation

The thermofeel library also contains unit tests for all provided calculation methods and based on the pytest library. The inputs for the tests are based upon the average hourly data from ERA5 reanalysis (Hersbach et al., 2020) for the 2nd November 1996 and the 2nd August 2003. An example of the inputs can be seen in table 7.2 and the outputs in table 7.3. We implemented further tests on some methods, e.g. on the cosine of the solar zenith angle method, and these can be found on the software repository.

Table 7.2: The test variable values for thermofeel

t2m	**td**	**Va**	**mrt**	**Ssrd**	**ssr**	**fdir**	**strd**	**Strr**	**cossza**
K	K	m/s	K	W/m^2	W/m^2	W/m^2	W/m^2	W/m^2	°
310	280	2.00	300	604146	471818	374150	1061213	-182697	0.5
300	290	0.02	310	604135	467182	377084	1061000	-183218	0.5
277	273	0.59	286	607954	464531	383763	1061090	-184536	0.5
277	273	0.59	286	613806	463360	391216	1061362	-186295	0.5
277	273.	0.60	286	619349	462326	398038	1062483	-187558	0.5
277	273	0.59	286	626611	463422	406661	1063639	-189544	0.5
277	273	0.59	286	634958	465688	416602	1064458	-192353	0.5
277	273	0.59	287	638089	463850	418866	1066043	-194661	0.5
277	273	0.59	287	640019	462945	42167	1066746	-196444	0.5

Table 7.3: The test outputs for thermofeel calculated using the inputs from table 7.2.

rhp	**svp**	**Heat Index**	**Heat Index Adjusted**	**Humidex**	**mrt**	**net**	**utci**	**wbgt**	**wbgts**	**Wind Chill**
%	hPa	°C	°C	°C	°C	°C	°C	°C	°C	°C
15.93	62.31	68.27	34.59	31.82	286.04	40.75	33.50	35.61	26.72	60.09
54.31	35.37	52.14	27.53	23.12	286.11	31.49	29.93	25.78	19.99	50.75
74.75	8.19	16.82	2.51	1.07	286.29	3.41	8.63	3.27	6.02	9.30
74.77	8.20	16.86	2.53	1.09	286.54	3.43	8.64	3.29	6.03	9.32
74.74	8.23	16.93	2.58	1.14	286.81	3.50	8.76	3.34	6.06	9.41
74.47	8.27	17.07	2.67	1.21	287.11	3.60	8.93	3.42	6.11	9.56
74.32	8.31	17.17	2.73	1.27	287.42	3.68	9.10	3.48	6.15	9.66

73.80	8.40	17.40	2.88	1.40	287.70	3.85	9.28	3.63	6.23	9.90
73.41	8.44	17.53	2.95	1.47	287.85	3.94	9.37	3.71	6.28	10.01

Illustrative Examples

To test how a user might apply the methods presented in section 4.2.2, table 4.1 to meteorological data, we produced visual maps of all the indices using data from ERA-5 (Hersbach et al., 2020) reanalysis for 06UTC on the 8th June 2020 which is shown in figure 4.1. These figures can be easily produced from our library and the existing netCDF4, matplotlib and cartopy libraries using source code 1. We also provide examples using other python libraries developed by ECMWF such as magics and eccodes these can be seen in the GitHub examples directory (https://github.com/ecmwf-projects/thermofeel/tree/master/examples).

In addition, in figure 4.2, we present two approaches to calculating the cosine of the solar zenith angle (Hogan & Hirahara, 2016). A method which is integrated over forecast steps and is specialised for a forecasting system with a beginning and end time, where radiation values are accumulations, as well as an instantaneous method which only needs the UTC (Universal Time Zone) hour to calculate the cosine of solar zenith angle. Cosine of the solar zenith angle is a key component of mean radiant temperature (Di Napoli, Hogan, et al., 2020b) which is used to calculate the thermal indexes the UTCI and WBGT (Guo et al., 2018; Di Napoli et al., 2021).

The difference between these two approaches (mean value) is tiny at 1×10^{-8} for the UTCI and 2×10^{-9} WBGT final output, and this allows for an accurate cosine solar zenith angle to be calculated with a simpler method that requires less parameters.

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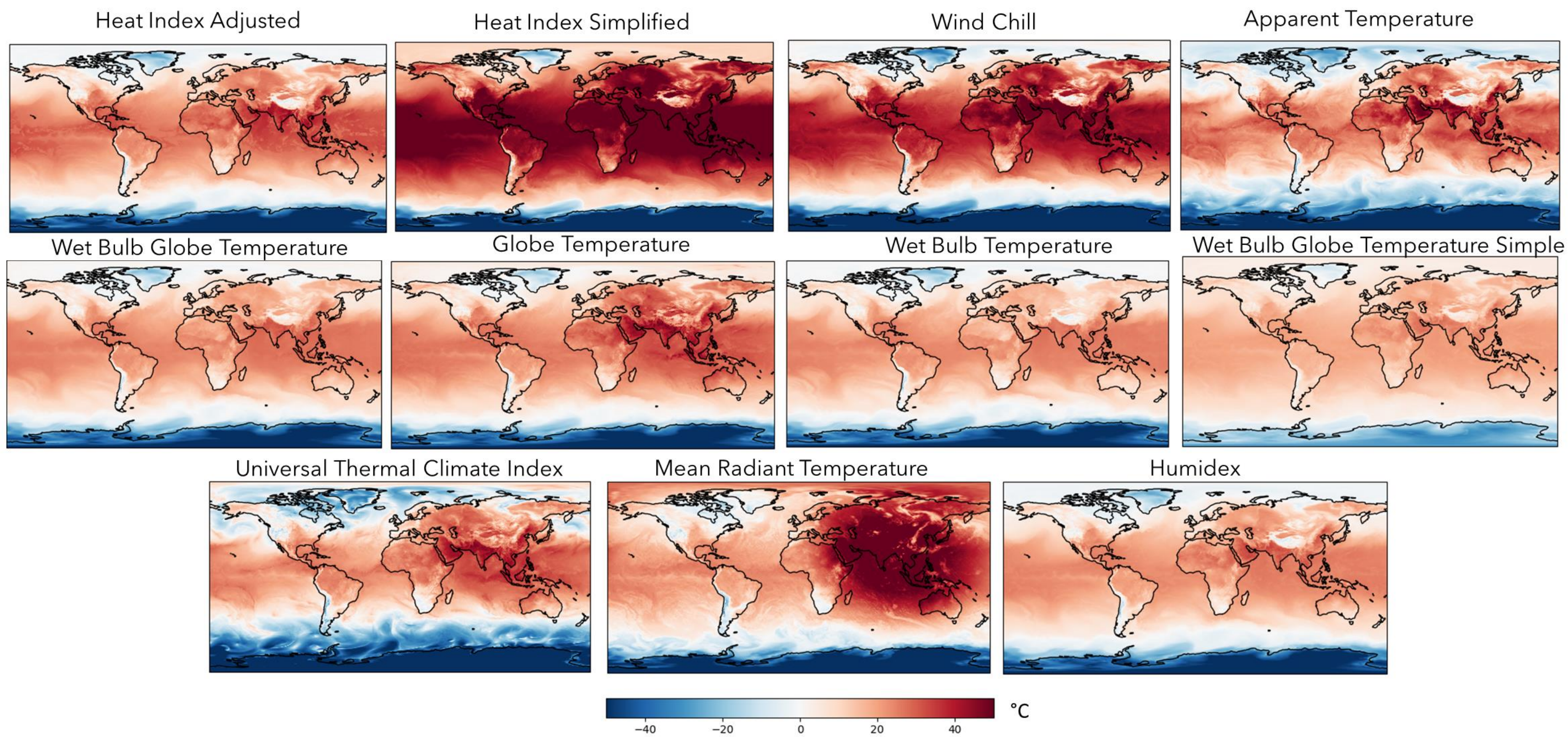


Figure 7.1: Global maps of thermal indexes for 06UTC on the 8th June 2020 as described in section 4.2.2, table 4.4.1

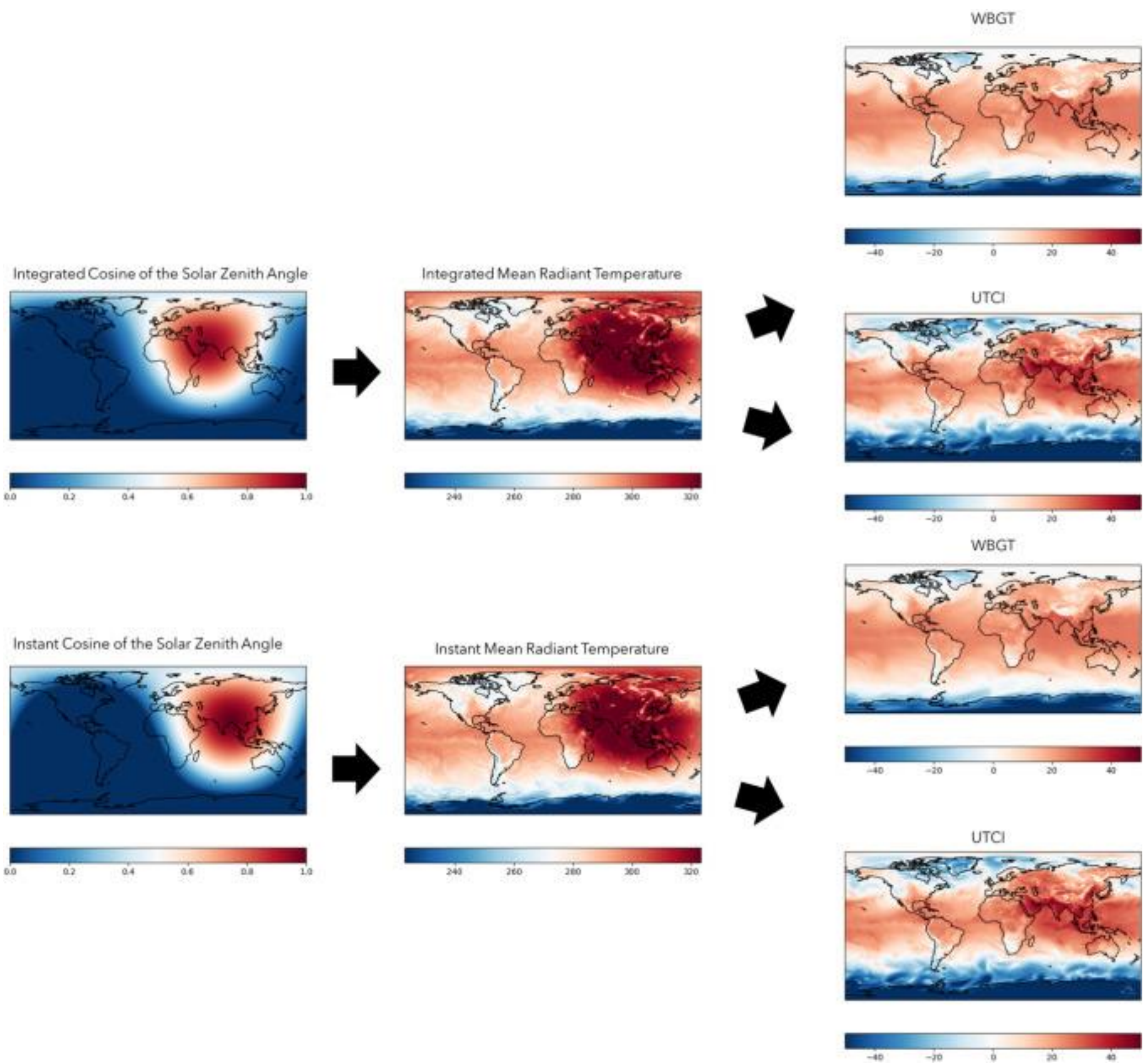


Figure 7.2: Methods for using the two cosine of the solar zenith angle calculations

7.3 Impact

Heat stress is a growing impact of climate change, with heatwaves increasing in intensity, frequency and duration (Perkins-Kirkpatrick & Lewis, 2020).In addition, cold stress is continuing to have an impact (De Perez et al., 2018). It is therefore important to have a robust set of methods to aid research and the development of early warning systems in this field (WMO & WHO, 2015). We anticipate *thermofeel* will have a large impact on the research of heat stress, heatwaves and thermal comfort as a whole. It allows for open science practices (Nosek et al., 2015) to be more readily applied to the extreme thermal research area in a way not available before. We also expect this library to be easily extendable by the research and operational weather forecast communities, as well as those in the humanitarian sector.

In addition, it allows for easy integration of thermal comfort indexes into operational weather forecasting. Further, we envision that cross-sectional users will benefit from our library, from researchers and operational meteorologists (Di Napoli et al., 2021) to health professionals (Campbell et al., 2018) and those in engineering and urban planning (CIBSE, 2017).

Thermofeel calculation methods are being tested and integrated into the operational weather forecasting systems at ECMWF. On a global scale this will be the first time these methods will be forecasted, and lead to practical applications. For example, with the right preparedness measures *thermofeel* methods could save lives and build heat resilience (WMO & WHO, 2015). The library has also the potential to be commercialised and applied to the growing area of climate services (Cullmann et al., 2020; Hewitt et al., 2012) through the development of a mobile app for health services.

7.4 Conclusions

Here we have set out the key information of the python library *thermofeel.* This library has been designed so that thermal indexes can easily be incorporated into numerical weather prediction and operational forecasting systems. In addition, it adheres to open source development and robust operational testing and acceptance procedures. We have produced comprehensive documentation and provided examples of how to use this library to further aid users. We envision that this library will be of benefit to a wide range of users across sectors and could aid in the further development of early warning systems for thermal extremes.

Funding

This work has been funded by the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement no 824115.

8. Tech Memo: Calculating the Cosine of the Solar Zenith Angle for Thermal Comfort Indices

Commentary:

I carried out the research in this tech memo as a request from ECMWF to assess the differences between the Cosine of the Solar Zenith Angle methodology in thermofeel in comparison to in the pre-operational C code that is used to create ERA5-HEAT. This is a key solar angle that is used in the calculation of Mean Radiant Temperature which is needed to calculate the UTCI and WBGT. An overview of this is also presented in the chapter discussing *thermofeel*, this extends that analysis. As with *thermofeel* this chapter fits more within the computer science field and is appropriate to include because of the interdisciplinary nature of this thesis.

Chapter 8 is published under the reference:

Brimicombe C, Quintino T, Pappenberger F, Smart S, Di Napoli C and Cloke H L 2022a Technical Memorandum: The cosine of the solar zenith angle for thermal comfort indices https://doi.org/10.21957/O7PCU1X2B

The main science advances made are that this tech-memo is a cornerstone to how the UTCI and WBGT should be calculated in the future. Although specific to ECMWF it has lessons that any numerical weather prediction service should take into account. These are outlined demonstrating a number of scientific findings this included building on the work of Hogan to develop a new integral cosine of the solar zenith angle and evaluating the difference between direct solar radiation proportion and it's approximation known as Istar and how this influenced outputted thermal comfort index values. The new method of the integral of the cosine of the solar zenith angle, also reduced computational cost in comparison to the previous method and allowed for the resolution of a bug in the original code that had been introduced.

This chapter is part of component 3 Essential Technologies in this thesis because it provides evidence for the objective develop new technologies to reduce the risk to extreme heat by making improvements to technologies for modelling heat stress.

Abstract:

The cosine of the solar zenith angle (cossza) is a key component in Mean Radiant Temperature (MRT). Mean Radiant Temperature is used in the calculation of the Universal Thermal Climate Index (UTCI) and can be used in the calculation of Globe Temperature a component of the Wet Bulb Globe Temperature (WBGT), both of which are important thermal comfort and heat stress indices. It has previously been demonstrated that in numerical weather prediction services cossza should be integrated over a time step for the most accurate results. Here, we present the comparison of the operational cossza being used to create ERA5-HEAT, an instantaneous approach and a Gauss-Legendre Integration cossza. We further calculate MRT and UTCI for the ERA5-HEAT method and the methodology in the *thermofeel* library and see discrepancies in the approaches of on average -1.5K for MRT and -0.42K for UTCI. We suggest that the methodology in the *thermofeel* library supersedes the operational c code and is published alongside the existing ERA5-HEAT dataset in addition to forecast data being published, for users to make their own comparisons and extend this data's usefulness. We also suggest that a sensitivity analysis of the UTCI is carried out to aid better understanding of this thermal comfort index.

8.1 Introduction

The cosine of the solar zenith angle (cossza) is the angle between the sun's rays and the vertical (Aktaş & Kirçiçek, 2021). It is a key component in the calculation of mean radiant temperature (MRT), (Di Napoli, Hogan, et al., 2020a; Vanos et al., 2021) which is used to calculate other thermal and heat indexes such as the Universal Thermal Climate Index (UTCI) (Fiala et al., 2012; Di Napoli et al., 2021) and the Globe Temperature component of Wet Bulb Globe Temperature (WBGT) (De Dear, 1987; Guo et al., 2018). In addition, MRT has been shown to be a better predictor of mortality than air temperature (Ta) which is one of the main impacts of extreme heat (Thorsson et al., 2014).

Each heat index has its benefits and limitations for modelling human thermal comfort. It has been shown for operation forecasts (i.e ECMWF) the most accurate version of cossza is a numerical integration over a forecast time step (Hogan & Hirahara, 2016). Different approaches to provide a cossza over a time step can be employed. These include integration methods as well as a simpler instant cossza.

Here we provide an overview of the current operational method for using cossza. Cossza is part of the ERA5-HEAT dataset (Di Napoli et al., 2021). We further compare this to an instantaneous method and a Gauss-Legendre Quadrature approximation of an integral, available as part of the new python thermal comfort library *thermofeel (Brimicombe, et al., 2021, 2022)*. This allows us to make recommendations for both *thermofeel* (Brimicombe, et al., 2021,2022) and ERA5-HEAT (Di Napoli et al., 2021).

8.2 Methods

To calculate the cossza there are a number of different approaches that can be taken because an instantaneous cossza (hereafter instant) is required for the exact recorded time of the observation. Whereas using numerical weather prediction services leads to the requirement to calculate the integrated average cossza over a time step period, to have an accurate cossza. As such *thermofeel* provides both an instant cossza and an integrated cossza.

Instant cossza

Instant cossza is the simplest approach to calculating a cossza, it is calculated using equation 8.1 and 8.2 (Hogan & Hirahara, 2015, 2016). It involves the solar declination angle which is the angle between the equator and the center of the earth the center of the sun. In addition, it involves the local solar time.

$$\mu_0 = \sin\delta \sin\phi + \cos\delta \cos\phi \cos h$$

[8.1]

δ is the solar declination angle and ϕ is latitude, h is the local hour angle.

$$h = T + \lambda + \pi$$

[8.2]

T is local solar time and λ is longitude.

Integrated cossza

Integrated cossza is the method currently used in operations at ECMWF to calculate the ERA5-HEAT dataset it can be summarized by equation 8.3 (Hogan & Hirahara, 2015, 2016). It also takes into account sunrise and sunset when the value of cossza reduces to zero.

$$\overline{\mu_{0m}} = \sin\delta\sin\phi + \frac{\cos\delta\cos\phi\,(\sin h_{max} - \sin h_{min})}{h_{max} - h_{min}}$$

[8.3]

δ is the solar declination angle and ϕ is latitude, h_{max} is the end time of a time step and h_{min} is the beginning time of the time step.

Gauss-Legendre Quadrature integrated cossza

An accurate way to reduce the cost to a computer, in terms of computational power and time taken of integrating a cossza is to use an approximate numerical integration method and apply it to an instant cossza. Empirical experiments were carried out to compare Gauss-Legendre Quadrature to a Simpsons integral rule and Gauss-Legendre Quadrature chosen because it incurs in less redundant calculations when called over multiple time steps, since it does not evaluate the function at the interval boundaries(Zienkiewicz et al., 2005; Babolian et al., 2005; Goldstein, 1965). The Gauss-Legendre Quadrature is outlined in equation 8.4 where f(x) is equation 5.1 and visually in figure 5.1. ξ is the i-th coordinate of interval boundaries at which the function for cossza instant is evaluated and ω is the i-th weight factor for the numerical integral corresponding to the i-th coordinate.

$$\int_{h_{min}}^{h_{max}} f(x)dx \approx \frac{h_{max} - h_{min}}{2}\sum_{i=1}^{n}\omega_i f\left(\frac{h_{max} - h_{min}}{2}\xi_i + \frac{h_{min} + h_{max}}{2}\right)$$

[8.4]

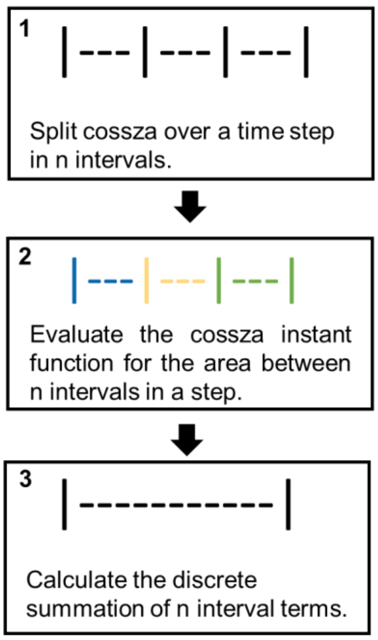


Figure 8.1: a schematic outlining the steps (1 to 3) taken to calculate a discrete summation integrated cossza using the instant cossza method (I.e., the distinct colours in step 2) in combination with the Gauss-Legendre quadrature approximation.

Mean Radiant Temperature

The mean radiant temperature can be defined as the incidence of radiation on a body. For a numerical weather prediction service, it requires 5 input radiations (surface-solar-radiation-downwards, surface net solar radiation, total sky direct solar radiation at surface, surface thermal radiation downwards, surface net thermal radiation) in addition to the cosine of the solar zenith angle (cossza). The full methodology for mean radiant temperature is available in Di Napoli et al., 2020 and is summarized in table 8.1 and equations 8.5 and 8.6.

$$\mathrm{MRT}^{*} = \frac{1}{\sigma}\left\{\mathrm{f_a}\ \mathrm{L}_{\mathrm{surf}}^{\mathrm{dn}} + \mathrm{f_a}\ \mathrm{L}_{\mathrm{surf}}^{\mathrm{up}}\left[\frac{\mathrm{a_{ir}}}{\varepsilon_{\mathrm{p}}} + \left(\mathrm{f_a}\ \mathrm{S}_{\mathrm{surf}}^{\mathrm{dn,diffuse}} + \mathrm{f_a}\ \mathrm{S}_{\mathrm{surf}}^{\mathrm{up}} + \mathrm{f_p}\ \mathrm{I}^{*}\right)\right]\right\}^{0.25}$$

[8.5]

$$\mathrm{f}_p = 0.308\cos\left(\gamma\left(\frac{0.998-\gamma^2}{50000}\right)\right)$$

[8.6]

Table 8.1: The radiation variables that are used in the calculation of the MRT in Equations 8.5 and 8.6. Table 1 from Di Napoli et al., 2020

Name	Symbol/Equation
Surface solar radiation downwards	Sdnsurf=Sdn,directsurf+Sdn,diffusesurfSsurfdn=Ssurfdn,direct+Ssurfdn,diffuse
Surface net solar radiation	Snetsurf = Sdnsurf − SupsurfSsurfnet=Ssurfdn−Ssurfup
Direct solar radiation at the surface	Sdn,directsurfSsurfdn,direct
Surface thermal	Ldnsurf Lsurfdn

radiation downwards	
Surface net thermal radiation	Lnetsurf=Ldnsurf−Lupsurf

A key component of Mean radiant Temperature is known as Istar this is defined as "*radiation intensity of the Sun on a surface perpendicular to the incident radiation direction"* (Di Napoli et al, 2020) in the current operational code this is calculated using equation 8.7. Where Direct Solar Radiation (dsrp) is available I* is equal to this variable.

$$I * = \ fdir \ / \ cossza \ (where \ cossza \ > \ 0.01)$$

[8.7]

Universal Thermal Climate Index

The UTCI is a bio-thermal comfort index which makes use of the meteorological parameters of 2m temperature, water vapour pressure, 10m wind speed and mean radiant temperature and a body model it is estimated by a 6-order polynomial which is summarized by equations 8.8 and 8.9 (Bröde et al., 2012; Fiala et al., 2012; Di Napoli et al., 2021).

$$UTCI(Ta, Tr, Va, Pa) = Ta + Offset(Ta, Tr, Va, Pa)$$

[8.8]

Where Ta= air temperature, Tr= mean radiant temperature, Va= wind speed Pa= water vapour pressure

$$Pa \ = \ Ps \ \times \ \frac{\varphi}{100}$$

[8.9]

Where Ps = Saturation Vapour Pressure and φ= relative humidity percent.

8.3 Results

The implementation of the integrated cossza (figure 8.2, a) visually is different from the other cossza methods implemented, being clipped at the top of the parabola for the 42nd time step after the initial date of the 21st May 2021.The difference between the integrated cossza and the Gauss-Legendre cossza is at most ±0.1° (Figure 8.2, d).The instant cossza has the largest area with complete darkness indicated by 0° values in (figure 8.2, c). In addition, visually the instant cossza covers a slightly different area than the integrated approaches (figure 8.2, c). This is because it is for the instant time at the 42nd time step whereas the integrations are the average of step 39th to 42nd. Further, both the integrated cossza (figure 8.2,a) and the Gauss-Legendre cossza (figure 8.2,b) have a small gradient than the instant cossza (figure 8.2,c) which can be seen in the color gradient in figure 8.2. This allows for sunset and sunrise to be considered more accurately because there is a greater range in cossza values between maximum sun and darkness.

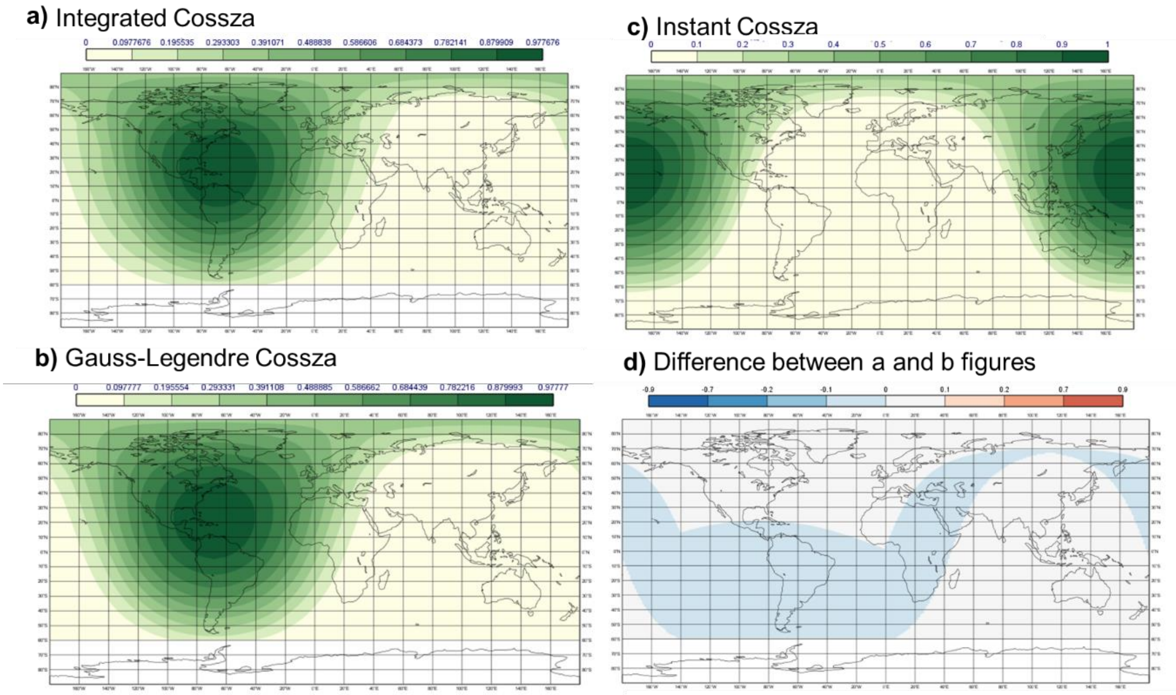


Figure 8.2: Showing the difference cossza approaches for 42hr lead time from the 21st May on a 3 hour time step, a) the current operational (integrated) cossza for ERA5-HEAT calculated in the c coding language, b)an average of an gaussian integration of the instant cossza for a time step, c) an Instant cossza for a given hour and d) the difference between parts a and b of this figure.

The biggest difference is more than +10K between the operational MRT (figure 8.3, a) and the Gauss-Legendre method (figure 8.3,b) employed by *thermofeel* to calculate MRT in the area surrounding North America (120W,20W,20S,60N) for the 42nd step after an initial date of 21st May 2021 around where the continent is experiencing it's maximum cossza value (figure 8.3,c). Whilst there are up to -5K anomalies evident for North America (figure 8.3, c). Notably the current operational calculation of MRT does not consider the continent of Antarctica (figure 8.3, a) and as such this is cropped out in all output plots.

In addition, considering the medium range forecast for the initial date 21st May 2021 00UTC, the maximum positive anomaly is 19K. In comparison, the largest negative anomaly is -28K. However, the difference in the mean anomaly over all time steps is -1.5K. This demonstrates that the difference in the methods is more evident in the extremes of the distribution of MRT.

In comparison, the biggest difference for the UTCI mirrors the patterns seen for the MRT. There is around a +5K difference between the operational UTCI (figure 8.4, a) and the *thermofeel* Gauss-Legendre UTCI (figure 8.4,b) in areas around North America, where cossza is at its maximum (figure 8.4,c). Whilst there is a -10K anomaly where cossza is at its maximum (figure 8.4, c). When considering the medium range forecast for the initial date 21st May 2021 00UTC, the maximum positive anomaly is 6.6K, whereas the mean anomaly is -0.42K.

In addition, there is a noticeable difference between both MRT and UTCI values (figures 8.5 and 8.6) when dsrp is present in the calculation of MRT using *thermofeel* in comparison to when it is approximated using fdir and cossza (equation 8.7). The biggest difference is in Greenland at up to +17K for MRT (figure 8.5, c) and +6K for the UTCI (figure 8.6, c). For MRT at the 42nd time step after an initial date of 27th July 2021 the mean anomaly between the approaches is +2K, whilst the min is 0K and the max +17K. In comparison the mean anomaly at the same time step for UTCI is 0.62K, the min is also 0K and the max anomaly is 6.5K.

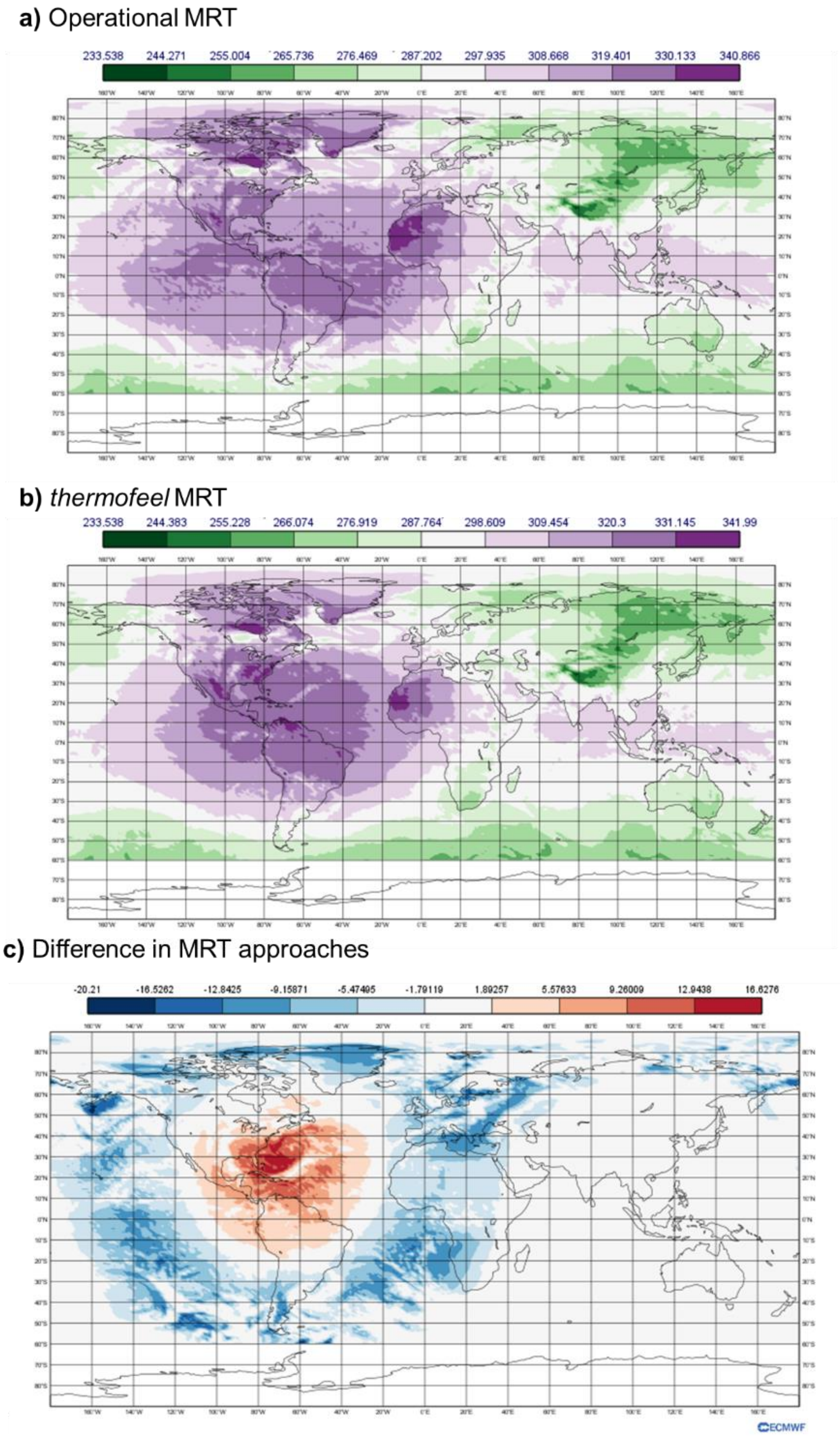


Figure 8.3: the operational c mean radiant temperature (top), the thermofeel mean radiant temperature (middle) and the anomaly plot of the approaches (bottom). For the 42nd step after the initial date 21st May 2021 at 00UTC.

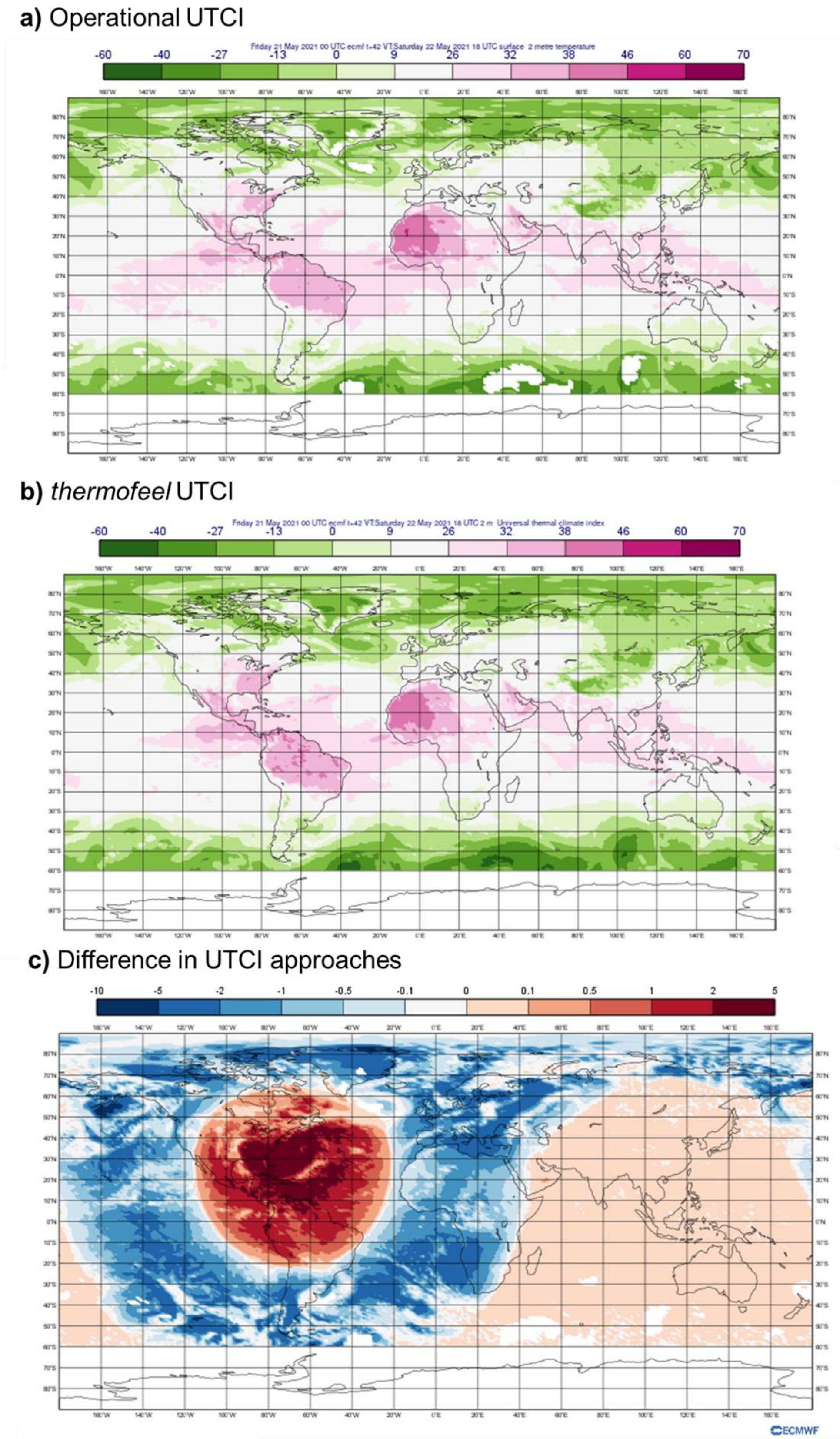


Figure 8.4: the operational c universal thermal climate index(top), the thermofeel universal thermal climate index (middle) and the anomaly plot of the approaches (bottom). For the 42nd step after the initial date 21st May 2021 at 00UTC.

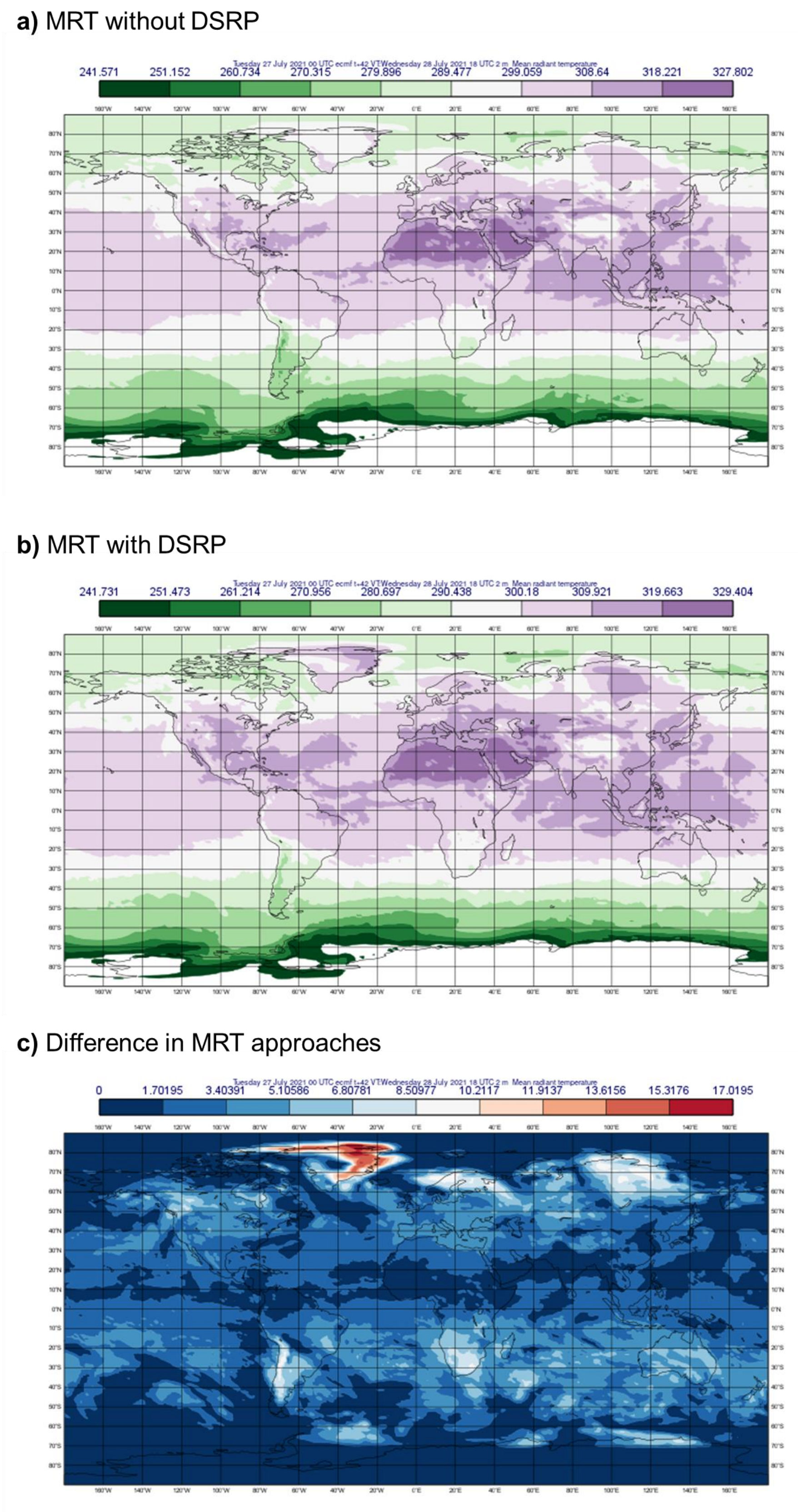
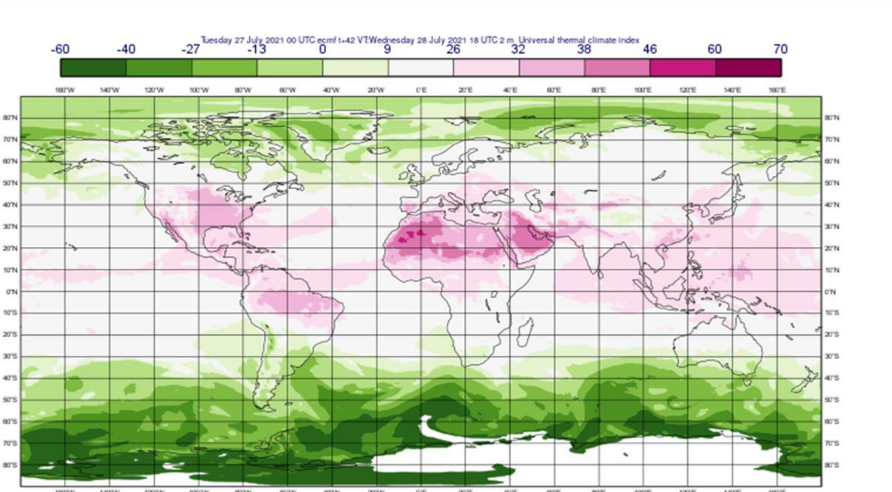
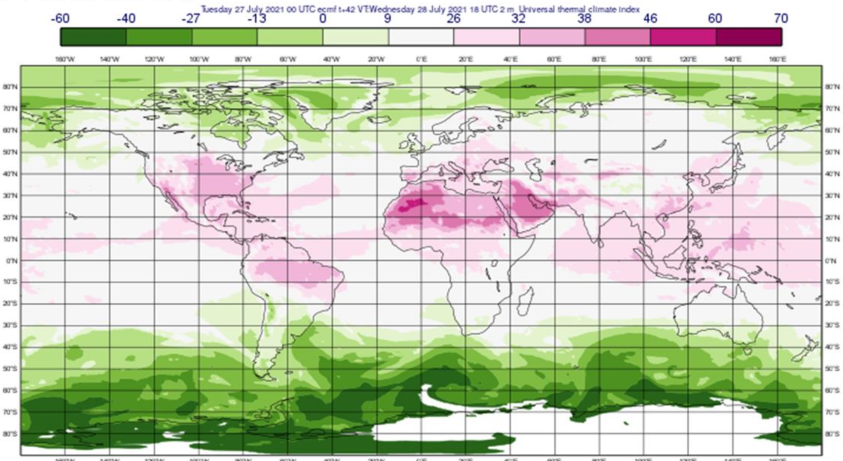


Figure 8.5: thermofeel MRT without dsrp(top), the thermofeel mean radiant temperature with dsrp (middle) and the anomaly plot of the approaches (bottom). For the 42nd step after the initial date 27th July 2021 at 00UTC.

a) UTCI without DSRP



b) UTCI with DSRP



c) Difference in UTCI approaches

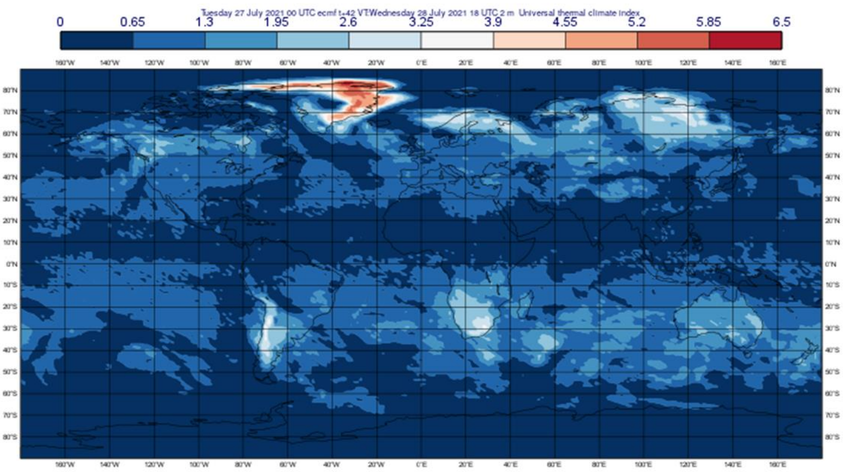


Figure 8.6: thermofeel UTCI from MRT without dsrp(top), the thermofeel UTCI from MRT with dsrp (middle) and the anomaly plot of the approaches (bottom). For the 42nd step after the initial date 27th July 2021 at 00UTC.

8.4 Discussion

We recommend that the Gauss-Legendre integrated cossza and the thermofeel methodology supersedes the operational c code used to calculate the ERA5-HEAT dataset. This is because the thermofeel method removes the clipping at the top of the parabola that is present in the c code (figure 8.2).

There is a substantial difference between the Gauss-Legendre integrated cossza employed in the thermofeel methodology to calculate MRT and UTCI in comparison to the operational c code currently creating the ERA5-HEAT dataset (Brimicombe et al., 2022; Di Napoli et al., 2021). This is more so evident in the extremes of the distribution of both UTCI and MRT. This suggests that the ERA5-HEAT dataset may be underestimating heat stress values while overestimating cold stress values, which could have implications for the health sector who can use heat stress forecasts to make lifesaving decisions (Blazejczyk et al., 2012; Jendritzky & Tinz, 2009; Di Napoli et al., 2019; Urban et al., 2021). The biggest difference is observed around where cossza is at its maximum (figure 8.3 and 8.4). However, the observed differences are larger when the step duration is bigger, and therefore the magnitude of error is less at 1 hour time step (i.e., ERA-5) in comparison to a 6 hourly forecast time step (i.e., after a 144-step). Further, there is a substantial difference between both MRT and UTCI values when dsrp is used in the place of fdir in the MRT calculation (equation 8.6 and 8.7).

We therefore recommend that if ERA5-HEAT is rereleased using the thermofeel methodology with fdir in the MRT calculation alongside the existing 'legacy' dataset available that the documentation indicates that differences are observed when dsrp is used in the place of fdir to be transparent with users. We recommend that the full forecast data is released as calculated using fdir for MRT using thermofeel to aid with decisions that are increasingly being made about thermal comfort conditions as a beta forecast and urge that dsrp be released in IFS (on all lead times) as a priority (Brimicombe et al., 2021, 2022).

In the ERA5-HEAT dataset Antarctica is currently cropped out and this is because of the many missing values that occur in this region (Di Napoli et al., 2021). We recommend that when the data is rereleased using the methodology introduced using the thermofeel library that Antarctica remains part of the dataset and that missing values and anomalous values are assigned as such, this is of benefit because it demonstrates to users that Antarctica does exist within the dataset but is often outside the range of the UTCI method (Bröde et al., 2012).

In addition, the UTCI and its components would benefit from a sensitivity analysis. We know that the windy and extreme cold conditions of Antarctica are outside the remit of the UTCI method, and previously it has been demonstrated that high MRT and low wind speeds lead to a higher UTCI values (Pappenberger et al., 2015), but, there is current understanding of which combination of the meteorological components of the UTCI (2m Air Temperature, MRT, Saturation Vapour Pressure and Wind Speed), lead to its hottest and coldest values. Such an analysis would allow us to better understand this thermal comfort index.

In addition, we suggest that the saturation vapour pressure method over ice is investigated in the calculation of saturation vapour pressure, a key component of the UTCI (Bröde et al., 2012; Hardy, 1998; Di Napoli et al., 2021). Currently the methodology for water saturation water vapour pressure is used universally, whereas for colder regions where ice is present on the ground the optimum approach is slightly different (Hardy, 1998). This could be useful as it could make the values for Antarctica within the range of the UTCI method and allow cold stress to be considered, which is currently not always possible.

8.5 Conclusion

We have demonstrated that the *thermofeel* methodology for calculating the variables of cossza, mrt and utci should supersede the operational c code that creates the ERA5-HEAT dataset. We recommend that it is used to create an ERA5-HEAT version 2 beta and is published alongside the legacy dataset, allowing for users to make their own comparisons as well as, the full forecast dataset as beta. In addition, we urge that dsrp is made operational in IFS so that a more accurate MRT can be calculated for the forecasts from *thermofeel*. In addition, we recommend that Antarctica is no longer cropped from the dataset, allowing users to recognize where data is missing and where it is present. Further, we recommend a sensitivity analysis of the UTCI is carried out to improve understanding of what combinations of the meteorological components lead to the highest and lowest values. Finally, the saturation vapour pressure over ice should be explored for the continent of Antarctica. Overall, the method introduced in *thermofeel* will allow for ERA5-HEAT to be readily expanded to operational forecasts and other thermal comfort indices, benefitting many users of ECMWF data.

9. The Development of a UTCIsimple method

Commentary: This was conceptualized out of discussion with members of staff at ECMWF, whilst I was on secondment at the organisation about calculating the UTCI and linear model research in the area for point/local scale data. It was seen as also important to better understand the sensitivity of the UTCI to its input variables, also given reviewer responses to Chapter 6.

I, therefore produced the research within this chapter in response to the discussion. The motivation was that this would go on to the development of a model that could be used by those with access to less computational power. This chapter is part of component 3 Essential Technologies because it provides evidence toward the objective: develop new technologies to reduce the risk to extreme heat, by demonstrating a linear model of the UTCI which improves the accessibility of the UTCI can be created.

Keywords: UTCI, Thermal Comfort, Heat Stress, Thermal Index Modelling

Abstract:

The Universal Thermal Climate Index (UTCI) is a model of human thermal comfort that, among other applications, has been demonstrated to infer mortality for both cold and heat stress, making it stand out amongst other heat and thermal indexes such as the wet bulb globe temperature (WBGT). Despite the growth in the UTCI in research, few studies focus on the sensitivity of the UTCI, i.e., on understanding how its input values contribute to a high or low UTCI value. In addition, it remains computationally costly to compute the UTCI in comparison to indexes such as humidex and heat index, suggesting an accurate, linear, and faster calculation for the UTCI could be highly beneficial across sectors. In this study, the aim is to evaluate what input variables cause a high or low UTCI value and assess whether an accurate multiple linear regression model could be created for the UTCI.

9.1 Introduction

The Universal Thermal Climate Index (UTCI) is a biometerological thermal stress index (Jendritzky, et al., 2012) .Previous research has demonstrated that the UTCI can be used to accurately model mortality rates both in conditions of cold and heat stress across Europe (Di Napoli et al., 2018; Urban et al., 2021). In addition, it has been shown to be second only to the most common heat stress index Wet Bulb Globe Temperature (WBGT) in being an indication of body response to heat stress conditions (Ioannou et al., 2022).

The UTCI method currently in use by most research is a polynomial approximation and is summarised by equations 9.1 and 9.2 (Bröde et al., 2012; Fiala et al., 2012; Jendritzky et al., 2012):

$$UTCI(Ta, Tr, Va, Pa) = Ta + Offset(Ta, Tr, Va, Pa)$$

[9.1]

where *Ta* is air temperature, *Tr* is mean radiant temperature, *Va* is wind speed, *Pa* is water vapour pressure and *Offset* is a 6-order polynomial, and

$$Pa = Ps \times \frac{\varphi}{100}$$

[9.2]

where *Pa* is determined from saturation vapour pressure (*Ps*) and relative humidity percent (φ)

From literature there is a growing body of work that evaluates developing a UTCI linear model and the sensitivity of the UTCI to its input values (Szer et al., 2022, Fang et al., 2018, Charalampopoulos & Nouri 2019, Provençal et al., 2016, Charalampopoulos, 2019). One such study demonstrated the possibility of developing a linear regression approximation of the UTCI for cities in Indonesia with a root mean square error of 0.7°C, but the robustness of the testing strategy is unclear (Setiawati et al., 2021). Only one study makes suggestions for a global gridded dataset (Pappenberger et al., 2015), this is important because it leads to an understanding of how meteorological conditions influence a high or a low UTCI value, in numerical weather prediction. In addition, the UTCI is still a computational costly index in comparison to other indexes such as humidex or heat index (Brimicombe, et al., 2022). In this study, the aim is to evaluate what input variables cause a high or low UTCI value and assess whether an accurate and accessible multiple linear regression model (UTCI simple) could be created for the UTCI.

9.2 Data and methods

9.2.1 UTCI calculation

To calculate the UTCI the state-of-the-art ERA5 reanalysis dataset is used, that provides a global gridded dataset every 1 hour at a 0.25x0.25° grid scale (Hersbach et al., 2020). Using ERA5 as input, the *thermofeel* python package was applied and the UTCI calculated via the *calculate UTCI* function (based on equations 9.1 and 9.2; we call this UTCI as "UTCI polynomial" hereafter); the mean radiant temperature was calculated using *calculate cosine of the solar zenith instant* and *calculate mean radiant temperature* functions (Brimicombe, et al., 2022). The global gridded datasets chosen were picked using a random sample approach and are summarised in Table 9.1. This approach was taken as this analysis was carried out on a personal laptop to ensure the outcome of this analysis was truly accessible.

Table 9.1: The random sample data used in this study

Day	Month	Year	UTC hour
6	June	2021	6
17	December	1981	14
20	February	1994	19
8	April	2005	3
16	August	2019	21

9.2.2 Sensitivity analysis

To assess the sensitivity of the input variables in comparison to the outputted UTCI variable, we first evaluated the visual trends in a scatter plot matrix to allow for comparison with a previous study on the topic that considers a global grid (Pappenberger et al., 2015). We then carried out a Spearman's rank analysis of the input variables in comparison to the UTCI to quantify the strength of the correlation between different variables (de Winter et al., 2016). All calculations were made using the python *pandas* library (VanderPlas, 2016).

9.2.3 Principal component analysis

A principal component analysis (PCA) was carried out. This is a popular type of multi-variance analysis that can be used to assess how input variables correlate with the outputted variable as well as, providing an overview of how much of the output variance (the variability of a variable from its mean) (Abdi & Williams, 2010; Yarnal, 1994). Whilst linear interdependencies between variables can affect the performance of a PCA, it is a valuable method in any case to demonstrate the make-up of variance, reducing the dimensions and space of variables.

The method used to carry out the analysis is a probabilistic principal component analysis, which uses likelihoods to determine the most probable make-up of the components as described in the method set out by Tipping and Bishop, (1999). In addition, this approach applies Singular Value Decomposition which projects values into simpler dimensions of space. It uses a type of orthogonal matrix which is created during the method that can be described as rotation (Pedregosa et al., 2011). First, the input variables were standardized to remove the units, because PCA responds to dimensionality and then a principal component analysis carried out making use of the *scikit-learn* python library (Pedregosa et al., 2011). It should be noted that this methodology is not carried out over a spatial domain as would be the case in an empirical orthogonal function (EOF) analysis, the focus is on the individual variables variance in the UTCI not their spatial composition. There are many studies that use this method these include pre-processing for detection of breast cancer, use in heart failure detection and classifying forum questions (Ibrahim et al., 2021; Reham et al., 2020; Fong et al., 2015).

9.2.4 Multiple linear regression

To construct a UTCIsimple model, a multiple linear regression was used, this approach was taken because of literature as presented in section 9.2.1, an assumption of multi-linear regression is that input variables are not highly linearly correlated to one another simply because the multi-linear regression can wrongly model the confounding effect. The training dataset chosen was the 6^{th} June 2021 at 6 UTC (top row of table 9.1). To ensure that the model created with the training data was robust, summary statistics including those denoted as an ANOVA were calculated. This was especially important given some variables had linear dependencies to check that the confounding influence was still portrayed by the model (Schneider, et al., 2010). In addition, testing was carried out on each of the other data rows in table 9.1. To assess the accuracy of the linear regression model in comparison to the polynomial a mean absolute error (i.e., average difference between the polynomial value and the linear regression value) was calculated. All calculations here were carried out with the *scikit-learn* python library.

9.3 Results

9.3.1 2m Temperature has the strongest positive relationship

For the 6th June at 6UTC in 2021, 2m temperature (t2m) and mean radiant temperature (mrt) have a strong positive linear relationship with the UTCI (Figure 9.1) as well as with one another. In comparison, saturation vapour pressure (ehPa) has a polynomial (curve) visual relationship with the UTCI, 2m temperature and mean radiant temperature (Figure 9.1). In contrast, wind speed (va) does not have a strong linear relationship with any of the other input variables or the UTCI. This is also in agreement with the scatter matrix shown in (Pappenberger et al., 2015).

Further, the Spearman's rank analysis (Figure 9.2) shows that for the 6th June at 6UTC in 2021 2m temperature has the strongest correlation with the UTCI of 0.94. Spearman's further reveals that mean radiant temperature (0.88) and the saturation vapour pressure (0.86) are also strongly positively correlated with the UTCI (Figure 9.2). In contrast, wind speed is negatively correlated with the UTCI (-0.44) (Figure 9.2).

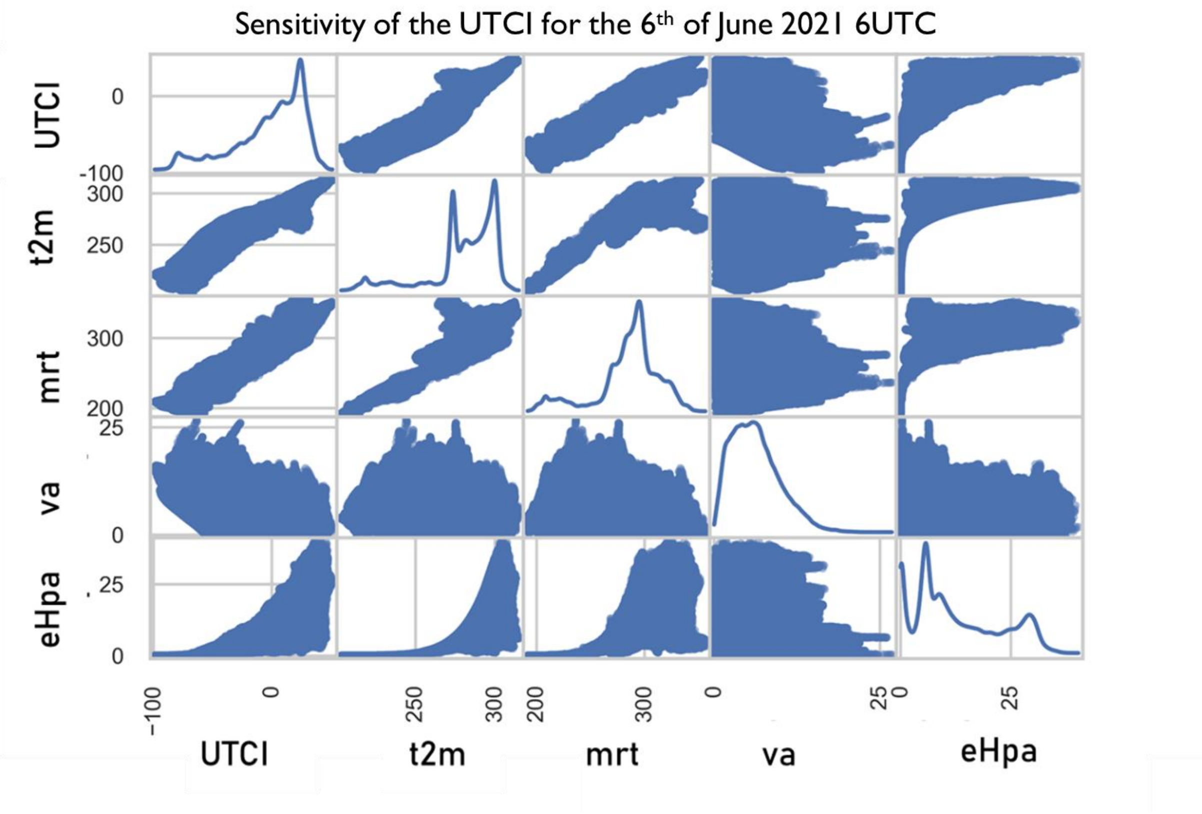


Figure 9.1: Scatter matrix of the input variables to the UTCI and the UTCI for the 6th June 2021 at 6 UTC. UTCI (k), t2m: 2m temperature (k), mrt: mean radiant temperature (k), va: 10m wind speed (m/s) and ehpa: saturation vapour pressure (hpa).

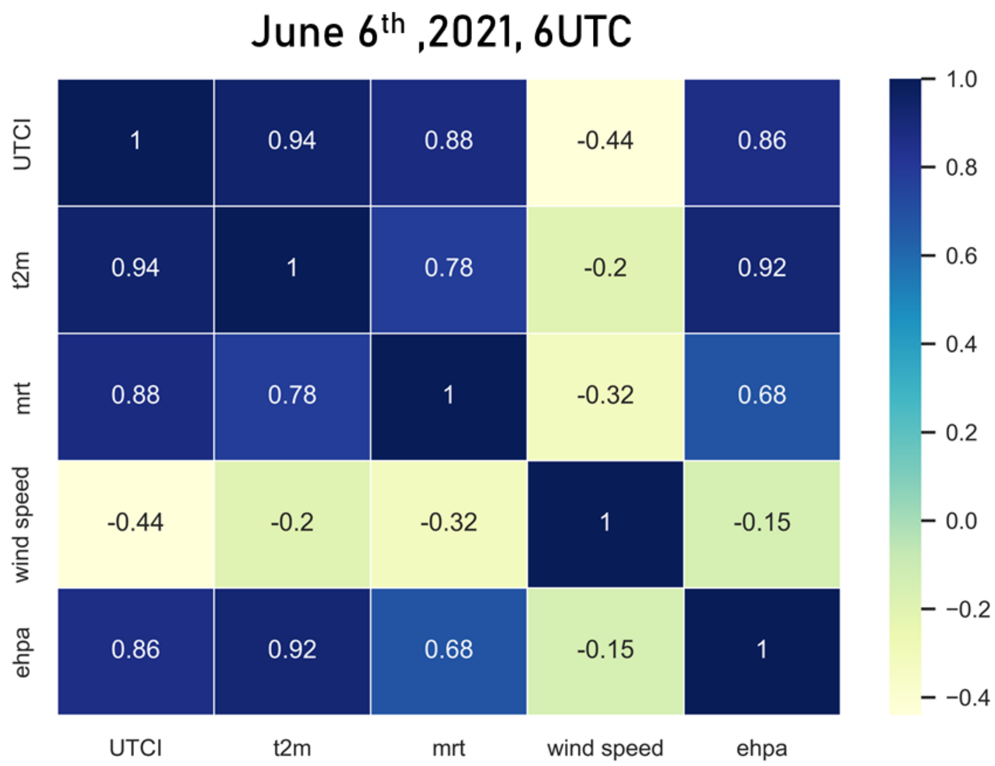


Figure 9.2: Spearman's rank correlation of different input variables of the UTCI and the UTCI output for the 6th June 2021 at 6UTC.

9.3.2 All inputs are important for UTCI variance

A UTCI linear model can be suggested to need all of the input variables, to fully capture the variance of the thermal comfort index as shown in results here. For example, Principal Component 1, shows the proportion of variance captured is 0.654 (Table 9.2). The majority of variance is captured by Principal Component 1 and 2 at 0.888 (Table 9.2). But, this can be suggested to not be at a high enough proportion to create an accurate model going forward.

Table 9.2: The Results of the Principal Component Analysis for the 6th June at 6UTC, 2021.

	Proportion of Variance	Cumulative Proportion

PC1	0.654	0.654
PC2	0.234	0.888
PC3	0.093	0.981
PC4	0.019	1

Table 9.3: The loading table for variables contribution of the Principal Component Analysis for the 6th June at 6UTC, 2021.

Input Features	PC1	PC2	PC3	PC4
2m Temperature	0.591680	0.166308	0.200025	0.763051
Mean Radiant Temperature	-0.571677	0.046761	0.557954	0.599738
Wind Speed	0.203303	0.975278	0.052689	0.068731
Saturation Vapour Pressure	0.530819	0.137795	0.803680	0.230961

9.3.3 A linear UTCI model

The results in section 9.3.1 and 9.3.2 demonstrate that theoretically an accurate linear model of the UTCI can be constructed. To accurately create a UTCIsimple that can reduce run time and is more accessible on a range of personal computers, all the input components for the 6th June 2021 at 6UTC of the UTCI are included in the method described in Section 9.2.3. This gives the model summarised in Equation 9.3:

$$UTCI_{simple} = -292.2897 + 0.75 \times t2m + 0.3013 \times mrt + -1.9309 \times va + 0.3990 \times pa$$

[9.3]

The training data for the 6th June 2021 at 6UTC has on average a mean absolute error (MAE) of 2.58°C between the UTCI polynomial and UTCIsimple (Figure 9.3, e). In addition, the model has an R^2 value of 0.986 suggesting it is highly robust. The supplementary material shows the ANOVA and overall summary statistics which show a large F-value meaning more variation between the groups means than by chance. In addition to showing, that the input variables are from different populations. This is supported by a P-value of 0 which means that the model is performing better than by random chance. Whilst the highest positive anomalies (up to 10°C) for the training data are seen in areas of high elevation (Figure 9.4,e), the lowest negative anomalies (up to 5°C) are seen in Southern Asia which is a region which often has high humidity levels.

Further, evaluating the UTCIsimple model for the test data reveals that on average for all the data there is a MAE of 2.77°C between the UTCI polynomial and UTCIsimple with the highest MAE value for 8th April 2005 at 3UTC of 2.98°C and the lowest MAE value for 16th August 2019 at 21UTC of 2.57°C. Overall on average the highest positive anomalies are up to +10°C (Figure 9.4 a-d); the biggest negative anomalies are up to -5°C (Figure 9.4 a-d).

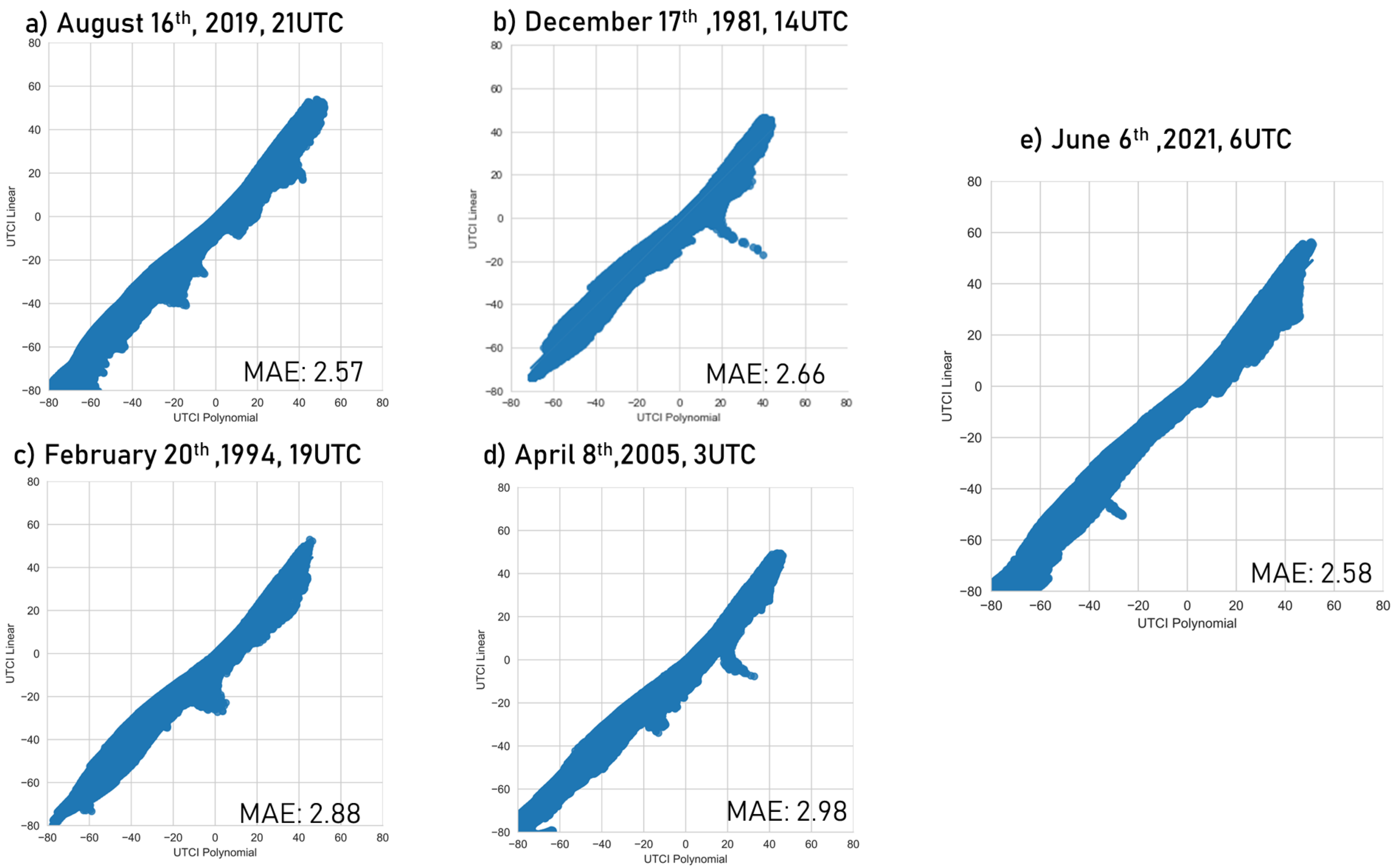


Figure 9.3: Linear relationship between the UTCI polynomial method and the UTCI linear method (UTCIsimple). Each plot displays the Mean Absolute Error (MAE). The test data is shown in a) August 16th 2019 at 21UTC, b) December 17th 1989 at 14UTC, c) February 20th 1994 at 19UTC and d) April 8th 2005, at 3UTC, as well as, e) which is the training data June 6th 2021 at 6UTC.

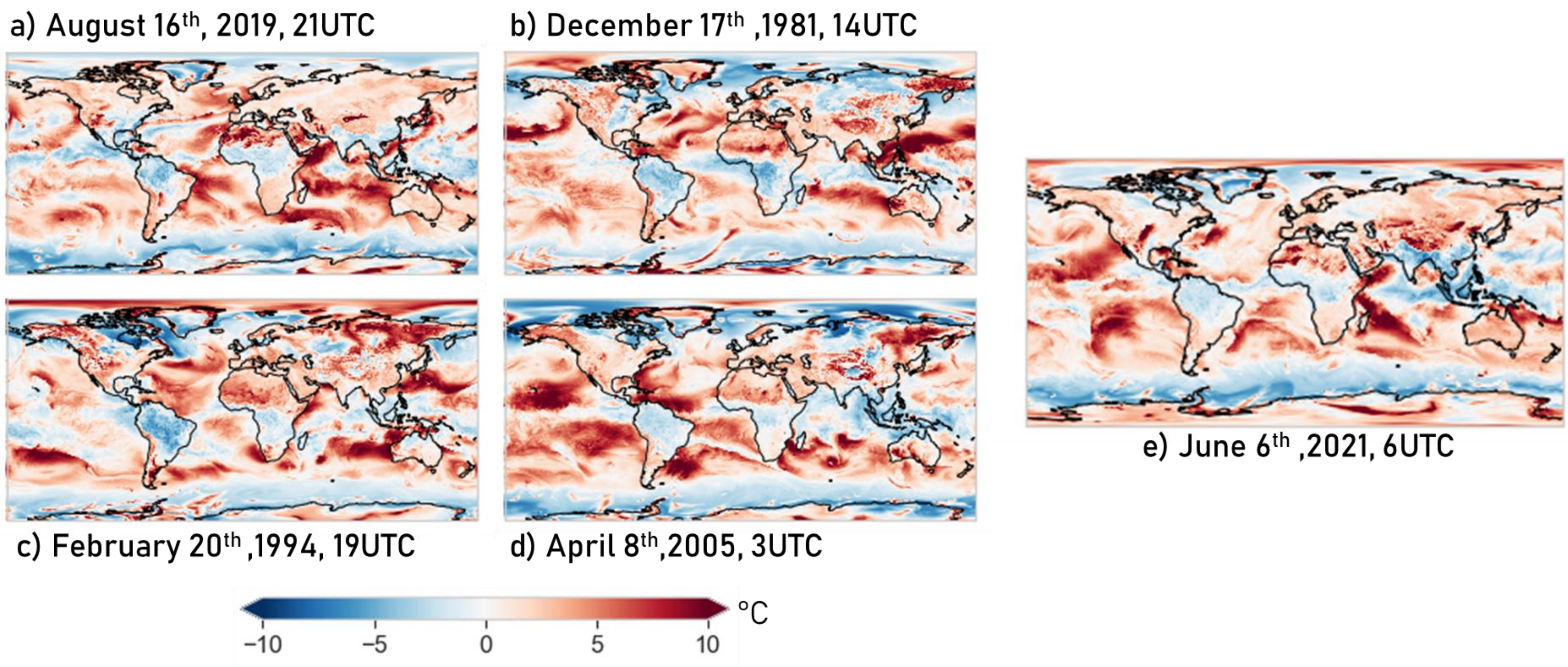


Figure 9.4: Anomaly in °C between the UTCI polynomial method and the UTCI linear method (UTCIsimple) the test data is shown in a) August 16th 2019 at 21UTC, b) December 17th 1989 at 14UTC, c) February 20th 1994 at 19UTC and d) April 8th 2005, at 3UTC, as well as, e) which is the training data June 6th 2021 at 6UTC.

9.4 Discussion

It is shown that a higher value of 2m temperature, mean radiant temperature, saturation vapour pressure and low wind speed lead to the highest value of the UTCI. This is in keeping with the body's transfer of heat where radiation is considered to contribute to 60% of heat gain of the human body (Kuht & Farmery, 2021). Conversely, low temperature, low values of mean radiant temperature and saturation vapour pressure with high wind speeds will lead to the lowest UTCI values.

The UTCI is known to not be accurate for high wind speeds. Experiments with random data demonstrated that a high wind speed had the biggest influence on inaccurate values of the UTCI being outputted, even whilst mid values of the other input values were given (further information in the supplementary material).

This study demonstrates that an accurate UTCIsimple method can be created using a multi-linear regression model from a polynomial when using all the same input values. The decision to keep all the inputs was taken because of the interdependencies between the input variables (Figures 9.1 and 9.2) as well as because of the inaccuracy demonstrated in simplified methodologies for other indices such as the WBGT (Buzan et al., 2015; Kong & Huber, 2021).

9.5. Conclusion

In this study, it has been demonstrated that (a) a higher value of 2m temperature, mean radiant temperature, saturation vapour pressure and low wind speed lead to the highest value of the UTCI (Figure 9.1), and (b) low temperature, low values of mean radiant temperature and saturation vapour pressure with high wind speeds will lead to the lowest UTCI values. A proposed UTCIsimple method is presented in equation 9.3; this has a mean absolute error of 2.77°C across the testing data compared to the UTCI polynomial method (Figure 9.4). Further work should test UTCI simple with a more extensive dataset and look to decrease number of required input values whilst maintaining accuracy.

9.6 Supplementary Material

Table S9.1: Showing the PCA results for random data where the linear relationship between the input variables is removed.

	Proportion of Variance	Cumulative Proportion
PC1	0.289	0.289
PC2	0.261	0.55
PC3	0.246	0.796
PC4	0.204	1

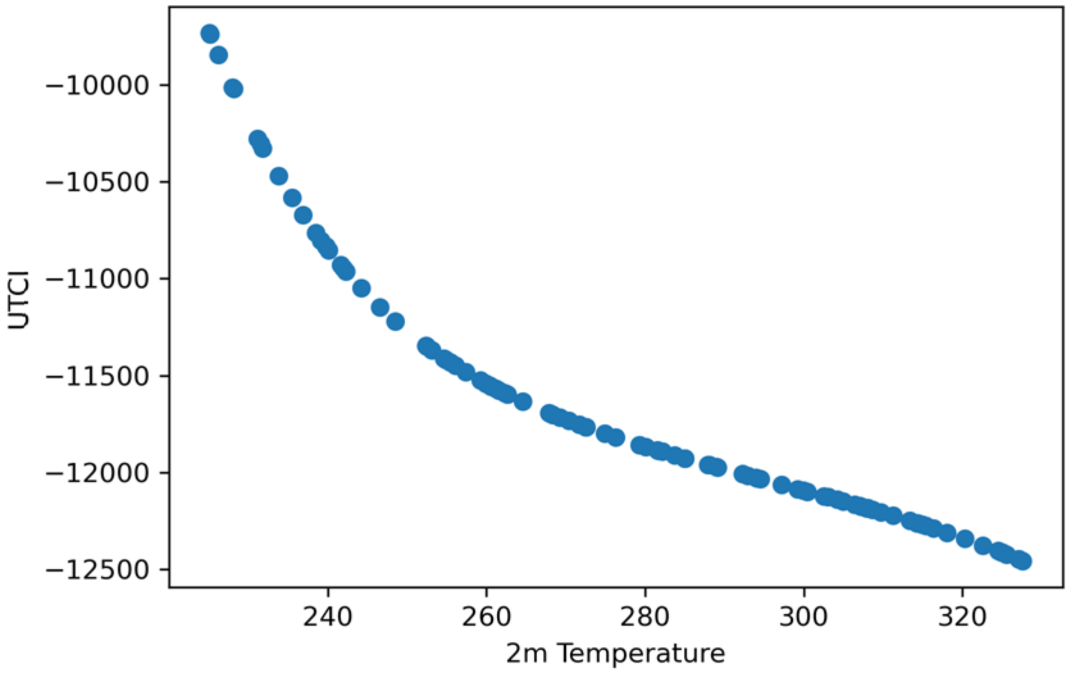


Figure S9.1: For random data the UTCI output and the relationship with 2m Temperature when the Mean Radiant Temperature, Saturation Vapour Pressure and Wind Speed are set to high values with Wind speed outside the optimum range for the UTCI.

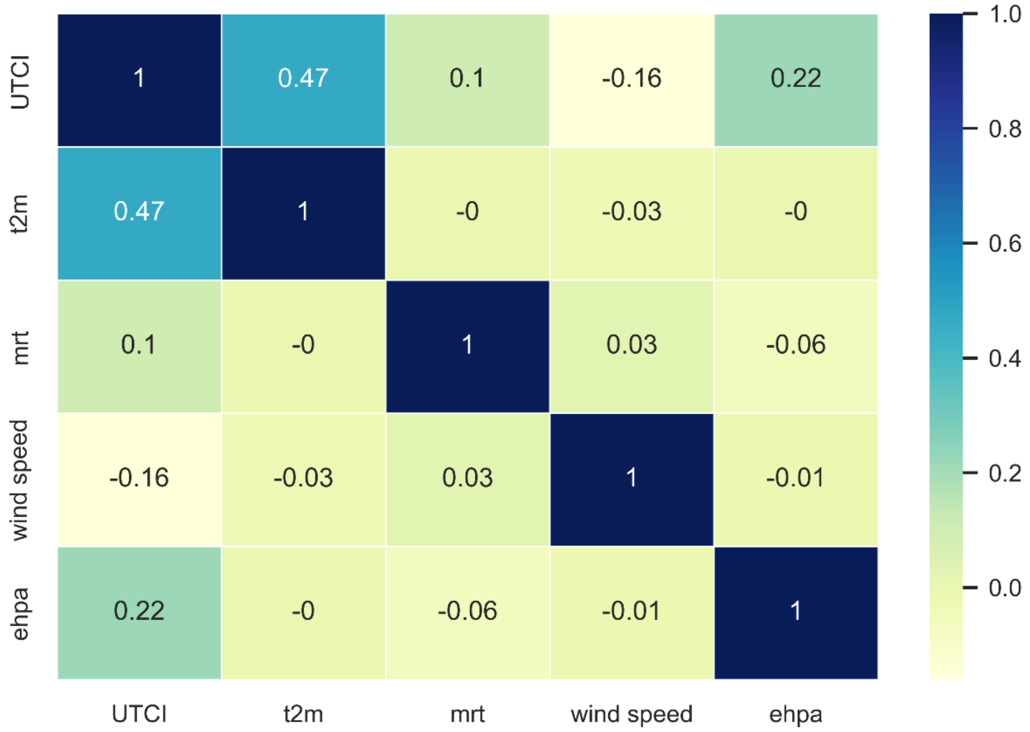


Figure S9.2: Spearman's Rank for random data inputs for the UTCI and the outputted UTCI, demonstrating the importance of the strong linear relationship of 2m temperature and Mean Radiant Temperature.

Table S9.2 Summary Statistics for the Linear Regression Model, demonstrating that it is robust and more accurate than a random model would be by chance.

	coef	std err	T	P>|t|	[0.025	0.975]
Intercept	-292.29	0.062	-4740	0	-292.41	-292.17
t2m	0.7543	0	1874	0	0.753	0.755
mrt	0.3013	0	1195	0	0.301	0.302
ws	-1.9309	0.001	-2162	0	-1.933	-1.929
ehpa	0.399	0.001	794.5	0	0.398	0.4

Table S9.3 an ANOVA output for the multi-linear regression also supporting that the multi-linear regression is robust.

	df	sum_sq	mean_sq	F	PR(>F)
t2m	1	828790000	828790000	85510000	0
mrt	1	25860000	25860000	2670000	0
ws	1	50080000	50080000	5170000	0
ehpa	1	6120000	6120000	630000	0
Residual	1040000	10060000	10		

10. Wet Bulb Globe Temperature: indicating extreme heat risk on a global grid

Commentary: when I was developing thermofeel, I realised that there was another heat stress index that incorporated radiation like the UTCI called Wet Bulb Globe Temperature (WBGT). From literature, it was widely considered to be the most popular heat stress index but was also said to have many approximations due to difficulties reproducing a method presented by Liljegren and a lack of observations, it also was seemingly difficult to create an accurate version for Numerical Weather Prediction services. I therefore developed a new methodology for WBGT, by repurposing an equation that created Mean Radiant Temperature from Globe Temperature to do the opposite and removed the need for iterative loops.

Chapter 10 is published under the reference:

Brimicombe C, Lo Brian C H, Di Napoli C, Machiel P, Quintino T, Pappenberger F, Cornforth R and Cloke H L (2023) Wet Bulb Globe Temperature: indicating extreme heat risk on a global grid *GeoHealth* doi: 10.1029/2022GH000701

This chapter is part of component 3 Essential Technologies because it provides evidence toward the objective: develop new technologies to reduce the risk to extreme heat, by creating a new methodology for WBGT developed to improve the accuracy and the ability to incorporate it into numerical weather prediction services.

Highlights:

- We create an accurate method for calculating WBGT using Mean Radiant Temperature termed $WBGT_{Brimicombe}$
- It is found that $WBGT_{amsc87}$ also known as WBGTsimple is not an accurate approximation of WBGT.
- $WBGT_{Brimicombe}$ can assist with robust heat stress standards across sectors including in public and occupational health.

Abstract:

The Wet Bulb Globe Temperature (WBGT) is an international standard heat index used by the health, industrial, sports and climate sectors to assess thermal comfort during heat extremes. Observations of its components, the globe and the wet bulb temperature, are however sparse. Therefore WBGT is difficult to derive, making it common to rely on approximations, such as the ones developed by Liljegren and colleagues (2008, $\mathrm{WBGT_{Liljegren}}$) and by the American College of Sports Medicine ($\mathrm{WBGT_{ACSM87}}$). In this study, a global dataset is created by implementing an updated WBGT method using ECMWF ERA5 gridded meteorological variables and is evaluated against existing WBGT methods. The new method, $\mathrm{WBGT_{Brimicombe}}$, uses globe temperature calculated using mean radiant temperature and is found to be accurate in comparison to $\mathrm{WBGT_{Liljegren}}$ across three heatwave case studies. In addition, it is found that $\mathrm{WBGT_{ACSM87}}$ is not an adequate approximation of WBGT. Our new method is a candidate for a global forecasting early warning system.

Plain Text Summary:

The Wet Bulb Globe Temperature (WBGT) is an international standard for how we measure the effect of heat on the human body. It is used across sectors in health, industry, sports and climate to calculate how we feel and how our body responds during heat extremes. Its calculation has historically relied on globe thermometer and wet bulb temperature observations, which are however not widely available. This has made WBGT difficult to calculate and meant approximations have been created. Here we formulate a new WBGT method that can be used with global gridded data that are freely available and we compare it against other methods in common use. We find that our method is accurate when compared to the existing gold standard WBGT method.

10.1 Introduction

The Wet Bulb Globe Temperature (WBGT) is an ISO (International Standards Organisation) approved metric of heat stress in humans (Int Org Standard, 2017). Heat stress is caused by the build-up of body heat either as a result of exertion and/or exposure to the external environment (air temperature humidity, solar radiation, wind speed etc.) (D'Ambrosio Alfano et al., 2014; Ioannou et al., 2022; Jacklitsch et al., 2016; McGregor & Vanos, 2018; Parsons, 2006). WBGT was originally developed in the 1950s as part of a campaign to lower the risk of heat disorders during the training of US Army and Marine troops (Minard, 1961).

The WBGT has many applications and is used widely in many research areas such as the occupational and public health sectors. In addition, it is used in the sports and exercise field, industrial hygiene and in climate change research and is one of the most popular heat stress indices (Heo et al., 2019; Kjellstrom et al., 2009; Lemke & Kjellstrom, 2012; Lucas et al., 2014; Racinais et al., 2015).

The WBGT (°C) is defined by three environmental variables via the following equation (Minard, 1961):

$$WBGT = 0.7T_w + 0.2T_g + 0.1T_a \quad (10.1)$$

where T_a is 2m air temperature (i.e., dry bulb temperature, in °C), T_g is globe thermometer temperature (°C) and T_w is natural wet bulb thermometer temperature (°C).

Whereas 2m air temperature is easily measurable, observations of globe thermometer and wet bulb thermometer temperatures are often sparse (Budd, 2008; D'Ambrosio Alfano et al., 2014). Consequently, it has been historically challenging to calculate WBGT from equation 10.1 and it is instead common to rely on approximations. These include the approximation from the American College of Sports Medicine (termed $\mathrm{WBGT_{ACSM87}}$), which is a linear model of the WBGT (American college of sports medicine, 1987), and the approximation by Liljegren and colleagues (termed $\mathrm{WBGT_{Liljegren}}$), which is a more complex approximation based on the fundamentals of heat transfer (Liljegren et al., 2008).

In this study, we compare a new approach to approximate WBGT (termed $\mathrm{WBGT_{Brimicombe}}$) with $\mathrm{WBGT_{ACSM87}}$ and $\mathrm{WBGT_{Liljegren}}$. Our approach is novel in calculating WBGT from gridded data using the variable of mean radiant temperature and is designed for operational forecasting systems. Comparisons are performed globally by using the ERA5 hourly global gridded reanalysis from the European Centre for Medium-Range Weather Forecasts

(ECMWF), Observation data from the World Radiation Monitoring Center–Baseline Surface Radiation Network (Driemel et al., 2018) and are here discussed within the context of three heatwave case studies (India and Pakistan in July 2003, the Western Sahel in March 2013 and Australia in December 2019).

10.2. Method

Nomenclature

$\cos\theta$: Cosine of the solar zenith angle (°)

h_{cg}: mean convection coefficient (W/m^2K)

A_h: the convective heat transfer coefficient (W/m^2K)

T_a: 2m Temperature/ Dry Bulb Temperature in K or °C as described

T_g: Globe Temperature in K or °C as described

T_w: Wet Bulb Temperature in K or °C as described

e_a: Saturation vapour pressure of the air(kpa)

e_w: Saturation vapour pressure of the wick (kpa)

α_g: albedo of the globe (0.05)

α_{sfc}: albedo of the surface (0.45)

ε_a: the emissivity of the air (W/m^2)

ε_g: the emissivity of the globe (0.95)

ΔF_{net}: the net radiant heat flux (W/m^2K)

D: Globe Diameter 0.15 meters

dsrp: downward solar radiation proportion (W/m^2)

h: mean convection coefficient (W/m^2K)

ssrd: Solar Surface Radiation downwards (W/m^2)

T_{mrt}: Mean Radiant Temperature in K or °C as described

v_a: 10 meter wind speed m/s

ε: Emissivity 0.98 that of a clothed body (Bedford & Warner, 1934; De Dear, 1987)

Nu: Nusselt Number is the ratio of convective to conductive heat transfer (dimensionless)

P: Surface Pressure (kpa)

Pr: Prandtl Number is the ratio of momentum diffusivity to thermal diffusivity (dimensionless)

RH: Relative Humidity (%)

Sh: Sherwood Number a mass transfer operation (dimensionless)

Sc: Schmidt Number is the ratio of the kinematic viscosity to the molecular diffusion coefficient (dimensionless)

a: is a constant of the value 0.56

e: Saturation Water Vapour Pressure Hpa(hPa)

σ: the Stefan-Boltzmann constant (dimensionless)

10.2.1 Brimicombe WBGT Approximation ($WBGT_{Brimicombe}$)

This new approach to approximate WBGT has been developed for numerical weather prediction post-processing as it takes an optimized approach to the calculation of WBGT by removing the need for iterative loops. We calculate globe temperature using an adapted version of the original Bedford & Warner equation, making use of mean radiant temperature, a measurement of incidence of radiation on a body which is appropriate for indoor or outdoor use depending on given inputs (Bedford & Warner, 1934; De Dear, 1987; Guo et al., 2018; Thorsson et al., 2007; Vanos et al., 2021).

Here equation 10.2 is used to solve for globe temperature as the subject because the ERA5 reanalysis data contains the variables of 2m air temperature (T_a), 10-meter wind speed (v_a) and mean radiant temperature (T_{MRT}). All temperatures are in Kelvin; 10-meter wind speed was found to be within ±1°C of an approximated 2m wind speed which used the method found in Spangler, et al., 2022 and therefore is used (not shown). The code to compute this is available as part of thermofeel: https://doi.org/10.21957/mp6v-fd16 (Brimicombe, et al., 2021, 2022a)

$$T_{mrt} = \sqrt[4]{T_g{}^4 + \frac{h_{cg}}{\varepsilon \times D^{0.4}} \times (T_g - T_a)}$$

(10.2)

In equation 2, h_{cg} is the mean convection coefficient and is calculated using equation 3. This is an additional correction from the original method and reduces the impact weighting of high wind speeds on the outputted globe temperature (De Dear, 1987; Guo et al., 2018).

$$h_{cg} = 1.1 \times 10^8 \times v_a{}^{0.6}$$

(10.3)

To calculate the wet bulb temperature, a theoretical method by Stull (2011) is used and is shown in equation 10.4, where T_a is 2m air temperature in °C and RH is relative humidity in percent. This method is valid between -20°C and 50°C and between 5% and 99% humidity, which are the ranges the method is optimised for and with which it has been used in previous studies (Freychet et al., 2020; Heo et al., 2019; Raymond et al., 2017). In addition, this method provided a test case, an expected value for a given set of inputs, which allowed validation of the calculated value (Stull, 2011).

$$\begin{aligned} T_w = T_a \tan^{-1}(0.151977(RH + 8.313659)^{1/2}) \\ + \tan^{-1}(T_a + RH) \\ - \tan^{-1}(RH - 1.676331) \\ + 0.00391838(RH)^{3/2} \times \tan^{-1}(0.023101 \times RH) - 4.686035 \end{aligned}$$

(10.4)

Once calculated, the globe temperature and wet bulb temperature along with 2m air temperature are used in equation 10.1 to provide the $\mathrm{WBGT_{Brimicombe}}$.approximation.

10.2.2 Liljegren WBGT Approximation (WBGT$_{Liljegren}$)

WBGT$_{Liljegren}$ can be considered a existing 'gold standard' benchmark WBGT value as it is widely considered the most accurate WBGT approximation available (Kjellstrom et al., 2009; Kong & Huber, 2021; Liljegren et al., 2008). To obtain WBGT$_{Liljegren}$, wet bulb temperature is calculated as per equation 10.5 and globe temperature is calculated as per equation10.6 which are then used in equation 10.1. Specifically, wet bulb temperature is calculated as

$$T_w = T_a - Nu \times Sh \times \left(\frac{Pr}{Sc}\right)^a \left(\frac{e_w - e_a}{P - e_w}\right) + \frac{\Delta F_{net}}{A_h}$$

(10.5)

where Nu is the Nusselt number, Sh is the Sherwood Number, Pr is the Prandtl number and Sc is the Schmidt number and $\left(\frac{e_w - e_a}{P - e_w}\right)$ is the change in saturation water vapour transfer between the hygrometer wick and its surroundings. $\frac{\Delta F_{net}}{A_h}$ is the net radiative heat flux divided by the convective heat transfer coefficient. Full details can be seen in (Liljegren et al., 2008). Globe temperature is calculated as

$$T_g^4 = \frac{1}{2}(1 + \varepsilon_a)T_a^4 - \frac{h}{\varepsilon_g \sigma}\left(T_g - T_a\right) + \frac{ssrd}{2\varepsilon_g \sigma}(1 - \alpha_g)\left[1 + \left(\frac{1}{2\cos\theta}\right) dsrp + \alpha_{sfc}\right]$$

(10.6)

where the $\frac{h}{\varepsilon_g \sigma}\left(T_g - T_a\right)$ *and* $\frac{S}{2\varepsilon_g \sigma}(1 - \alpha_g)$ terms denote the energy gain from diffuse downwards and direct downward solar radiation respectively. dsrp is the projected area and α_{sfc} is the reflected solar radiation and ssrd is downward solar radiation. Full details can be seen in (Liljegren et al., 2008). Here data for $\mathrm{WBGT}_{\mathrm{Liljegren}}$ is provided by Kong & Huber, (2021), instead of calculation using the HEAT-SHIELD methodology, because the method presented by Kong & Huber appears to be more robust and closer to the original methodology (Casanueva, 2017).

10.2.3 American College of Sports Medicine WBGT Approximation ($\mathrm{WBGT}_{\mathrm{ACSM87}}$)

The $\mathrm{WBGT}_{\mathrm{ACSM87}}$ (American college of sports medicine, 1987) was also calculated (Equation 10.7) as it continues to appear widely in literature, despite it being known to have large bias (Chen et al., 2019; Grundstein & Cooper, 2018; Kong & Huber, 2021). $\mathrm{WBGT}_{\mathrm{ACSM87}}$ is calculated from 2m air temperature and saturation water vapour pressure (e) as:

$$\mathrm{WBGT}_{\mathrm{ACSM87}} = 0.567 \times T_a + 0.393 \times \mathrm{e} + 3.94$$

(10.7)

10.2.4 Methodological difference between $WBGT_{Brimicombe}$ and $WBGT_{Liljegren}$

Several methodological differences between our new WBGT approximation and the existing 'gold standard' WBGT approximation are present (Brimicombe et al., 2022a; Liljegren et al., 2008).

One key variable that is necessary in the calculation of T_g (both in equation10.2 and 10.6) is the cosine of the solar zenith angle. In previous studies it is found that radiation in the Liljegren Tg methodology has inaccuracies at sunrise and sunset due to the method used to calculate this variable (Kong & Huber, 2022; Lemke & Kjellstrom, 2012). These inaccuracies are known to become greater in a numerical weather prediction service time step (a period of several hours) (Brimicombe et al., 2022b; Hogan & Hirahara, 2016). For the Brimicombe Tg methodology this does not occur because a specially designed cosine of the solar zenith angle is implemented (Brimicombe et al., 2022a; Brimicombe et al., 2022b).

Another difference is in the number of radiation input variables used to calculate Tg in the Liljegren methodology. In this only 2 radiation components are used (Liljegren et al., 2008) in comparison to the 5 that calculate Tmrt (please refer to: Di Napoli et al., 2020) which goes on to calculate the Brimicombe Tg. Equation 10.2, which expresses mean radiant temperature Tmrt as a function of Tg and Ta, is comparable to the heat balance expressed in Bedford & Warner 1934, therefore relating mean radiant temperature to the temperature of surrounding surfaces. Similarly, equation 10.2 can also be rearranged in order of Tg^4, where many comparable terms to equation 10.6 are identifiable.

In the Liljegren Tw methodology a psychrometric wet bulb temperature is calculated using fundamentals of mass transfer. In addition a key input of saturation water vapour pressure is calculated differently over ice and water (and the land surface) as in Hardy, (1998). In comparison, in the Brimicombe Tw methodology an empirical theoretical wet bulb temperature is calculated (Stull, 2011). As previously mentioned, this computationally removes the need for iterative loops, which are onerous to run for a gridded dataset. In addition, the saturation water vapour pressure method is only for over water (and the land surface) in contrast to being over either water or ice, given that WBGT is a human heat stress index. How these methodological differences introduce errors will be explored within this study.

10.2.5 WBGT approximation comparisons

To compare the WBGT approximations, this study uses variables available as part of the ERA5 and ERA5-HEAT gridded reanalysis datasets produced by ECMWF on a 0.25° x 0.25° grid at an hourly time step (Hersbach et al., 2020; Di Napoli et al., 2021). ERA5 was chosen for this study as a state-of-the-art gridded reanalysis dataset; it is an ideal dataset to test out a new gridded based methodology and has the added benefit of outputting the mean radiant temperature variable (the incidence of radiation on the body). ERA5 and ERA5-HEAT variables of 2m air temperature, 2m dew point temperature, 10m wind speed and mean radiant temperature are used in the relevant equations to calculate $\mathrm{WBGT_{Brimicombe}}$ and $\mathrm{WBGT_{ACSM87}}$. $\mathrm{WBGT_{Liljegren}}$ is also calculated using ERA5 reanalysis data. There are known limitations of ERA5; these include inaccuracies at higher elevations (Brunamonti et al., 2019; Senyunzi et al., 2020).

The approximations are calculated and compared for three past heatwaves on dates where heat stress is known to have occurred. One affected India and Pakistan in July 2003, another the Western Sahel in March 2013 and another Australia in December 2019 (CRED, 2020).In addition, this study also considers the full global gridded datasets of WBGT values including those below a heat stress threshold.

The gridded ERA5 reanalysis output for $\mathrm{WBGT_{Brimicombe}}$ is compared to the observed $\mathrm{WBGT_{Brimicombe}}$ calculated using data from the Tateno TAT (36.1N,140E) and Nya Långenäs NYA (78.9N,11E) stations from the World Radiation Monitoring Center–Baseline Surface Radiation Network (WRMC–BSRN, Driemel et al. 2018) for Daily Maximum WBGT for July 2003 and March 2013. In addition, for March 2013 the Stull Wet Bulb Temperature method is compared to the Davies-Jones method (available at: https://github.com/smartlixx/WetBulb/blob/master/WetBulb.py) (Stull, 2011; Davies-Jones, 2008). We are constrained by the available observation data.

The comparison between the three approximations uses the observed WBGT thresholds set out by the International Standards Organisation, ISO (Jacklitsch *et al* 2016, Table 1). According to ISO, which considers heat stress by reference to recommended lifting and hard labour workloads, 33°C is known as a critical health threshold for WBGT (Heo et al., 2019).

Table 10.1: Heat stress thresholds for wet bulb globe temperature and recommended labour legal definitions of workloads for an average period of work. Adapted from Jacklitsch *et al.*, 2016.

WBGT (°C)	Recommended maximum workload	Approximated Work/Rest Cycles (Minutes)	Category
> 33	Resting	Rest	5
30-33	Light	15/45	4
28-30	Moderate	30/30	3
25-28	Heavy	30/15	2
23-25	Very Heavy	45/15	1
<23	No recommendations	No recommendations	0

$\mathrm{WBGT_{ACSM87}}$ and $\mathrm{WBGT_{Brimicombe}}$ are compared against the existing gold standard approximation of $\mathrm{WBGT_{Liljegren}}$ in two ways. The first is through evaluation of the spatial anomaly in WBGT values. $\mathrm{WBGT_{Liljegren}}$ is subtracted from the corresponding $\mathrm{WBGT_{ACSM87}}$ or $\mathrm{WBGT_{Brimicombe}}$ values. Second, is a correlation between $WBGT_{Liljegren}$ and the other WBGT approximations is assessed together with the mean absolute error (MAE). in addition the sensitivity of the outputted $\mathrm{WBGT_{Brimicombe}}$ and $\mathrm{WBGT_{Liljegren}}$ approximations to key input variables is assessed.

10.3. Results

10.3.1 Gridded outputs of WBGT for the three heatwaves

In July 2003, the highest values of $\mathrm{WBGT_{Liljegren}}$ are over 33°C for the border of northern India and Pakistan, which is indicative of extreme heat stress in category 5 (Figure 10.1, left column). This pattern is well matched by $\mathrm{WBGT_{Brimicombe}}$. The lowest values for both of these WBGT approximations are over the Himalayas bordering the north-east of India, indicating no heat stress. $\mathrm{WBGT_{ACSM87}}$ has lower heat stress values and only reaches 33°C, category 4.

In March 2013, the highest values of $\mathrm{WBGT_{Liljegren}}$ are over 33°C and are indicative of extreme heat stress (category 5) for the north of Ghana and Nigeria (Figure 1, middle column). This pattern is broadly matched by $\mathrm{WBGT_{Brimicombe}}$ although the extreme region of heat stress has slightly lower values. Similarly to the July 2003 heatwave, $\mathrm{WBGT}_{\mathrm{ACSM87}}$ has much lower values than the other approximations and only reaches at the maximum up to 33°C (category 4) in one small area. The pattern of heat stress is not well captured and $\mathrm{WBGT}_{\mathrm{ACSM87}}$ is consistently at least two heat stress categories lower than $\mathrm{WBGT}_{\mathrm{Liljegren}}$ and $\mathrm{WBGT}_{\mathrm{Brimicombe}}$. over the whole region.

For the heatwave of December 2019 in Australia, there are strikingly similar heat stress patterns for $\mathrm{WBGT}_{\mathrm{Liljegren}}$ and $\mathrm{WBGT}_{\mathrm{Brimicombe}}$ (Figure 10.1, right column). $\mathrm{WBGT}_{\mathrm{ACSM87}}$ also performs better for this heatwave than for the July 2003 and March 2013 heatwaves and heat stress values are close to those of $\mathrm{WBGT}_{\mathrm{Liljegren}}$. However, $\mathrm{WBGT}_{\mathrm{ACSM87}}$ again does not capture the same shape of the areas under heat stress.

These similarities and differences can also be seen clearly at the global scale for each heatwave (Figure 10.2). $\mathrm{WBGT}_{\mathrm{Liljegren}}$ and $\mathrm{WBGT}_{\mathrm{Brimicombe}}$ values are similar worldwide in each of the three months considered (Figure 10.2), particularly focussing on parts of North Africa, southern Asia and Australia. It is however noteworthy that $\mathrm{WBGT}_{\mathrm{Brimicombe}}$ does not always capture the highest heat stress category indicated by $\mathrm{WBGT}_{\mathrm{Liljegren}}$ in South America (Figure 10.2). $\mathrm{WBGT}_{\mathrm{ACSM87}}$ is very different from the other approximations on a global scale. It consistently has heat stress values that are too low, sometimes three heat stress categories lower, and only captures the heat stress in some parts of Australia.

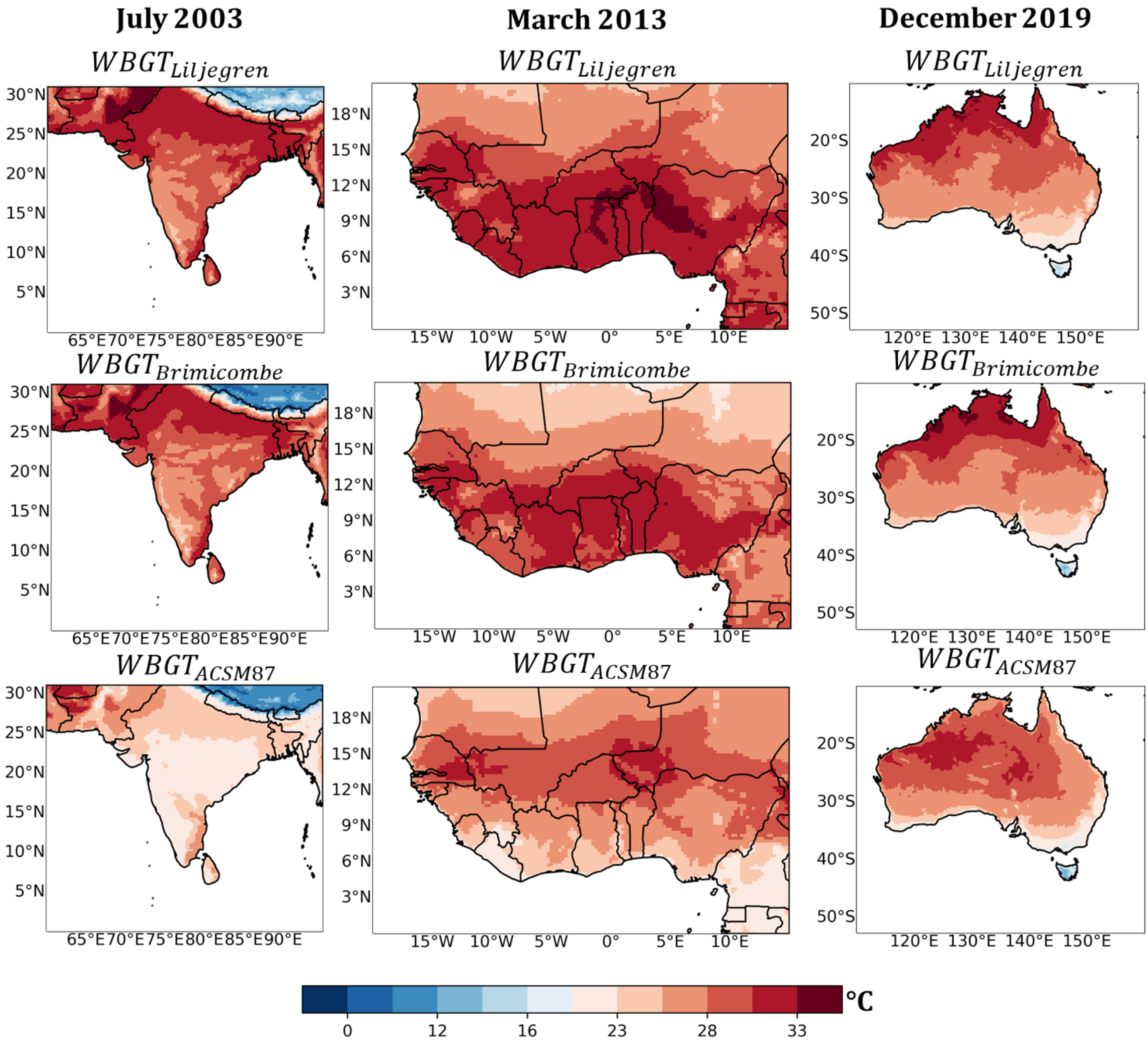


Figure 10.1: Heat stress calculated via $WBGT_{Liljegren}$, $WBGT_{Brimicombe}$ and $WBGT_{ACSM87}$. Monthly mean of daily maximum WBGT heat stress (left to right) for the heatwaves that affected India and Pakistan in July 2003, the Western Sahel in March 2013, and Australia in December 2019. Sea area has been masked.

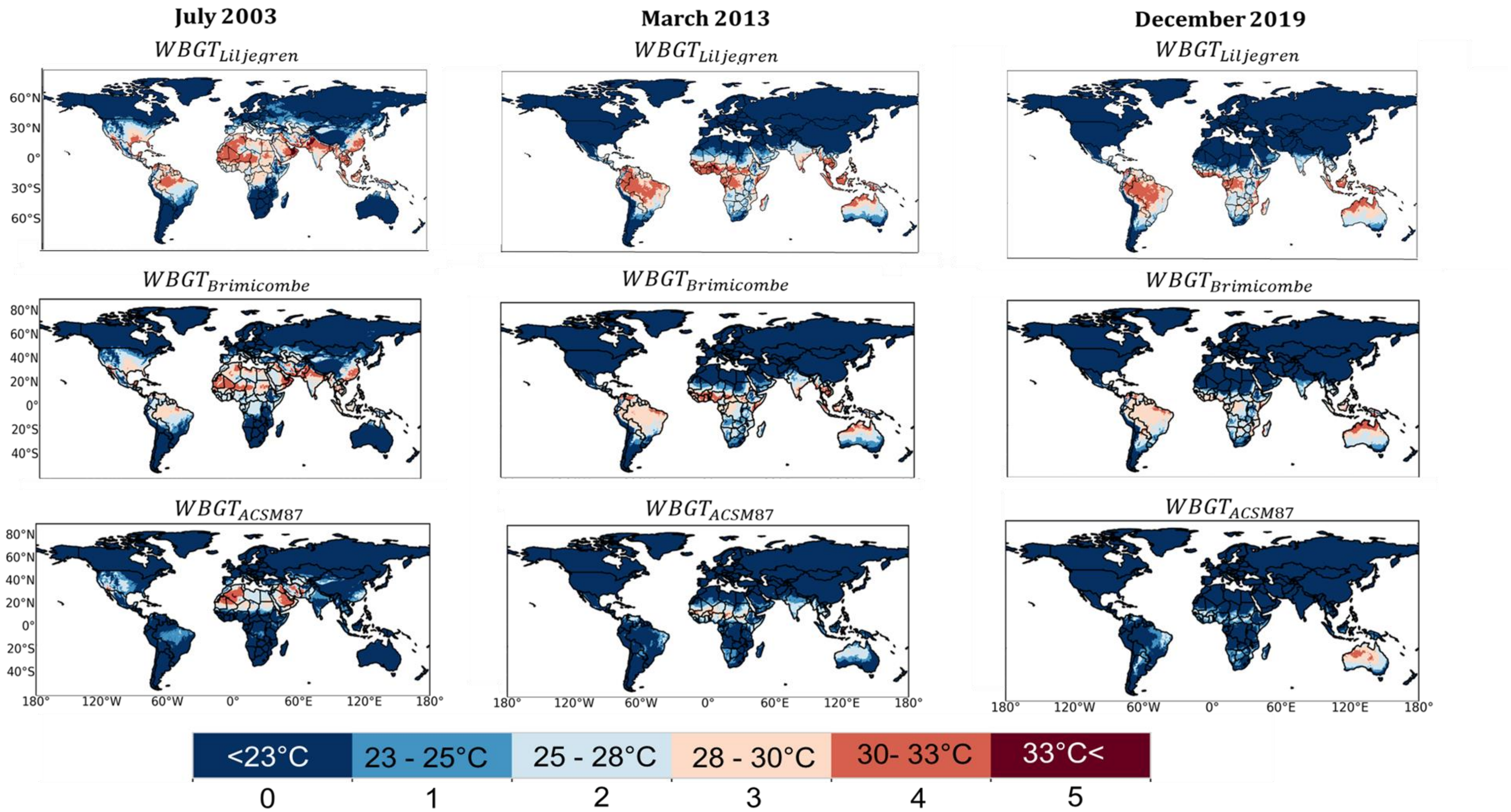


Figure10.2: Categorical heat stress calculated via $WBGT_{Brimicombe}$, $WBGT_{ACSM87}$ and $WBGT_{Liljegren}$. Monthly mean of daily maximum WBGT heat stress (left to right) for the heatwaves of July 2003, March 2013 and December 2019. Categories refer to the different levels of WBGT as indicated in Table 1. Sea area has been masked.

10.3.2 WBGT approximations anomalies

Overall, the anomalies between $\mathrm{WBGT_{Liljegren}}$ and $\mathrm{WBGT_{Brimicombe}}$ are small, with negative anomalies indicating where $\mathrm{WBGT_{Liljegren}}$ has higher values than $\mathrm{WBGT_{Brimicombe}}$, the term anomaly is used to denote deviations of WBGT approximations in comparison to the current gold standard $\mathrm{WBGT_{Liljegren}}$. In July 2003, $\mathrm{WBGT_{Liljegren}}$ has higher values than $\mathrm{WBGT_{Brimicombe}}$ across most of the land surface (Figure 3, left column). In addition, anomalies can be seen to be no more or less than ±2°C, except in Greenland which has anomalies of up to -4°C. In comparison, March 2013 has a similar pattern where anomalies can be seen to not be more or less than ±2°C between $\mathrm{WBGT_{Liljegren}}$ and $\mathrm{WBGT_{Brimicombe}}$ (Figure 10.3, middle column). However, for March 2013, more of the northern hemisphere has anomalies of -4°C, for example in Canada and Siberia colder regions. Fewer regions experience anomalies of -4°C for December 2019, with this only present in the Himalaya into Tibet and the Canadian Rockies regions of higher elevation (Figure 10.3, right column). Overall across each of the three case studies, most of the land surface has anomalies of only ±2°C between $\mathrm{WBGT_{Liljegren}}$ and $\mathrm{WBGT_{Brimicombe}}$.

For $\mathrm{WBGT_{Liljegren}}$ in comparison to $\mathrm{WBGT_{ACSM87}}$ averaging across all years for the southern hemisphere, $\mathrm{WBGT_{Liljegren}}$ have values higher than $\mathrm{WBGT_{ACSM87}}$ by 4°C. In contrast, for the March 2013 and December 2019 heatwaves, the northern hemisphere has anomalies of +4°C. Anomalies are less in the Sahara desert and Australia. For the July 2003 heatwave, anomalies match with those seen in the Southern hemisphere of -4°C.

10.3.3 WBGT approximations correlations

Across both $\mathrm{WBGT_{ACSM87}}$ and $\mathrm{WBGT_{Brimicombe}}$ there is a strong linear correlation to $\mathrm{WBGT_{Liljegren}}$ (Figure 10.4). $\mathrm{WBGT_{Brimicombe}}$ has smaller MAE values across all 3 case studies than $\mathrm{WBGT_{ACSM87}}$, with the smallest value being 0.76°C, being on average smaller for values about the heat stress threshold. $\mathrm{WBGT_{ACSM87}}$ MAE values are large and range between 3.39°C and 5.51°C across the 3 case studies but are significantly smaller above the heat stress threshold ranging from 2.87°C to 3.11°C. $\mathrm{WBGT_{Brimicombe}}$ heat stress values (above 23°C, category 1 onwards) have a stronger linear relationship than across the whole distribution. In comparison, $\mathrm{WBGT_{ACSM87}}$ has a bigger spread in the cluster of points than $\mathrm{WBGT_{Brimicombe}}$ over the whole distribution.

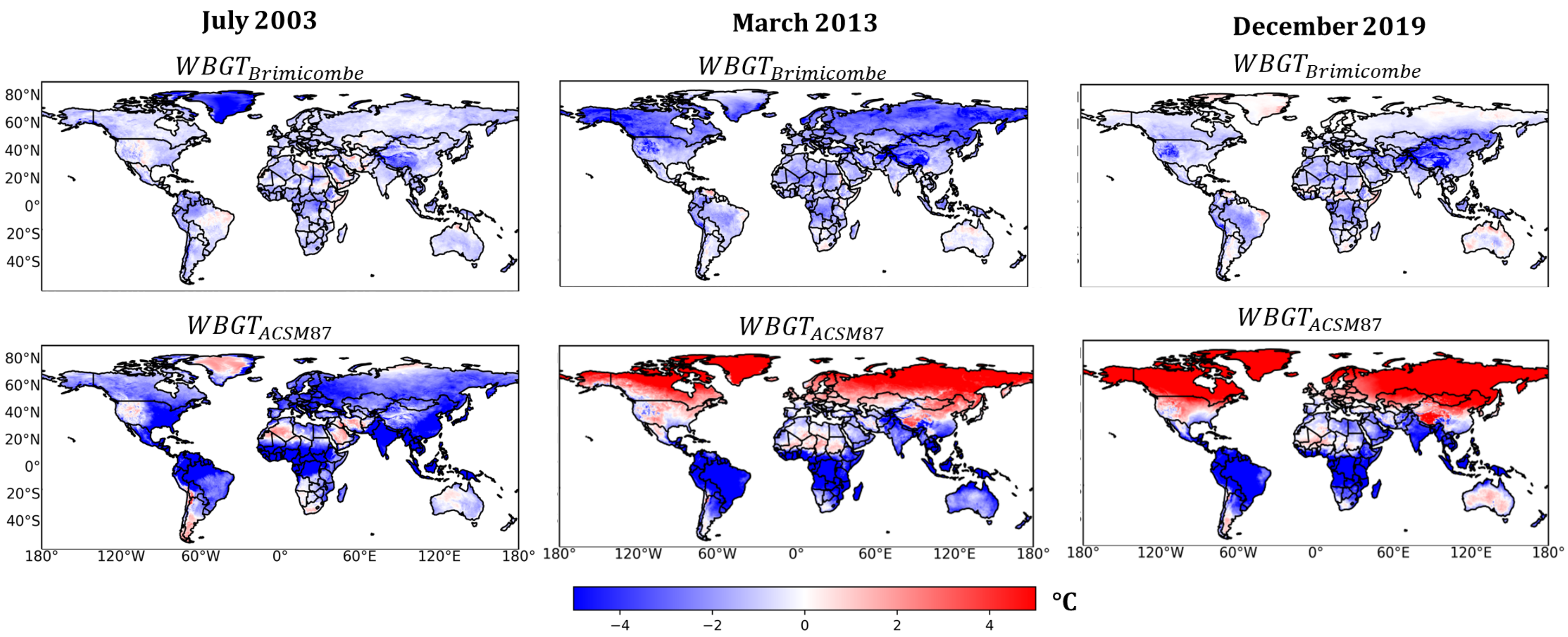


Figure 10.3: The monthly mean of the daily maxima anomalies of $WBGT_{Brimicombe}$ and $WBGT_{ACSM87}$ in comparison to $WBGT_{Liljegren}$ for the 3 heatwaves considered by this study for July 2003, March 2013, and December 2019.Negative values are where $WBGT_{Liljegren}$ has higher values than the other approximations

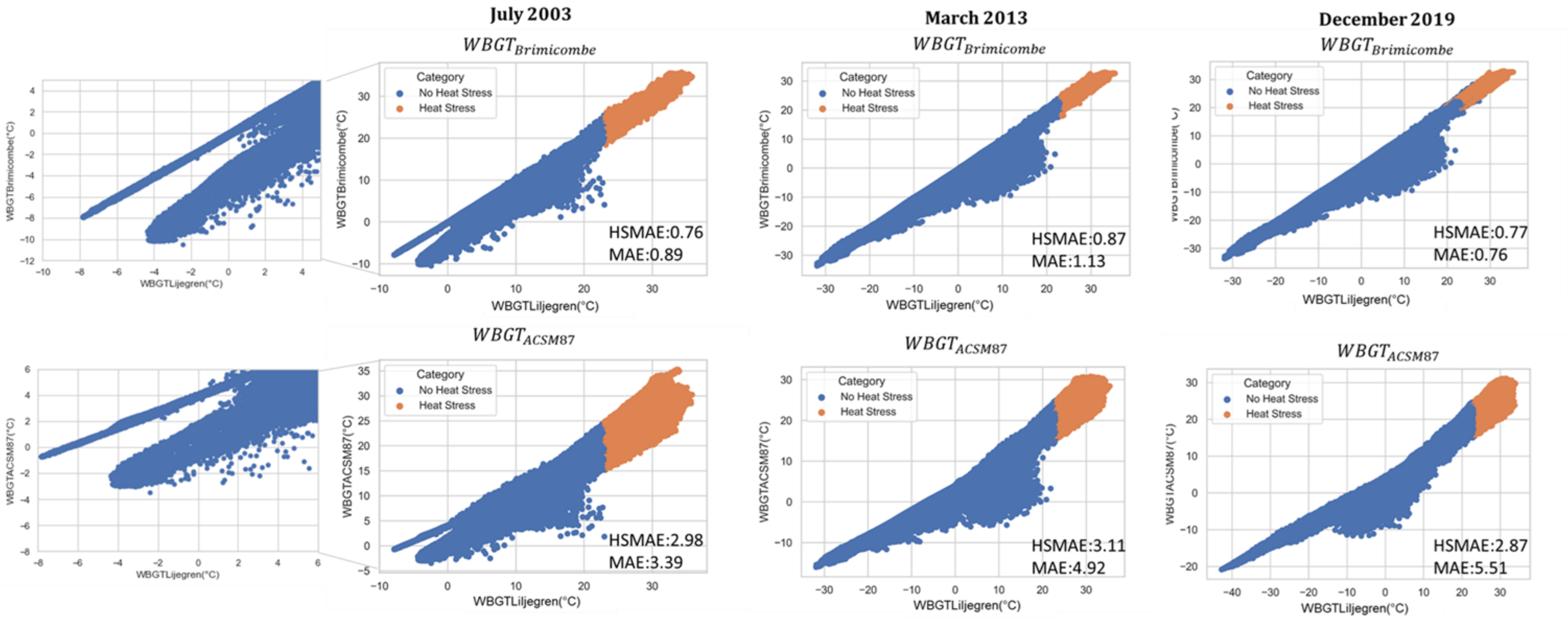


Figure10.4: Global Grid Spatial Domain Correlation plots of $WBGT_{Brimicombe}$ *and* $WBGT_{ACSM87}$ *in comparison to* $WBGT_{Liljegren}$ *(orange indicated heat stress, i.e. WBGT values above 23°C). The mean absolute error (MAE, °C) for all points and just the heat stress points (HS) is indicated in each plot for the 3 heatwaves considered by this study (July 2003, March 2013 and December 2019)*

10.3.4 WBGT approximation differences

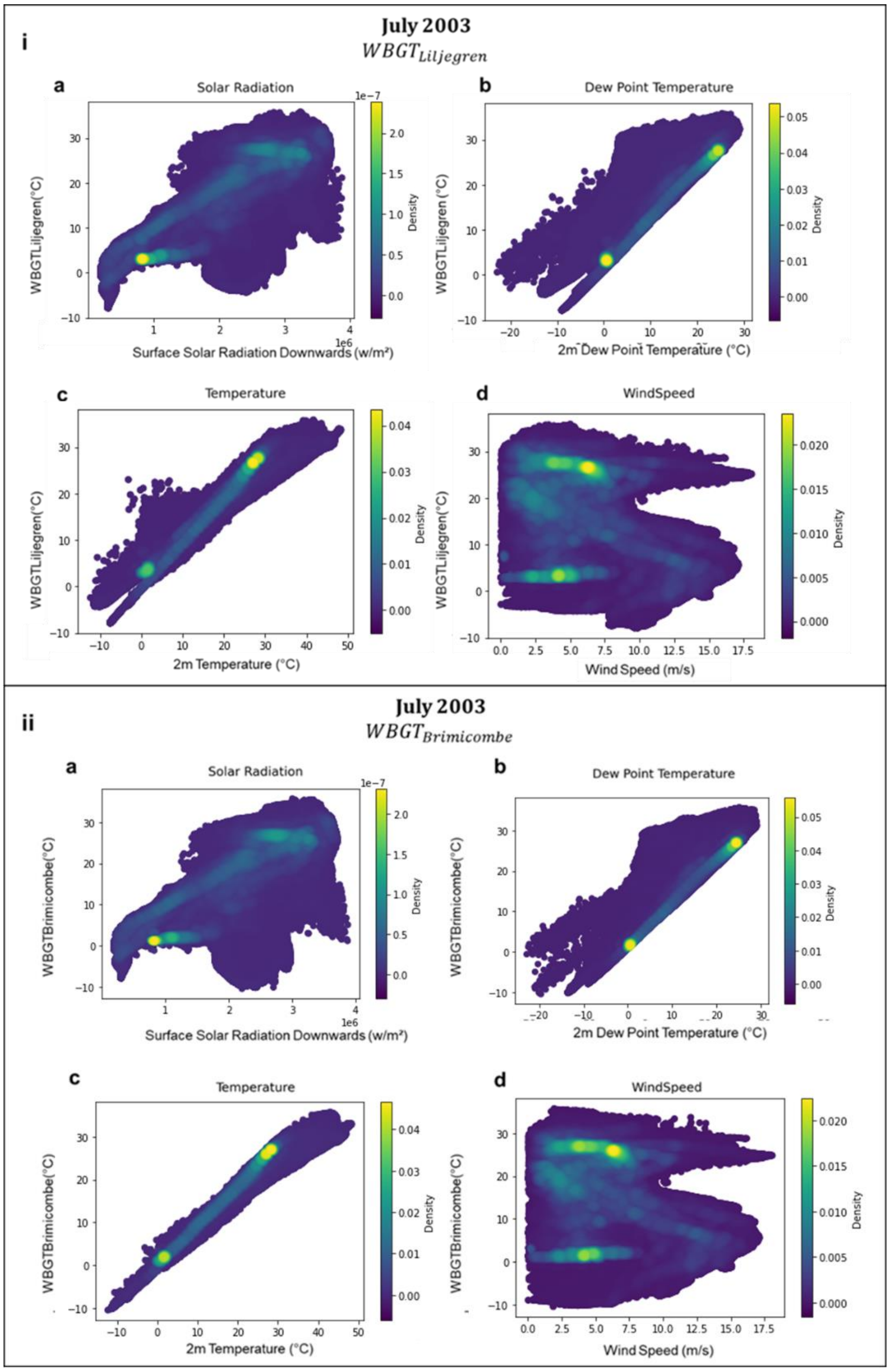


Figure 10.5: Global Grid Spatial Domain of the sensitivity of the output WBGT approximations with input variables for the July 2003 heatwave where i is $WBGT_{Liljegren}$ and ii is $WBGT_{Brimicombe}$ and where a is surface solar radiation downwards (ssrd), b is 2m dew point temperature, c is 2m temperature and d is 10m wind speed. Input variables shown are those that are input to both WBGT approximations. Colour shading denotes density of points. A similar relationship is observed for the other 2 heatwaves (not shown).

It has already been demonstrated that $WBGT_{ACSM87}$ differs significantly from the other WBGT approximations presented. Therefore, here the sensitivity of only $WBGT_{Liljegren}$ and $WBGT_{Brimicombe}$ to key input variables is shown in more depth. Figure 10.5 demonstrates that broadly for both $WBGT_{Liljegren}$ and $WBGT_{Brimicombe}$ high solar radiation, temperature, humidity with low wind speeds lead to the highest WBGT values. In Figure10.5 similarly to Figure 10.4 a bifurcation is seen for 2m temperature (Figure 10.4,i,c) and somewhat for dew point temperature (Figure 10.4,i,b) with the outputted $WBGT_{Liljegren}$. This confirms the trend is due to the $WBGT_{Liljegren}$ Saturation Water Vapour pressure method (Figure 10.4,ii,c). As suggested in section 10.2.4 this discrepancy comes from the difference in the Tw methodology, specifically from how saturation vapor pressure is calculated.

The sensitivity of $WBGT_{Liljegren}$ and $WBGT_{Brimicombe}$ is highly similar for solar radiation and wind speed and can be suggested to provide further evidence that equations 10.2 and 10.6 are comparable. This is despite the potential discrepancies that were suggested in section 10.2.3. This should be explored further to inform more about the inter-dependencies of the different types of radiation. Further we find that WBGT does not have a dynamical response to wind similar to previous findings and this can be suggested to be a limitation of the heat stress index (Foster et al., 2022).

10.3.5 WBGTBrimicombe Observations comparisons

$WBGT_{Brimicombe}$ for reanalysis data performs robustly in comparison to $WBGT_{Liljegren}$ it also performs accurately compared to $WBGT_{Brimicombe}$ observed (Figure 6). $WBGT_{Brimicombe}$ has R^2 values between its ERA5 values and observation values of between 0.56 and 1(Figure 6, b-e). It performs better for the TAT station (Tateno) situated in Japan, where WBGT values are higher than the NYA (Nya Långenäs) station situated in the Artic circle in Svalbard overall. MAE values range from 0.97 to 5.06°C (Figure 6 b-e). The R^2 and error values are comparable with those seen between observed MRT and ERA5 MRT in Di Napoli et al., 2020.

In addition, when evaluating the Stull method in comparison to the Davies-Jones method to calculate wet bulb temperature (WBT) for March 2013 in the observed data small differences are observed (Table 10.2). The biggest MAE value is 1.43°C in WBT for NYA decreasing to 1 in WBGT. The least significant R^2 value is 0.61 for WBT for TAT. It therefore can be suggested that using Stull in comparison to Davies-Jones makes no substantial difference in the resulting WBGT.

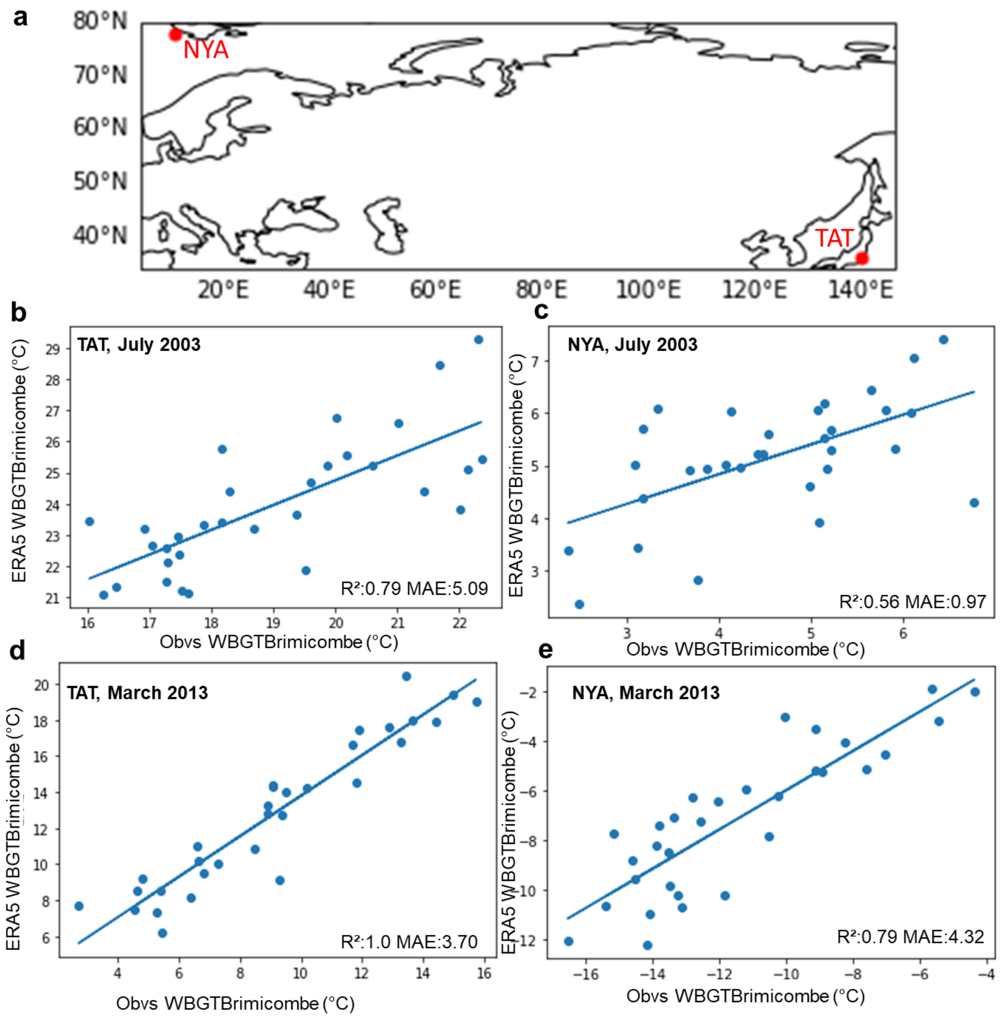


Figure 10.6: a) the location of the observation stations NYA and TAT from the BSRN dataset to calculate observed WBGT using the method in thermofeel termed WBGTBrimicombe. b-e the linear relationship, R2 and MAE values for b) TAT Daily Max July 2003, c) NYA Daily Max July 2003, d) TAT Daily Max March 2013 and e) NYA Daily Max March 2013.

Table10.2: The Mean Absolute Error and R^2 Values between Stull Wet Bulb Temperature and Davies-Jones Wet Bulb Temperature and when they are subsequently used to calculate WBGT for two sets of observations taken during March 2013.

Station	*Wet Bulb Temperature*		*Wet Bulb Globe Temperature*	
	Mean Absolute Error	R^2	Mean Absolute Error	R^2
TAT 2013	0.808	0.611	0.56	0.81
NYA 2013	1.431	0.898	1	0.94

10.4. Discussion

10.4.1 Why another WBGT approximation?

We demonstrate that $\mathrm{WBGT_{Brimicombe}}$ is a useful approximation of WBGT. As discussed in section 10.2.4 and supported by the results in section 10.3.4, $\mathrm{WBGT_{Brimicombe}}$ is a beneficial method to use in the place of $\mathrm{WBGT_{Liljegren}}$ for gridded data sets and numerical weather prediction services. Comparisons between $\mathrm{WBGT_{Brimicombe}}$ and $\mathrm{WBGT_{Liljegren}}$ show only small differences (a difference of 1 heat stress category and a MAE of between 0.76°C and 1.13°C) across the case studies considered. $\mathrm{WBGT_{Brimicombe}}$ reanalysis has at most an MAE value of 5°C in comparison to it being observed (Figure 10.6). $\mathrm{WBGT_{Brimicombe}}$ performs with the least accuracy in cold climates such as Greenland and at higher altitudes such as the Tibetan Plateau, regions that are not highly populated and are cold which is outside the scope of a heat stress index (Figure 10.3). As such, it has been shown with confidence that $\mathrm{WBGT_{Brimicombe}}$ can be considered an accurate approximation of WBGT (Figures 10.1-6).

There are many approaches to calculating the WBGT and these derive from the fact that measurements from globe and wet bulb thermometers are not widely available (Dally et al., 2018; Lemke & Kjellstrom, 2012; Lima et al., 2021; Orlov et al., 2020; Yengoh & Ardö, 2020). Unless measurements come from these instruments and provide all the input parameters required in equation 1, all approaches to calculate the WBGT are approximations, which are wide ranging in accuracy, a wide scale observation study, in terms of both weather and physiological observations. would therefore be beneficial. This research, however, clearly demonstrates that the approximation by the American college of sports medicine, $\mathrm{WBGT_{ACSM87}}$, is not an accurate indication of WBGT and recommends that it is not used for a like-for-like approximation. This finding is in agreement with current literature on the topic (Chen et al., 2019; Grundstein & Cooper, 2018; Kong & Huber, 2021; Lemke & Kjellstrom, 2012; Lima et al., 2021; Orlov et al., 2020; Yengoh & Ardö, 2020).

Previous research has suggested that the approximation by Davies-Jones, (2008) is a more accurate approximation of natural wet bulb temperature than the approximation by Stull (Buzan et al., 2015). However, the results presented here demonstrate the accuracy of the $\mathrm{WBGT_{Brimicombe}}$ results and the similar sensitivity of this approximation using Stull, (2011) in comparison to $\mathrm{WBGT_{Liljegren}}$ and observed calculations of $\mathrm{WBGT_{Brimicombe}}$. Further, for observation data it has been shown by this study that there is no more than a 1°C MAE between a WBGT output using Davies-Jones (2008) in comparison to Stull (2011). In addition, and of particularly practical relevance, the approximation by Stull (2011) is not iterative and therefore easier to use and more readily scalable than the Davies-Jones approximation. $\mathrm{WBGT_{Brimicombe}}$ was developed for gridded datasets from numerical weather prediction datasets and is as accurate as $\mathrm{WBGT_{Liljegren}}$ whilst removing the need for complicated iterative convergence methods that can practically take a long time to run and are not readily designed for gridded data. Given all of this evidence it is unnecessary to assess Davies-Jones further by this study.

10.4.2 How useful are set thresholds for WBGT?

$\mathrm{WBGT_{ACSM87}}$ was found to be significantly lower than $\mathrm{WBGT_{Liljegren}}$ for heat stress categories and overall is not an accurate indication of WBGT heat stress risk (as per Kong & Huber, (2021). This could be of particular disadvantage to the health sector where thresholds are often used to identify life-threatening conditions or to recommend heat-suitable workloads (Budd, 2008; Chen et al., 2019; Jendritzky et al., 2012; Zare et al., 2019).

In this study, it is demonstrated that $\mathrm{WBGT_{Brimicombe}}$ can use the same thresholds to indicate heat stress as $\mathrm{WBGT_{Liljegren}}$ with these being meaningful values for hazard preparedness. The deliberate decision is taken to use heat stress categories for WBGT as set out by Jacklitsch et al., (2016), where the highest value of 33°C has been shown to be a critical level for heat stress illnesses and to correlate with an increase in hospital admissions and mortality (Cheng et al., 2019). Many studies assessing heat stress and extreme heat are now making use of percentiles compared to a climate (Guigma et al., 2020; Heo et al., 2019) or a standard deviation compared to average conditions (Harrington & Otto, 2020). Whilst we acknowledge that heat indexes and their studies, as the present one, often still do not take into account acclimatization and that 26°C will not be experienced the same by someone in the UK in comparison to Australia (Buzan & Huber, 2020; Nazarian & Lee, 2021), we see the categorical approach as fundamental to heat hazard preparedness. We support more research into acclimatization and how to best model this with heat stress thresholds and health outcomes in mind.

10.4.3 The use of WBGT in weather forecasting

The WBGT is widely used across sectors. Our approach to the WBGT has been validated in its component parts, namely in the globe thermometer temperature and the wet bulb thermometer temperature (De Dear, 1987; Guo et al., 2018; Stull, 2011). It has been demonstrated for the first time (section10. 3.4) that the Tg method of $\mathrm{WBGT_{Brimicombe}}$ and

$WBGT_{Liljegren}$ are comparable. Going forward this could be used to inform more about radiation. In addition, it is designed for easy integration into operational weather prediction outputs and for use with gridded datasets, with a view to forecast heat stress and heatwaves on a global scale (Brimicombe *et al* 2022a).

The ISO status of the WBGT makes it stand out as a heat index that is worth forecasting across multiple sectors (Heo et al., 2019). It is important to forecast WBGT to inform decisions about heat stress warnings and adaptations. There are many benefits when forecasts are made openly accessible and many factors to consider(Budd, 2008; Buzan et al., 2015; Lemke & Kjellstrom, 2012). These include: the accuracy of a WBGT approximation in comparison to the ISO observed values used in equation 1; the robustness of thresholds in indicating heat hazards and heat stress risk levels; the appropriateness of WBGT for different climates and acclimatization levels (Ahn et al., 2022; Budd, 2008; D'Ambrosio Alfano et al., 2014). These factors also hold true for other heat indices and should be carefully considered (Ahn et al., 2022; Zare et al., 2019).

10.5. Conclusion

$WBGT_{Brimicombe}$ has been demonstrated to be an accurate approximation of WBGT. $WBGT_{Brimicombe}$ is within 1 heat stress category of $WBGT_{Liljegren}$ across the land surface and in general has anomalies of no more than ±2°C for the 3 heatwave case studies here chosen. In addition, it has a strong positive correlation with $WBGT_{Liljegren}$ and low MAE. In addition, the Tg method for $WBGT_{Brimicombe}$ can be suggested to be equivalent to that of $WBGT_{Liljegren}$ enhancing understanding of the relationship of different forms of radiation. Further, $WBGT_{Brimicombe}$ has a strong linear relationship between it's observed and reanalysis data and at most an MAE of 5°C.

$WBGT_{ACSM87}$ is not an accurate approximation of WBGT and should not be continued to be used. $WBGT_{ACSM87}$ often has a three heat stress category difference to $WBGT_{Liljegren}$ and it widely has anomalies of ±4°C for the three heatwave case studies chosen. Although $WBGT_{ACSM87}$ has a strong positive correlation with $WBGT_{Liljegren}$, it shows high MAE values.

It is hoped that by integrating $WBGT_{Brimicombe}$ into reanalysis, climate models and forecasts, that this information would be made openly accessibly and incorporated into sectors heat warning and adaptations, providing improvements to early warning systems and adaptation policy. Finally, $WBGT_{Brimicombe}$ is a worthy heat stress index candidate for a global forecasting early warning system and would not only be beneficial to a range of sectors but also has the real potential to save lives.

Open Data Section:

ERA5 is freely accessible from [Hersbach et al., 2020]. $WBGT_{Brimicombe}$ and $WBGT_{ACSM87}$ can be calculated using *thermofeel* [Brimicombe et al., 2021,2022] and $WBGT_{Liljegren}$ is available on request from [Kong and Huber 2021].

Brimicombe, Chloe, Di Napoli, Claudia, Quintino, Tiago, Pappenberger, F., Cornforth, R., & Cloke, H. L. (2021). *thermofeel.* https://doi.org/https://doi.org/10.21957/mp6v-fd16

Brimicombe, Chloe, Di Napoli, Claudia, Quintino, Tiago, Pappenberger, Florian, Cornforth, Rosalind, & Cloke, H. L. (2022). thermofeel: a python thermal comfort indices library. *Software X*

Driemel A, Augustine J, Behrens K, Colle S, Cox C, Cuevas-Agulló E, Denn FM, Duprat T, Fukuda M, Grobe H, Haeffelin M, Hodges G, Hyett N, Ijima O, Kallis A, Knap W, Kustov V, Long CN, Longenecker D, Lupi A, Maturilli M, Mimouni M, Ntsangwane L, Ogihara H, Olano X, Olefs M, Omori M, Passamani L, Pereira EB, Schmithüsen H, Schumacher S, Sieger R, Tamlyn J, Vogt R, Vuilleumier L, Xia X, Ohmura A, König-Langlo G (2018) Baseline surface radiation network (BSRN): structure and data description (1992–2017). *Earth Syst Sci Data* 10:1491–1501. https://doi.org/10.5194/essd-10-1491-2018

Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., et al. (2020). The ERA5 Global Reanalysis. *Quarterly Journal of the Royal Meteorological Society*, qj.3803. https://doi.org/10.1002/qj.3803

Kong, Q., & Huber, M. (2021). Explicit calculations of Wet Bulb Globe Temperature compared with approximations and why it matters for labor productivity. https://doi.org/10.1002/ESSOAR.10507637.1

11. Is there a climate change reporting bias? A case study of English language news articles, 2017-2022

Commentary: I carried out this piece of research as a continuation to Chapter 4 and 5, but specifically focusing on the English Language News Media. It was developed to provide evidence that heatwaves were underreported in comparison to other weather hazards by the news media, which there was a lack of evidence for. I used a Google search method instead of ProQuest which is a bespoke search tool for English media articles, in keeping with the open research methodology of this interdisciplinary thesis. In the future, I would like to compare a Google advance search with ProQuest outputs, to justify how big the number of articles found was between the two and compare trends. It had good reception when I originally shared the publication, this is my first single author paper and had another purpose of demonstrating to me that I had the skills to publish and carry out research independently.

This research is published in Geoscience Communications under the reference:
Brimicombe, C. (2022). Is there a climate change reporting bias? A case study of English-language news articles, 2017-2022. *Geoscience Communication*, *5*(3), 281–287. https://doi.org/10.5194/GC-5-281-2022

This chapter is part of component 4 Service Delivery because it provides evidence towards the objective: consider the communication of heat risk and impacts within wider culture by evaluating the communication of heatwaves in comparison to other weather hazards within the English language news media.

Abstract: How weather hazards are communicated by the media is important. Which risks are understood, prioritised, and acted upon, can be influenced by the level of attention they receive. The presented work investigates if the number of weather hazard news articles increased since 2017; which weather hazards receive the most attention in the news articles; and how often climate change was discussed in these news articles in relation to weather hazards. The methods used are advanced Google searches of media articles and the emergency disaster database (EM-DAT) that considered the weather hazards floods, heat waves, wildfires, storms and droughts from 2017 - 2022. Results suggest that storms are more likely to be reported than any other climate risk. But wildfires generate more news articles per event. Bias in reporting needs to be addressed and is important because it can exacerbate un-preparedness.

Plain Text Summary:

Climate change is increasing the risk of weather hazards (i.e. Storms and heat waves). Using open science methods it is shown that there is a bias in weather hazard reporting. Storms have had a large number of articles in the last five years. But, wildfires have a large number of articles per individual occurrence. Science and media collaborations could address the bias and improve reporting.

11.1 Introduction

The Intergovernmental Panel on Climate Change's AR6 report demonstrates that storms, flooding, heat waves, wildfires and droughts have been increasing in intensity and frequency with climate change (IPCC, 2021). Since 2017, there have been a number of notable weather events: Pacific Typhoon season 2018, European floods in 2021, Mediterranean heat wave and wildfires in 2021 (Gao et al., 2020; Kreienkamp et al., 2021; Sjoukje Philip et al., 2021; Sullivan, 2021).

Communication of a risk does not always lead to the risk being understood (Porter and Evans, 2020), however the media is a key actor in communicating climate change and has a moral obligation to highlight the risk of extreme weather and what action is needed(Boykoff and Yulsman, 2013; Kitzinger, 1999).In addition, it has been found that the media gives more attention to sensationalist views on climate change, instead of the consensus view (Meah, 2019; Petersen et al., 2019).

Research demonstrates that the bias in reporting hazards and climate change leads to attention and material resource deficit, not fully recognising or addressing the risk (Brimicombe et al., 2021a; Howarth and Brooks, 2017).In comparison, it has been found that when visual hazards such as floods and storms (Wilby and Vaughan, 2011) are used to demonstrate climate change risk there is an improved understanding of climate risk, also known as objectifying climate change (Höijer, 2010).

Reported here for the first time, this study uses open science principles (Armeni et al. 2021; Nosek et al. 2015) alongside the advanced search tools provided by Google, and the emergency database (EM-DAT) (CRED,2020), to examine how weather hazards are mentioned in news articles, from 2017-22. The aim is to understand: (1) has the number of articles focused on weather hazards increased since 2017; (2) which weather hazards receive the most attention; and (3) how often is climate change discussed in relation to those weather hazards.

11.2 Methods and Data

All the methods and data chosen by this study are in keeping with open data and open science. Open data is where the research results are reproducible and transparent, whilst open science is a term given for removing the barriers for sharing any kind of output (Armeni et al., 2021).

11.2.1 Advanced Google Search

An advanced Google search of the news category was carried out for the period 1st January 2017 to the 1st January 2022. Google was chosen as it has the most comprehensive results in comparison to other search engines (i.e. Bing) and tools that assisted with advanced search. The search involved two stages: first, a search for all news articles in the period containing keywords – flood, heat wave, wildfire, storm and drought, was conducted, and second, this search criterion was repeated with the keywords – climate change(cf. Brimicombe et al., 2021).Each term was assessed to consider whether it captured the most articles, for example using heat wave not heatwave and climate change not climate crisis or global warming. Each hazard was evaluated separately, and their results compared, with duplicated results not included. Articles that mention more than one weather hazard are counted twice.

To counter any overestimates that occur where articles are not discussing a weather hazard but are using the term to describe something else, the approach taken is to look at the first 100 articles headlines and remove articles not discussing a weather hazard, to give a better estimate of the true number of news articles. Examples included articles discussing 'Goal droughts', 'NFL Storm' and 'Glass Animals single heat wave'. Then, this proportion of articles was removed from the overall total, giving a new overall count of articles. For example, for Storms in 2017, the initial search returned 6.31 million articles, but 21 out of the first 100 were not about the weather hazard so 4.98 million articles were counted for Storms.

Limitations of this method do remain it can still capture articles not explicitly about the weather hazard; however, this is limited by the proportional approach taken. In addition, it is only likely to capture the English news media and will give a slightly different number of articles between users. As such it is recommended that further in-depth research should be carried out looking at news media sentiment.

11.2.2 EM-DAT Hazard Reporting

To supplement the findings of the advanced, google search, another source of data is used that is in keeping with open science, the emergency events database (EM-DAT). EM-DAT is the leading international disaster database, it contains details of over 22,000 mass disasters worldwide since 1900 and is compiled from a range of sources including UN agencies and Non-Governmental Organisations (NGOs) (CRED, 2020). This provides an overview of the number of weather hazards that have occurred every year for the last 5 years. This then allows for an assessment on average how many articles have been written about each weather hazard. Figure 1 shows a count of the weather hazards every year from 2017 to 2021 considered by this study included in EM-DAT (CRED, 2020).

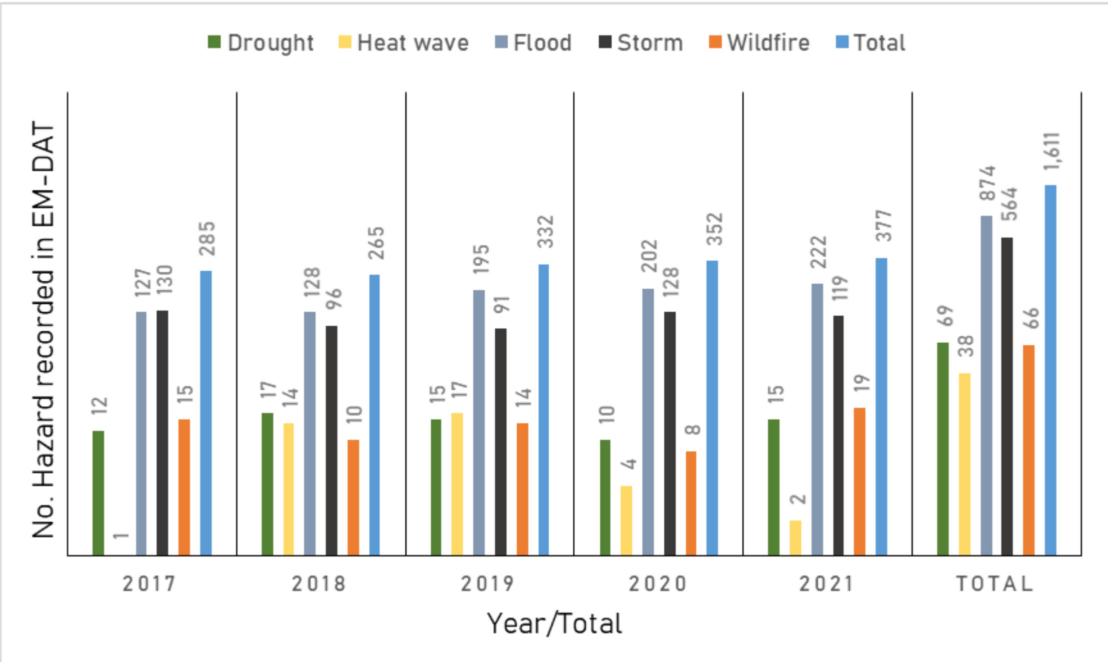


Figure 11.1: Displaying the total number of disaster reported per weather hazard for the last 5 years as reported by EM-DAT (CRED, 2020).

Limitations of this method are that there are biases in how hazards in this database are reported and there is under-reporting of hazards by this database (Brimicombe et al., 2021a; Gall et al., 2009). In addition, this database only includes hazards that are considered a disaster, where an agency declares a state of emergency, or where it is reported that over 100 people have been affected(CRED, 2020). However, it remains the most comprehensive source of reported weather hazards (Brimicombe et al., 2021a; Gall et al., 2009).

11.3 Results

11.3.1 Have the number of weather hazards news article increased since 2017?

There has been an increase in the number of English language news media articles for all weather hazards from 2017 to 2022, amounting to more than 142 million articles over the 5 years. In 2021, 28.1 million articles are about storms, whereas 169,000 articles are about heat waves (Figure 11.2). Of interest, only 0.7% of all news articles mentioned climate change and the weather hazard together. The results for number of articles mirror those for overall news articles written.

11.3.2 Which weather hazards receive the most attention in news articles?

The results in section 11.3.1 change when the number of articles is considered as a proportion of the number of weather hazards reported in EM-DAT in figure 11.1. The approach taken here is to aggregate the totals for the 5 years per hazard to reduce the influence of the under-reporting bias in EM-DAT. Figure 11.3 is another representation of the reporting bias introduced by EM-DAT where total costs for each hazard each year are show, no losses are attributed to heat waves, the results for total damages mirror those for total number of articles written. It can therefore be suggested that articles are more likely to be written for hazards that have the biggest financial loss reported for them.

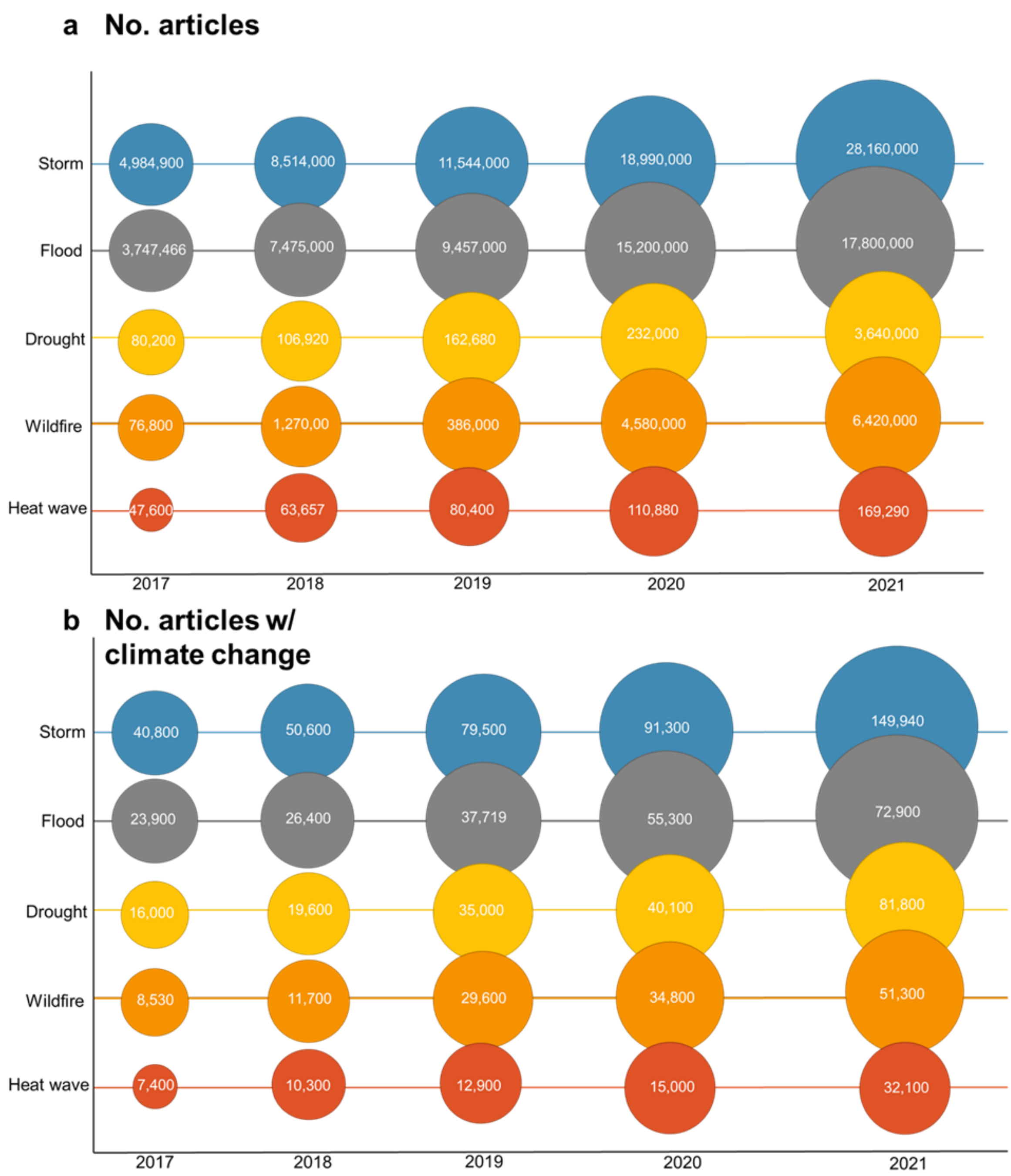


Figure 11.2: number of articles per hazard per year for 2017 to 2022 a) indicates overall article numbers whilst b) indicates only articles that contain the weather hazard and climate change as its subject.

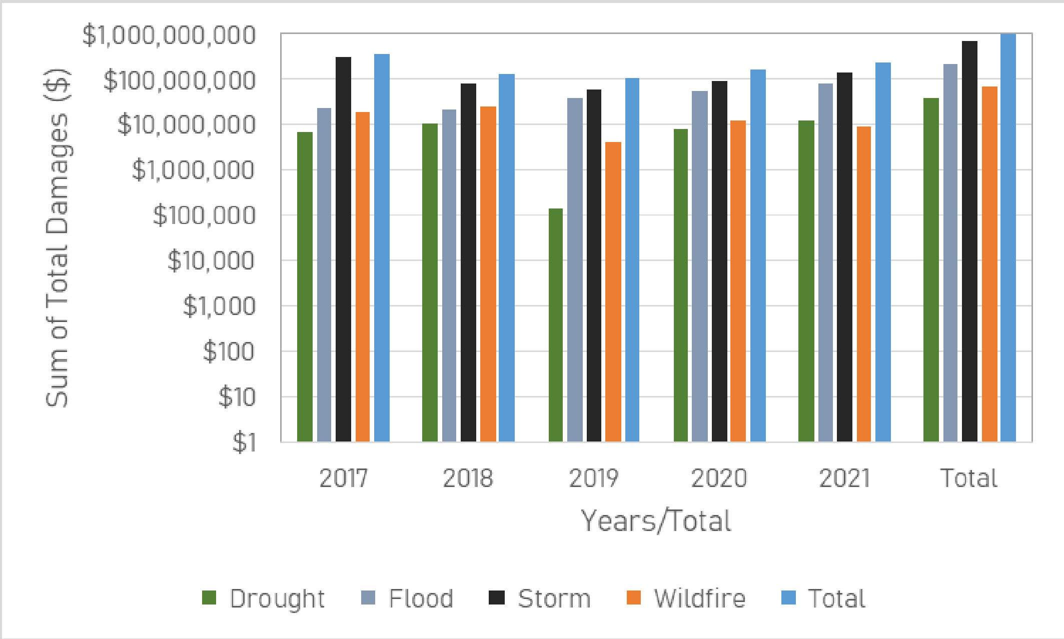


Figure 11.3: Sum of Total Damages for each hazard per year as reported by EM-DAT, heat wave cannot be seen as no damages are recorded (CRED, 2020)

Overall, on average for each individual weather hazard (Total number of articles for all hazards in Figure 11.2/Total number of reported hazards in figure 11.1), 89,000 articles were written, however, the picture for each hazard varies widely, for example one storm can have 10 times more articles written about it than another, and a future study on this would be beneficial. On average per wildfire (total number of articles about wildfire/total number of reported wildfires), there have been in total 175,000 articles written in the last 5 years (Figure 11.4). The weather hazard with on average the least number of articles per weather hazard occurrence over the last 5 years are heat waves with 12,000 articles (Figure 11.4).

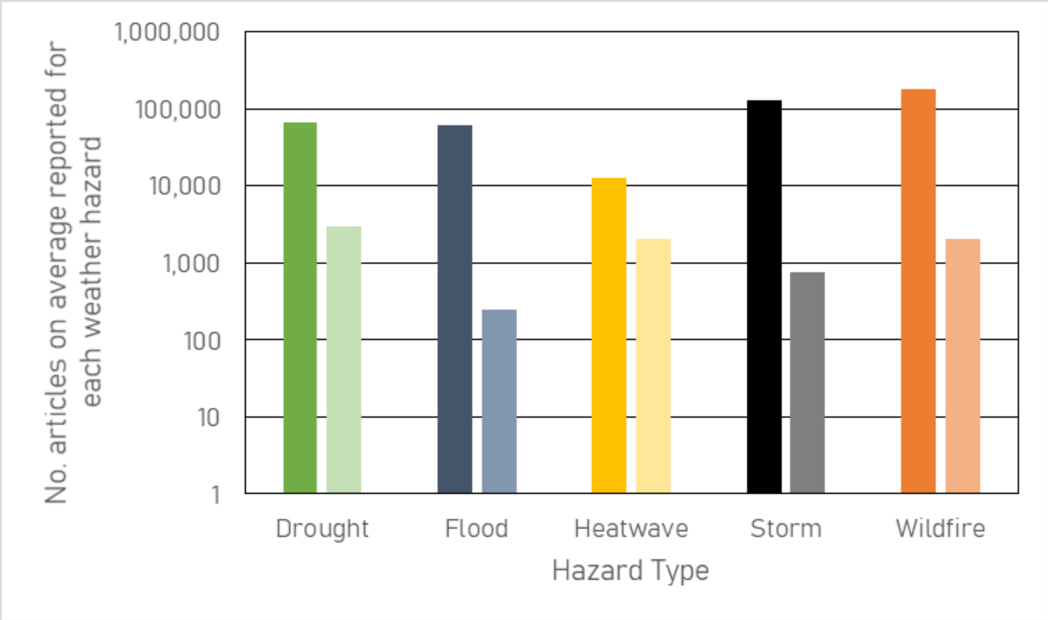


Figure 11.4: The average number of articles per individual hazard category for the last 5 years. Dark colour is total number of articles and light colour is articles including climate change. (Number of articles in figure 11.2a or b/total recorded hazards for each hazard type in figure 11.1)

11.3.3 How often is climate change discussed in these news articles in relation to weather hazards?

Overall, on average for each individual weather hazard, 650 articles were written that also consider climate change (total number of articles including climate change in figure 11.2/total number of hazards reported in figure 11.1). The hazard with the most articles written is drought, on average per drought, there have been 3,000 articles in the last 5 years (Figure 11.4). The weather hazard with on average the least number of articles per weather hazard occurrence over the last 5 years are floods with 200 articles (Figure 11.4).

11.4. Discussion

11.4.1 Why are some hazards discussed by the English Language News media more?

Heat waves have the least amount of news media articles. This should not be of surprise given other research demonstrating the consistent underreporting of this weather hazard (Harrington and Otto, 2020; Vogel et al., 2019). It however, may be of surprise given the number of record-breaking heat waves during recent years such as the June 2021 Pacific North-West heat wave which was attributed to climate change (Sjoukje Philip et al., 2021).

How notable events or weather hazards get attention and are reported is subject to 'newsworthiness', which can also be known as the political economy between society and the media (Boykoff and Yulsman, 2013; Kitzinger, 1999). This is made up of 4 main factors: *the availability effect/heuristic which is if a hazard is presented as risk before it is more likely to be remembered in this manner, stories from impacted groups, geographically bound and are visually impactful* (Kitzinger, 1999; Tomlinson et al., 2011). The results of this study show that the hazards that fit the criteria the most were storms which have the most articles by quantity and wildfires that have the most articles per individual occurrence.

11.4.2 How does the English Language News Media discuss climate change and hazards?

The number of articles on average per individual weather hazard that also considers climate change is not following the 'newsworthiness' criteria and therefore drought, wildfire and heat waves have the most articles. Instead, the media can be suggested to follow the science where it is seen these hazards are easier to attribute to climate change than floods or storms (Ciavarella et al., 2020; Kreienkamp et al., 2021). Whilst the media does have a moral obligation and plays a key role in communicating climate risk, how science, the public and those in position of power communicates climate change has influence on what is portrayed by the media (Boykoff and Yulsman, 2013; van der Hel et al., 2018; Howarth and Anderson, 2019).

Therefore, it could be suggested that this reporting of climate change has come about by the increasing collaboration between science (across career stages) and the media examples include Science Media Centre, The Conversation and Voice of Young Science. This comes in spite of the discourse around the role of science in both communication and policy spaces (Boykoff and Yulsman, 2013; Pielke, 2007).

11.4.3 Why is consistent reporting important?

Attention deficit in the English Language News Media leads to a lack of investment in adaptation for some hazards, making us unprepared. In addition, this pushes us towards more precarious tipping points where adaptation becomes more of a challenge for society (Howarth and Brooks, 2017). This study's results highlight a huge reporting bias in favour of storms and wildfire in the news media. This has a material cost where storms receive more research, funding and policy than other hazards (Brimicombe et al., 2021b; Harrington and Otto, 2020; Howarth and Brooks, 2017; Vogel et al., 2019).

However, despite ranking second in terms of the overall number of articles, per individual occurrence floods have the least number of articles. This could be an indication that there are a bigger range of number of articles written per flood (i.e. one flood has 1 million articles but another only has 1,000 articles) and this is something that should be explored further in a news media sentiment study, with particular focus given to geographical bias.

11.4.4 What does using an open science approach demonstrate?

This study uses advance google search trends to show the bias that is apparent in the English Language News Media surrounding weather hazards and climate change. This is not the most robust method to carry out a study of this kind, however it is the most accessible. For example, long-scale newspaper databases are not free to access.

Using an open science approach highlights the transparency surrounding the reporting bias (Armeni et al., 2021). This is a positive because it means that it is easy to track improvements and changes in reporting. Bias reduces the ability of reporting as a tool to reduce hazard risk and highlighting it is the first step in changing the narrative (Brimicombe, et al., 2021a, b).

11.5 Conclusion

There is a bias in terms of which weather hazards English language news media report on, and a bias in terms of which weather hazards are linked to climate change. This is important because in terms of material cost some hazards have more investment than others. This leads to hazards being subject to under preparedness as a result of underreporting of their impacts. Reporting is a keyway that we can improve communication and plays a part in avoiding societal tipping points. This study suggests greater collaboration between scientists (across career stages) with the English news media is key to improve reporting overall and continue to grow the reporting of the risk of weather hazards and their intrinsic links with climate change.

12. The Portrayal of Extreme Heat in popular culture

Commentary: I carried out this part of my research to understand better why heatwaves might not be a policy prioritization and how improving communication of the risk could reduce extreme heat impacts, taking into account cultural portrayals of heat. I presented this research to my department at the University of Reading as part of our post-graduate research conference, where it was well received. I also consider that it helped to improve understanding of my thesis as a whole to an audience not readily familiar with the area.

This chapter is part of Component 4, Service Delivery, because it provides evidence towards the objective: consider the communication of heat risk and impacts within wider culture by evaluating the way extreme heat is portrayed in popular culture using a cultural theory of risk framing, alongside sentiment analysis. I think understanding this aspect of communication is critical in the wider context of extreme heat policy and service delivery

12.1 Introduction

Visualisation and sight are fundamental to Western Culture (Classen, 1997; Hutmacher, 2019; San Roque et al., 2015; Shao & Goidel, 2016). Through the anthropologies of the senses it is seen that as far back as the philosopher Aristotle, sight was seen as the dominant sense and this further became true when through science acquiring knowledge was attributed to sight, in a 'seeing is believing' manner (Classen, 1997). In addition, across cultures there is a distinct separation of sight from the other senses across linguistics of different languages (San Roque et al., 2015).

It has previously been presented that extreme heat is an invisible risk (Brimicombe, Napoli, et al., 2021; Brimicombe, Porter, et al., 2021). The main way an individual experiences and perceives extreme heat is through thermal sensations which are not visual (Kuht & Farmery, 2021). In addition, the focus of many studies on heat perception highlights how it is not perceived as a risk (Howarth et al., 2019; Hussey & Arku, 2020; Taylor et al., 2014). For example, in the UK under 45's are seen as having a positive view of heatwaves, and the over 65's, a vulnerable group, do not see themselves as vulnerable (Taylor et al., 2014).

Given the predominance of the visual news media in the Global North, this should be exploited as a tool to communicate extreme heat risk (Beck, 2001; Lester & Cottle, 2009).

Indeed, it has been found that viewing a warm or cool colour influences perception of thermal sensations (Wang et al., 2018). In this study, the portrayal of extreme heat in different mediums of popular culture (TV series, documentary and musical) are explored using the cultural theory of risk and sentiment analysis. This will demonstrate to what extent the risk of extreme heat is already portrayed across popular culture.

12.2 Literature Review

It is argued by the eminent sociologist Ulrich Beck in his work on globalisation and 'cosmopolitanism' that as society and cultures have become more cosmopolitan (i.e. where issues of global concern, such as climate change become part of everyday experience and nations live out globalization) sight is cemented as the dominant sense (Beck, 2001). This leads him to suggest that action on climate change will only occur through the visualisation of its catastrophic consequences (Beck, 2010; Lester & Cottle, 2009). Kenis & Lievens, (2015) present a similar concept to Beck's cosmopolitan view in their consideration of the post-political landscape of Climate Change.

Further, studies have demonstrated that the media is a key actor in communicating Climate Change (Boykoff & Yulsman, 2013; Smith et al., 2018; Topp et al., 2019). With a focus on the English news media it is found that as culture maintain, it is subject to how well something is visualised through personalization, dramatization and novelty (Boykoff & Yulsman, 2013; Kitzinger, 1999). For the mainstream television English language media it has been demonstrated that engagement with the issue of climate change is improved through entertainment, as well as, being an important vocal source about issues of climate change, meaning it can be a useful place to explain climate information (Smith et al., 2018; Topp et al., 2019). However, in comparison it is also found that there is a lack of research on the influence of climate change in the mainstream television media on society's climate change perception, and this is attributed to a lack of easily accessible data source of transcripts, which is often problem some to access (Smith et al., 2018).

In contrast, often weather events are used metaphorically within popular culture. From the time of Chaucer terms for heat and hot in the English language have always had a dual meaning (Harris,2015). However, in a paper by Hulme, (2012), it is demonstrated that considering 'heatwaves' in a range of media and from a meteorological perspective reveals important details about perceptions and interactions with the weather that could have otherwise been missed. For example, Hulme, (2012) states:" *It is not possible for numerical descriptions of climate* *to tell us these things nor for models to predict the multiple meanings of a heatwave."* This in addition to the change in the consumption of TV series through streaming services and technology that have helped to fuel the cosmopolitan culture discussed by Beck-where climate change becomes simply a fact of life- suggests the need to evaluate the role of popular culture in heatwave perception (Afilipoaie et al., 2021; Beck, 2001; Lobato & Lotz, 2020).

12.3 Methods

12.3.1 Case Studies

Using a prior approach, a range of case studies from across popular culture was collected, these case studies were chosen as representations of different areas of culture and society, with Netflix shows being chosen for their representation of cosmopolitan culture. This includes popular Netflix shows (*Gilmore Girls, Emily in Paris and Bridgeton*), a musical based in a heatwave (*In the Heights*) and a recent climate change documentary featuring David Attenborough on the BBC, *(Perfect Planet)*. In can be seen that, perceptions of extreme heat and how communication through visuals in the mainstream media could improve adaptive responses can be revealed (Beck, 2001). Using so few case studies can be seen as a limitation of this study and more examples should be used by a future study.

Gilmore Girls is an American Sitcom from the early 2000s which was originally released on the Warner Brothers TV network in the US and then the CW channel. It is now a popular show on Netflix having been revived for a mini-series in 2016 (Brinkema, 2007; Detmering, 2012; Petersen, 2018). It follows multiple generations of the Gilmore family with a focus given to the female characters and is centred on the town of Star Hollows, fictionally set in Connecticut. *Gilmore Girls* given its main storylines has been the subject of much research focusing on its framing and discussion of feminism, the use of cultural references and popular culture throughout its narrative and the heteronormative nature of its featured relationships (Brinkema, 2007; Detmering, 2012; Petersen, 2018).

In 2020 and 2021 nearly 20 years after *Gilmore Girls* first aired, popular culture TV series released on Netflix included *Emily in Paris* and *Bridgeton*. *Emily in Paris* is a comedic drama and was one of the top 10 shows on Netflix in its first week of airing. It follows a girl from Chicago – Emily- who moves to Paris as part of her job for an American based marketing firm (Parc & LaFever, 2021). Previous research has focused on how this show demonstrates linguistic techniques often seen in those who are bilingual (Widowati & Bram, 2021) and the context of Emily in Paris being filmed in Paris in consideration of the European Parliaments act of streaming services (Parc & LaFever, 2021).

Bridgerton was released in spring 2021 and like *Emily in Paris* was in the top 10 on Netflix the week of its release. It became of the most watched series on Netflix of all time (Ostrowski, 2020; Padilla-castillo et al., 2021). *Bridgerton*, based on a book series by Julia Quinn, is a drama series that follows a fictional regency 'ton' and the Bridgerton family as they seek to marry off the sons and daughters. Previous research has explored the success of *Bridgerton* as a series (Ostrowski, 2020) and the portrayal of feminism within the series (Padilla-castillo et al., 2021).

In comparison, *In the Heights* follows a Latino community in the Washington Heights region of New York in a heatwave and has recently been made into a film. Previous research has focused on the marketing success of the musical (Craft, 2011), the way power and race are portrayed (Boffone, 2020) and the contrasts between this musical and Hamilton by the same writer and composer (Sáez, 2018).

As seen previously the media is a key actor in the communication of climate change. Previous research has focused on climate change communication as part of documentary and factual TV series, with the focus on 2006 and 2007 programs commissioned by the BBC in a phase called 'climate chaos' by the organisation. This research found that programs had very different uses of voice to project climate change, and concluded that at a commissioning level academic consultancy should work more closely with producers and programme makers (Smith et al., 2018). A further study discusses the impact of environmental wildlife series on audiences and how the BBC struggles to attract younger audiences. It also suggests that greater collaboration between scientists and the media could improve environmental programming (Aitchison et al., 2021). However, it appears that there are no studies that focus on extreme weather linked to climate change in documentaries and the influence this has on public perception.

The case study that will be the focus here is the BBC documentary series with *David Attenborough, Perfect Planet*. This was chosen as it is the most recent BBC climate documentary series and has transcripts of episodes available from Learning on Screen freely accessible to those in the UK academic sector. *Perfect Planet* has 5 episodes: *Volcanoes, The Sun, Weather, Oceans and Humans* and focuses on showcasing processes that ensure that nature can survive. There are currently no studies focusing on this documentary series. This differs from the other formats of mainstream TV series because the focus of the viewer is on the natural environment images on the screen and the narrator; this is explored partly by Smith et al., (2018) where they discuss who is voicing climate change in TV content.

12.3.2 Cultural Theory of Risk

Whilst Beck's theory of cosmopolitanism promotes the view that visualisation is key in action for climate change, to which extreme heat as a hazard is closely linked, it does not fully address the issue of perceptions (Beck, 2001; Classen, 1997). One way to frame perceptions is through Douglas's Cultural Theory of Risk which is grounded in social anthropology (Douglas, 1966, 2002; Douglas & Wildavsky, 1982). Cultural theory of Risk has 5 categories into which people broadly fit,4 are on a grid-group continuum: Egalitarian, Individualist, Hierarchical and Fatalists (Figure 12.1). The fifth, hermit is someone who does not interact with society and therefore is not found on the grid-group.

I, have selected the Cultural Theory of Risk to frame my analysis as this approach has been used as a framework to explore barriers to climate change adaptation. When used as a tool to frame communication, local barriers can be broken and in turn used to increase adaptive capacity. Case studies focusing on the US, Canada and Tuvalu have demonstrated this (McNeeley & Lazrus, 2014). In addition, it has also been demonstrated in the US that grid-group typology is a more powerful way to explore whether an individual will support climate policy and climate adaptation, than their political stance (Leiserowitz, 2006). Further, it has been found that when policy and communication of climate change is framed to fit the groups of Egalitarian, Individualist, Hierarchical and Fatalist, there is better engagement with adaptation than using one method of communication as shown by Thompson,(2003).

The framework has been mapped onto 'Nature Myths' as defined by Holling, (1986) (Thompson & Rayner, 1998) and onto 'Acting upon Climate Change' (Hulme, 2009, Chapter 6). Using this same approach we can apply the grid-group typology to extreme heat (Table 12.1). This demonstrates that there is a wide range of response as to how extreme heat might be perceived and therefore supports the view that a one-size fits all approach to communicating extreme heat is unlikely to be the most effective. (Thompson, 2003).

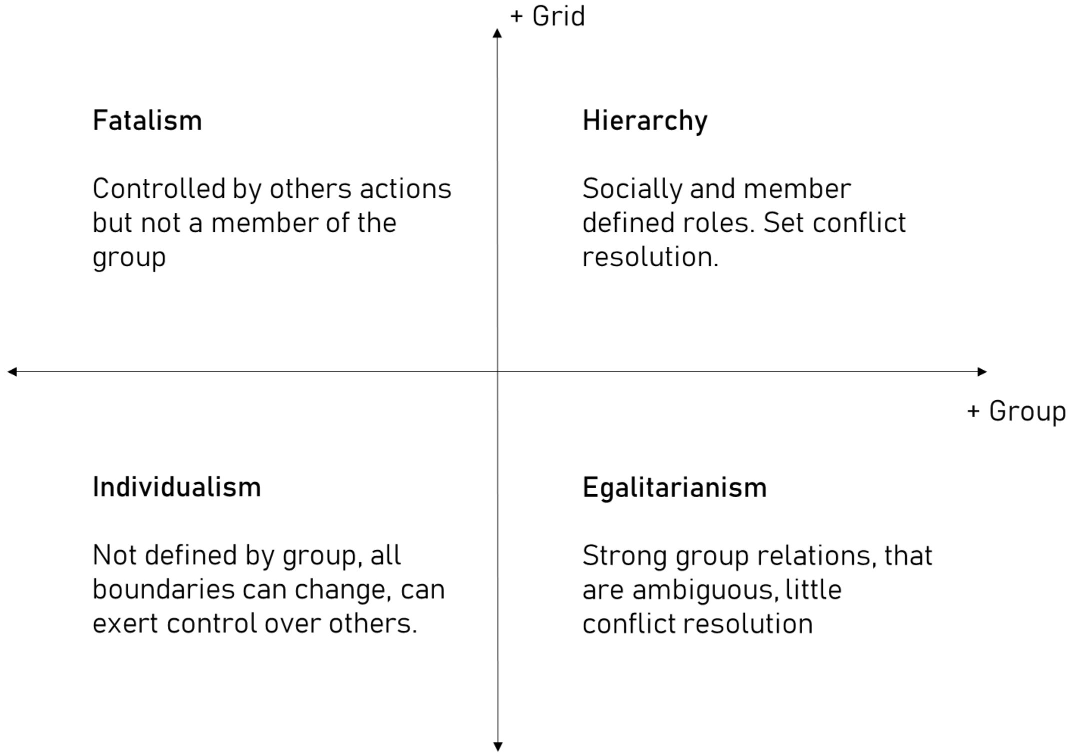


Figure 12.1 an adapted schematic based on Thompson et al., (1990) *to demonstrate the continuum of the 4 different categories from the Cultural Theory of Risk framework.*

Table 12.1: The Grid-Group perceptions applied to the nature myth, climate change and how this applies to extreme heat.

Grid-Group type	Associated Nature Myth (Thompson & Rayner, 1998)	Perceived reaction to climate change (Hulme, 2009, Chapter 6)	Perception to Extreme Heat
Individualist	Nature as Benign, Nature is helpful	'The climate system is favourable to humanity' 'Risks are viewed as manageable'	'Risks to extreme heat are easily manageable'
Egalitarian	Nature as Temporary	'climate system in a precarious state of balance' 'the system could collapse if humanity disturb the balance too much'	'Risks to heat have to be managed with care'
Hierarchist	Nature as Tolerant	'the climate system is to some extent uncontrollable' 'Risks are not trivial,	'Knowledge can address extreme heat risks'

		but with greater knowledge manageable'	
Fatalist	Nature as Capricious, Nature is unpredictable	'the climate system is unpredictable, and controlled by a number of factors' 'Risks associated with it have always and will continue to exist'	'there is nothing that can be done about extreme heat risk'

12.3.2 Transcript analysis

Here, sentiment analysis has been applied to the transcripts of the Netflix series and BBC documentary described in section 12.3.1 using the *NLTK* python library's pre-trained text classifier *VADER* (Kumaresh et al., 2019). This is one of the fastest and simplest sentiment analytic tools (Khozyainov et al., 2013; Kumaresh et al., 2019). The main limitation is the training dataset, is built using social media phrases and therefore most of the analysis focuses in that area. In addition, to the basic analysis, where appropriate a word cloud and word count of weather hazard and climate change keywords is created.

12.4 Results

12.4.1 How are cultural theory of risk grid-groups portrayed in popular culture?

Gilmore Girls genre is a sitcom, and as such weather is often mentioned and featured in episodes, for example a snowman building competition that takes place in Season 2, Episode 10 *"The Bracebridge Dinner"*, and extreme heat is mentioned in Season 3, Episode 2 *"The Haunted Leg"* which originally aired in October 2002. The scene depicts two of the characters Rory (Lorelai) Gilmore and Jess in the local town shop "*Doose's Food Market*" in which they are discussing the summer. Jess is discussing how it was very hot and there was a run on ice creams, when the freezer broken down, with chaotic results .

The significance of this is that a heatwave occurred in the US in the summer of 2001 and a warm spell in April 2002 prior to the release of this episode (Rippey, 2002; Thomas, 2001). In addition, reviewing this scene in the context of the Cultural Theory of Risk reveals that this show, whilst having Individualistic tendencies often in keeping with the overall culture of the US and the West, also demonstrates qualities of Egalitarianism given the description of the scene being chaotic (Thompson, 2003). Egalitarians are the grid-group typology who engage most with climate adaptation and policy (Thompson, 2003). It might be suggested that this is due to the utopian depiction of the town in which this series is set and therefore reflects an idealised view of culture, although as mentioned previously the storylines are often critiqued (Stern, 2012). This demonstrates the ease to which extreme heat can be subtly used in mainstream media storylines.

Whilst *Emily in Paris* mentions weather less than *Gilmore Girls*, in Season 2 Episode 7 *'The Cook, the Thief, Her Ghost and His Lover'* there is a storyline running behind the main story which focuses on a heatwave in Paris. This storyline mainly focuses on a supporting character, Mindy, and her desire to buy a fan. However, they are out of stock in all the shops, and the episode ends with Benoît her love interest, leaving a fan in the flat shared by Emily and Mindy. This behaviour could be seen, like that in *Gilmore Girls* as demonstrating Individualistic typology because Mindy is herself trying to adapt to extreme heat by buying a fan, but when Benoît steps in this indicates Egalitarian tendencies as he supports Mindy to adapt to extreme heat. The feature of a heatwave in Paris is significant mostly because of the impact of the 2003 heatwave on the city, causing the death of around 700 people in the city and more than 14,000 in France (Le Tertre et al., 2006).

In *Bridgerton* more focus is given to weather in Season 2 than in Season 1, with most of the focus on storms and rain, which mirrors the theme of the book on which season 2 is based. In *Bridgerton* Season 2, Episode 4 *'Victory'* there is short scene where one of the characters, Lady Portia Featherington is in a carriage and is seen to grab a fan from her daughter Prudence, as it is too hot. Unlike *Emily in Paris* and *Gilmore Girls* this can be seen as fitting within a Hierarchy typology as Lady Portia is of a higher ranking in the family than Prudence and therefore takes the fan.

The Musical *in the heights* is set during a heatwave very little reference is given to the extreme weather event occurring with the dynamics of the community at the core of the musical, although it builds up to a blackout near the end of the musical, which is not explained to be linked to the heatwave. This musical highlights a number of different grid-group types across the community, with people using fire hydrants to cool down, a more individualistic to egalitarian response because the heat is easy to deal with but this benefits multiple people. In addition to, when a key community figure known as Abuela dies as a result of heat stress featured in the song Alabanza, this is in a way an outcome of a fatalist typology as the older lady does nothing to adapt to the heat and those around her also do not help her.

"The paramedics said that her heart gave out… I mean, that's basically what they said. They said a combination of the stress and the heat…" - (Miranda, 2008, Alabanza)

The documentary series *Perfect Planet* is of a hierarchical grid-group type: there is a single, authoritative main voice, with the 'one to many' use of voice and because this fits well with 'knowledge can address extreme heat risk'. It is important to note that the creative process behind a documentary is different to that of a TV series or a musical. But as previously noted, it is also important to consider a range of media available as part of popular culture- explain why.

All the case studies so far can be argued to be examples of different grid-group type responses to extreme heat. The significance of this for viewers' understanding of extreme heat should be explored further in the future. Each of these case studies could be seen as demonstrating different grid-group engagement with the risk of extreme heat, and whilst not the key storyline in these episodes or musical and can be suggested to be a very effective way to communicate climate adaptation and climate change (Thompson, 2003; Topp et al., 2019).

12.4.2 What is the sentiment of the popular culture case studies?

The overall sentiment for the TV series are compound in nature with a slight skew towards a positive end of the spectrum. *Emily in Paris* and *Bridgerton* are more positive in nature slightly than *Gilmore Girls.* In addition, the findings for *Perfect Planet* are that the most significant tone is neutral; there is however more of a positive stance in the series than negative. These findings show that in the case studies chosen extreme heat is whilst allowing for *'doom and gloom'* narratives to be avoided because they have been shown to be ineffective in prompting climate action or adaptive responses, and is more in-keeping with the fatalism grid-group typology (Thompson, 2003).

Carrying out a sentiment analysis which is a way to assign text to emotions allows whilst using a simple approach of neutral, compound (a mix of emotions), negative and positive, categories is a powerful way to see what the emotive projection of the narrative of a series is (Feldman, 2013). And as shown here this can be useful to assess the extent of fear and fatalism narratives within a popular culture setting.

12.4.3 How does extreme heat feature in comparison to other weather extremes?

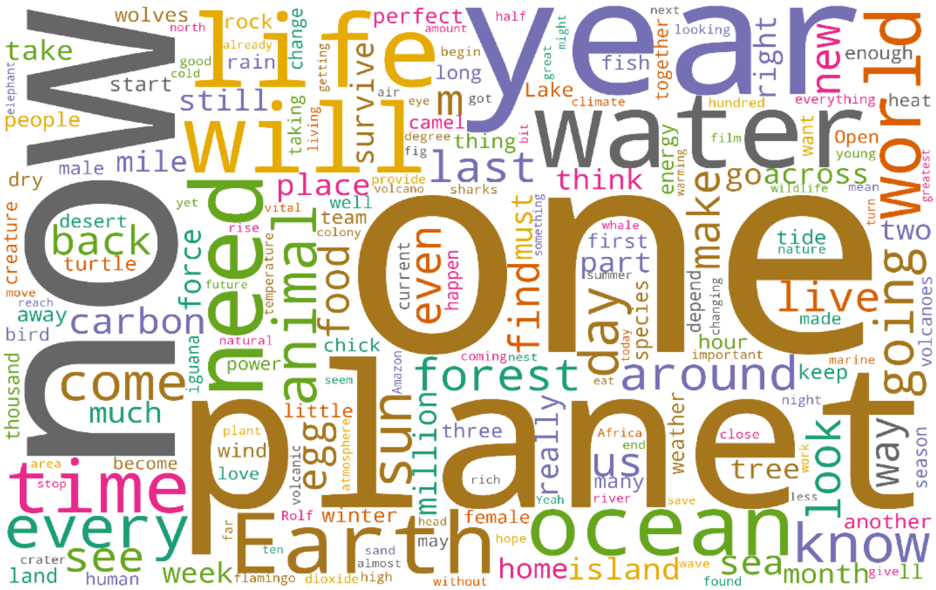


Figure 12.2: Top words used in the BBC Perfect Planet Documentary series.

Using transcripts allows us to assess the language used across the series *Perfect Planet*. The top words can be seen in figure 12.2 as a word cloud. The most common words include *One* and *Planet*, which is another documentary series featuring David Attenborough on Netflix. Other top words include *now*- the series focus is on processes that are happening now and also the need for climate action now and often uses stronger language that in prior series of this nature. Considering a word count of extreme weather increasing with Climate Change (IPCC et al., 2021) Flood* (i.e. Flood, Floods, Flooding) is the most mentioned at 19 times, Storm appears 14 times, Drought 11, Wildfire 1 and Heatwaves do not appear at all. However, heat does appear 26 times – but this is mostly in association with volcanoes or dryland environments. This supports previous research that demonstrates heatwaves are under-reported and this also appears to apply here in this documentary series (Brimicombe, Napoli, et al., 2021; Brimicombe, Porter, et al., 2021).

12.5 Discussion

It is demonstrated that extreme heat already is featured across the mainstream English language media in a number of different of grid-group types described in the Cultural Theory of Risk framework. These are *Gilmore Girls* and *Emily in Paris*: Egalitarian and Individualistic; *Bridgerton*; Hierarchical; and *In the Heights*: Individualistic, Egalitarian and also Fatalist. Whilst there is no evidence that the producers of these shows intended to engage with issues of climate change and extreme heat, the analysis demonstrates the ease with which extreme heat and heatwaves can be incorporated into the entertainment mainstream English language media which has the potential to improve engagement with the risk of extreme heat (Thompson, 2003; Topp et al., 2019). This is important because of the role the media plays in climate communication and that even though heatwaves are not primarily perceived by sight they can be referenced through the mainstream visual media (Beck, 2001; Boykoff & Yulsman, 2013). However, there is no evidence to suggest the mechanisms through which viewing content about extreme heat in mainstream media content changes individual responses and the likelihood of their adopting adaptive behaviours. Further research in this area would be beneficial.

There is also evidence in the mainstream English media that heatwaves are not perceived as a risk where popular culture uses the term 'heatwave' but makes no reference to the hazard or the risk. This supports findings that people in the UK largely do not perceive heat as a risk including in vulnerable groups (Abrahamson et al., 2008; Taylor et al., 2014) .However, perception of heat is also linked to socio-economic status, those with lower socio-economic status often knowing heat is a risk but have a fatalistic attitude because they feel unable to adapt (Guardaro et al., 2022; Shih et al., 2022) .This can be seen as similar to the response shown in the *In the Heights* story (Miranda, 2008). It is unclear the extent to which the mainstream media's failure to acknowledge the risk of heatwaves in their stories is fuelling perceptions; however, research demonstrates those who perceive heat as a risk and have adaptive capacity to respond are more likely to adapt (Adger et al., 2009; Nunfam et al., 2019).

Here it is found that *Perfect Planet* the documentary case study gives less prominence to heatwaves than other weather extremes becoming more likely with our changing climate. Prior research has found under-reporting of heatwaves and their impacts in Meteorological Reports (Brimicombe, Napoli, et al., 2021). Previous research has also suggested that better collaboration between producers, writers and science advisors could improve the communication of climate in the media (Smith et al., 2018), The content of climate change documentaries may also reflect the fields from which documentary advisors are drawn. This issue merits further research. In addition, in order to improve communication, it would also be interesting to explore how documentaries, comparted with mainstream entertainment media content, effect perceptions of extreme heat risk (Smith et al., 2018; Topp et al., 2019).

12.6 Conclusion

The visualisation of heatwaves is taking place in a number of ways that can be analysed through the lens of different grid group types described in cultural theory of risks and is in keeping with Beck's Cosmopolitan Society. *Gilmore Girls* and *Emily in Paris* reflect Egalitarian and Individualistic grid group types, *Bridgerton* Hierarchical and *In the Heights* Individualistic, Egalitarian and also Fatalist. It is however, not clear if this has a positive influence on the likelihood of viewers to adapt to extreme heat and perceive it as a risk. This is something which should be explored further.

Conversely popular culture also uses heatwaves in a way that has no association with the hazard or risk. It is important to research this issue in more detail to establish if this has a negative impact on individual perceptions of extreme heat (i.e. they are less likely to see it as a risk) and address this. And as demonstrated previously, this can also be a lens as to which we expand our understanding of how extreme weather events are perceived.

The finding that the *Perfect Planet* gives less prominence to heatwaves than other extreme weather leads to some suggestions on how this might be avoided in future documentaries, for example through greater collaboration between writers, producers, and academic advisors is needed. It is important that a holistic view of climate change risks are presented in the media since an holistic approach underlines the growing risk of climate change as a whole and contributes more to the media's key role in communicating climate change to the wider public.

13. Towards a global heatwave early warning system

Commentary: This chapter ties together the previous chapters and components of this thesis by providing my vision for a global heatwave early warning system. The strength of this thesis lies in its systems approach, tackling the breadth of key elements that make for a successful early warning system. Without understanding policy, trends, culture, technology, modelling, and communication in an interdisciplinary manner across sectors, I do not think the outcome would be robust and successful in reducing extreme heat risk and impacts. Here, I set out how I envision a successful global early warning system being implemented, what the barriers have been to its creation, and what barriers remain. I do this by building on the literature review presented in chapter 2, section 2.3.4.

This chapter is part of component 4 Service Delivery because it provides evidence towards the objective: consider the communication of heat risk and impacts within wider culture by bringing together all the other components of the thesis and truly presenting how a service might be delivered.

Abstract:

A Global heat early warning system is not yet operational. All other weather hazards and other risks such as food security have an early warning system (EWS) on a global scale. This is despite heatwaves being named the deadliest weather hazard. As well as the growing risk presented by heatwaves in our changing climate, cost-benefit analysis demonstrating economic savings for EWSs for heat and other hazards. Here the history of Early Warning Systems is explored using the paradigms set out by Basher et al., (2006). Then, the barriers to a Global Heat Early Warning system are presented using an integrated early warning systems approach. This shows the complex processes that surround a successful EWS. Finally, a vision of a OneHealth Global Heat Early Warning system is set out, that incorporates the surrounding hazardscape and requires collaboration across multiple disciplines.

13.1 Introduction

There is a mandate for all weather hazards (i.e., storms, floods, droughts, and heatwaves) to have an Early Warning System, for everybody by 2030, as set out by the World Meteorological Organisation at COP27 and as part of the Sendai Risk Reduction Framework(Nations Office for Disaster Risk Reduction, 2015). This is seen as a cost-effective way to adapt to increasing weather impacts because of climate change (Committee on Climate Change, 2020). Early Warning Systems mirror the development of the Disaster Risk Reduction sector, and the paradigm shifts that have been experienced, from disasters being seen as an act of God towards people focused interaction with the natural environment (Alcántara-Ayala & Oliver-Smith, 2019; Wisner et al., 2016).

The first Early Warning System (here after EWSs) is considered to be FEWs, developed in the 1980s to reduce the risk to famine across nations in the horn of Africa (Funk & Verdin, 2010). Since then, EWSs exist on some level for all weather hazards at different scales in nations. It is stated that "*The time is ripe for bold action to implement the globally comprehensive, systematic and people-centred early warning systems for all hazards and all countries"* by Basher et al., (2006).

EWS's exist along a EWS continuum from a linear systemic early warning system where a weather forecasting agency issues a warning to an integrated early warning system which could also be deemed a climate service where cross-sectoral collaboration is employed to issue a warning and put in place adaptations(Basher et al., 2006). At a global scale early warning systems exist for all weather hazards except heatwaves. A global heatwave early warning system is seen as necessary because it can be considered that heatwaves are not bound by geography in the same way as other hazards, it is found that the area and number of people exposed to extreme heat is increasing with climate change (Brimicombe, Napoli, et al., 2021; Rogers et al., 2021; Tuholske et al., 2019).

Heatwaves are currently considered the deadliest weather hazard linked to Climate Change (World Meteorological Organisation, 2013). They have had a mandate to have early warning systems, including at a global scale since 2004, after the European Heatwave in 2003 killed over 50,000 people (Bhattacharya, 2003; WMO & WHO, 2015). Often, heatwaves are considered only under the umbrella of the health sector (Brimicombe, Porter, et al., 2021; Linares et al., 2020), given their impactful nature to human health and therefore not at the forefront of the Disaster Risk Reduction agenda. This is in addition to them not presenting a clear economic cost, one key element and criticism of the Sendai Framework (Alcántara-Ayala & Oliver-Smith, 2019; Kelman & Glantz, 2015; Maini et al., 2017).

This manuscript aims to explore why a global early warning system for heatwaves currently is not operational. It first does this by presenting the history of Early Warning Systems as framed using the Disaster Risk Reduction paradigms. Next, key barriers framed using an integrated early warning systems approach that exist to a global early warning system for heatwaves will be discussed. Finally, a vision for an effective global early warning system for heatwaves will be outlined.

13.2 History of Early Warning Systems

During the course of human history there have been a number of paradigms that have existed for disaster risk reduction, the production of knowledge and early warning systems, here the history of early warning systems is briefly outlined using the framing provided in Basher *et al.,* (2006), with reference to the wider disaster risk reduction landscape made. It can be suggested that this fit best with the western world, however lessons for everyone can also be learnt and applied globally.

1. Pre-science early warning systems: In the era prior to scientific understanding societies and cultures understood disasters and risk through stories past down as myths (Basher & Ono, 2022). This is also sometimes tied to an extreme fatalist view of the world where disasters are seen as an act of divine beings, instead of the interactions of nature with human society (Schipper, 2010).

2. Ad hoc science-based early warning systems: These are signals from nature that were understood by societies to indicate a certain hazard was about to occur. For example, frogs are suggested to leave an area prior to a volcanic eruption, or the idea that cows lie down before it rains (Atkins, 2009; Spear et al., 2012) . Pre-science and ad hoc science fit within the paradigm of understanding disasters prior to the Lisbon Earthquake of 1755, which is attributed to being the first 'modern' disaster with an emergency response(Chester, 2001).

3. Systematic end-to-end early warning systems: It can be argued that most operational early warning systems in place now are still systematic end-to-end early warning systems. Where forecasts are issued and then sectors are expected to issue warnings(Alcántara-Ayala & Oliver-Smith, 2019). This fits within the Disaster Risk

Reduction paradigms that exist for resilience and sustainability, the idea of community and political economy that developed from the 1980s to the 1990s (van Aalst et al., 2008; Adger, 2000; Gallopín, 2006; Neumayer et al., 2014).

4. Integrated Early Warning System: are a participatory approach to disaster risk reduction, where there is collaboration across sectors on warnings and what resources and infrastructure is needed to dissemination and put in place preparedness(Mapfumo et al., 2013; Neumayer et al., 2014). Integrated Early warning systems should acknowledge people's interaction within the environment, including adaptive capacity and their stories as a key element to reducing risk through an early warning system (Alcántara-Ayala & Oliver-Smith, 2019; Hillbruner & Moloney, 2012). These systems fit within the move in the humanitarian sector towards anticipatory action (Coughlan de Perez et al., 2022). Integrated Early Warning Systems have 4 main elements as outlined in figure 13.1: *Risk Knowledge, Response Capability, Monitoring and Warning and Dissemination and Communication.*

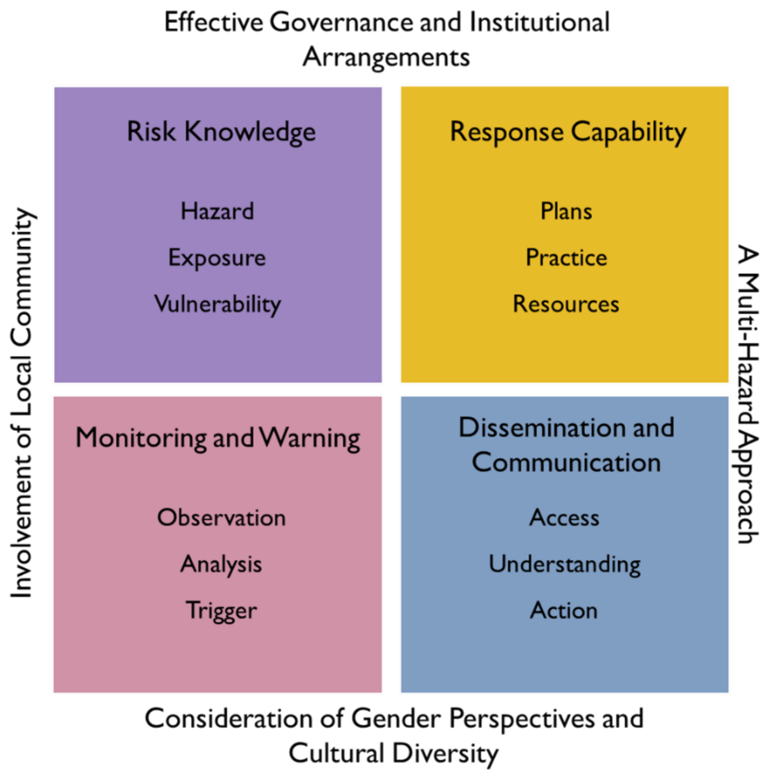


Figure 13.1: The Current Paradigm of Early Warning Systems as set out by Climate Risk and Early Warning Systems. Adapted from (Practical Action, 2020)

13.3 What are the barriers to a Global Heat Early Warning System?

Framing a global heat early warning system in terms of the current integrated early warning system paradigm, allows for key barriers to an effective system being implemented operationally to be revealed.

Risk Knowledge

For the hazard of a heatwave there is not a global definition and individual countries have different definitions. Therefore, from the outset there is a difference in what the hazard of a heatwave means, and this is intrisincally linked to exposure. There is a draft global definition proposed by the World Meteorological Organisation (WMO), where they state a heatwave is *"A period of marked unusual hot weather (maximum, minimum and daily average temperature) over a region persisting at least three consecutive days during the warm period of the year based on local (station-based) climatological conditions, with thermal conditions recorded above given thresholds."*(World Meteorological Organization, 2018, p. 4) .

There are also differences in the indices being used to demonstrate exposure to heatwaves and/or heat stress (Ioannou et al., 2022). Studies that compare different definitions of heatwaves find that there are tanginable differences in impacts often between definitions of heatwaves (i.e. Ilango et al., 2020), and there is also a difference in the understanding of risk level presented between heat indices (Emerton et al., 2022). Defining a heatwaves is a barrier to early warning systems because there is cultural and organisational differences in the understanding of what a heatwave is and this presents a challenge for tracking changing impacts of heatwaves across nations. In addition, it makes it difficult to assess the effectiveness of an early warning system and building capacity to adapt to this extreme, in a way that is equitable.

In addition, it is important to consider vulnerability, often within early warning systems and disaster risk reduction it is simplified to a static problem (Alcántara-Ayala & Oliver-Smith, 2019; Gallopín, 2006). Anybody can be vulnerable to a hazard at different times within their lives. However, vulnerability also has cross-sectional meanings for example, resilient building so that overheating is reduced, in comparison to keeping people cool in the face of a heatwave (Brimicombe, Porter, et al., 2021).

Monitoring and Warning

Previous research presents that heatwave impacts are under-reported in official meteorological reports and EM-DAT the emergency events disaster database (Brimicombe, Napoli, et al., 2021). There is a lack of long-term data recording heatwaves, the duration they occur for, the intensity and the impacts that occur alongside this for most of the globe except the US, who keep a record of when a heatwave warning is issued. This is yet another symptom of the silo of heat to the health sector.

For accurate warnings to be made on a technical basis, observations are a very important part of numerical weather prediction services. With a move towards more complex heat stress and thermal comfort indices now being explored more often (Vanos et al., 2020), there is a lack of especially radiation observations to ensure robust and accuracy within numerical prediction and weather forecasting (Ahn et al., 2022; Budd, 2008; Grundstein & Cooper, 2018; Kong & Huber, 2021; Vanos et al., 2021). In addition, a trigger is needed where there is a difference between what the trigger for a heatwave might be, with thresholds, percentiles and standard deviations all seen in literature and this should be explored further with EWSs in mind (Guigma et al., 2020; Perkins, 2015; Sambou et al., 2019).

Response Capacity

Heatwaves are historically siloed to the health sector (Brimicombe, Porter, et al., 2021). It is well documented in literature that those that work on the frontline of the health sector, do not have climate change education as part of their training. In addition, the perception of risk of climate change and heat is often sparse within the sector (Hussey & Arku, 2019, 2020). This presents a key challenge for a sector charged with adapting to the risk of heat and pushing for heatwave early warning systems including on a global scale. The resources and understanding are limited for effective measures to be implemented. There is also a lack of policy and legislation to support a global early warning system, heatwaves are an invisible risk within international climate policy (Brimicombe, Napoli, et al., 2021; Brimicombe, Porter, et al., 2021).

Dissemination and Communication

Effective communication is a keystone of a successful EWS. Heatwaves are under-reported in the English Language media in comparison to other weather hazards (Brimicombe, 2022). This presents a challenge where society doesn’t consider heatwaves a risk (O’Neill et al., 2022). For the UK, younger people have a positive bias associated with extreme heat making them more likely to report heat related illnesses and not effectively adapt to extreme heat (Williams et al., 2019). In addition, older people in the UK not seeing themselves as vulnerable, hinders their likelihood to adapt to extreme heat (Wolf et al., 2010). A recent study in Germany found that heat action was most effective if a warning was accompanied with a type of adapatation suggestion (Heidenreich et al., 2021), more research of this type is needed to understand how to improve effective communication in EWSs.

13.4 A vision for effective Global Heat Early Warnings

The main barrier to a Global Heat Early Warning system appears to be a lack of consensus between sectors on the best approach to move forward together and the equitable sharing of resources, alongside key factors to its success such as defining a heatwave, vulnerability, resources, and dissemination. New visions of a Global Heat Early Warning Systems do exist within literature for example, by Li et al., (2022) which is framed as a heat-health early warning system, again siloing the health sector with leading Early Warnings for heatwaves. Instead, the vision presented here in figure 13.2 at the onset demonstrates the need for the World Meteorological Organisation to integrate heat alongside other weather hazards and lead in closer collaboration with the World Health Organisation, perhaps through the successful joint office, who run the Global Heat Health Hazard Network. The WMO have more resources to forecast heatwaves and issue weather related warnings through their network of meteorological offices than the WHO.

It is also, important to acknowledge the overall hazardscape, the acknowledgement that hazards do not exist alone but intersect with each other and society (Alcántara-Ayala & Oliver-Smith, 2019; Khan, 2012). The only way to effectively consider a hazardscape is for one organisation to lead on Multi-hazard Early Warning Systems, but by participating across sectors, as is seen with FEWs, however successful EWSs only are effective with supporting adaptation and resilient infrastructure (Brimicombe, Napoli, et al., 2021; Funk & Verdin, 2010; Hillbruner & Moloney, 2012).

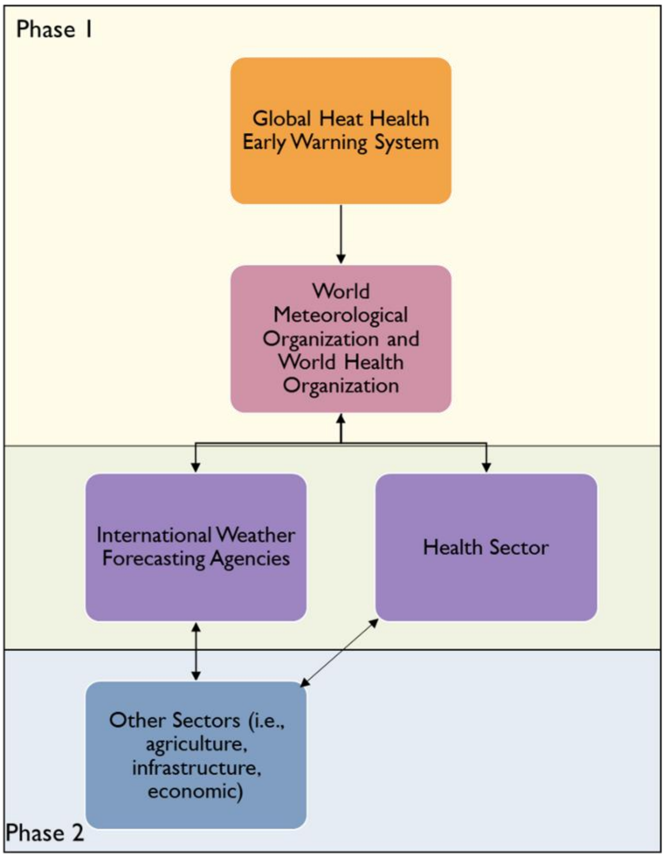


Figure 13.2 a schematic of a Global Heat Health Early Warning system, phase 1 involves close collaboration between international weather agencies and the health sector. Before a move under the OneHealth framing to integrating other sectors under a heat 'health' multi-sector early warning system.

Many countries have operational heat health early warning systems or heatwave early warning systems (Casanueva et al., 2019). The proposal would be to start out by forecasting multiple heat stress indices, that are present in these country scale EWS's (Brimicombe et al., 2022) at a global scale alongside key heat metrics as set out by Perkins & Alexander, (2013) and any heat health indicators that are part of the Lancet Countdown for climate change and health (Romanello et al., 2022). The next step should be to bring in other sectors alongside health and meteorology as part of a OneHealth approach to Heatwave early warning systems (Mackenzie & Jeggo, 2019).

A OneHealth approach is useful for heatwaves because it allows for the acknowledgement of the severe health impacts that this hazard causes, it also allows for an appreciation of the cross-sectional risk of heatwaves within the overall hazardscape in our changing climate. This would mean heat is no longer siloed and provides capacity to other sectors to adapt to this risk, in keeping with an integrated early warning system approach (Basher et al., 2006). This

OneHealth approach should mirror and bring in more disciplinaries in a similar way to that presented for the Lancet Countdown Working Group 1 (Di Napoli et al., 2022).

13.5 Conclusions

There are many barriers that have prevented an operational global heatwave early warning system from being put in place. Historically heatwaves have not been within the remit of disaster risk reduction or meteorological agencies, being siloed to the health sector. A global-scale early warning system is necessary to counter the borderless nature of heat hazards. In addition, a move from systematic early warning systems to an integrated, multi-hazard early warning systems approach would better fit the complex multi-sector nature of heatwaves.

Therefore, the time is now for a global heatwave early warning system. It is outlined here that in phase one this should build upon country level EWSs and be a collaboration between the World Meteorological and World Health Organisations. Next, in phase two using a OneHealth framing and consideration of a wider hazardscape, other sectors should begin to collaborate.

Key barriers that are still present but can be addressed as part of an operational global early warning system, these include which metrics, indices, and health indicators could be given priority within the system. Also, what should the trigger threshold for a heatwave be and how can this be meaningful at different scales and across sectors. As well as understanding the best approach to warning communications and how these fits within the wider hazardscapes and societal landscape. Finally, it is important to state that effective early warning systems are only able to exist with robust infrastructure, policy and adaptation measures. These should be part of a systems approach to tackling climate change alongside EWSs.

14. Discussion

This thesis has investigated the impact of extreme heat and policy measures and explored the development of a global heat hazard early warning system. This chapter discusses the evidence that answers the research objectives as framed using the WHO components presented in chapter 1 (WHO, 2015). It also highlights the original contributions and limitations of the thesis, as well as, suggesting future directions for research.

14.1 Research Components and Objectives

14.1.1 Mobilization and Governance: *Assess policy prioritization and governance*

The results from this thesis demonstrate that heat stress is borderless, covering a large proportion of the total land mass during an August heatwave (Chapter 4). In addition, during a heatwave the population exposed to the risk of heat stress is increasing and as such populations are experiencing a rise in baseline levels of mortality and morbidity more often during August. Moreover, with an increase in nations with an aging population this risk is greater, as those over 65 are especially vulnerable to heat illnesses and mortality (Arbuthnott & Hajat, 2017; Chambers, 2020; Kovats & Hajat, 2008; WMO & WHO, 2015). Also, this study shows for the first time with a focus on notable August heatwaves and the Northern Hemisphere that heat stress is growing in area and is larger during the month of August. It also demonstrates how heatwaves are borderless not constrained by political boundaries and that impacts are not adequately reported - a deficiency in risk reporting.

Chapter 5 of this thesis shows that on a national scale for the UK, outside of a select few policy domains, heatwaves remain an 'invisible risk' in the UK. However, a growing body of literature is seeking to change this by broadening the scope of research into other at-risk sectors. The grey literature may offer a template for the research community to follow here. In addition, it was found vulnerability was a central theme throughout the reviewed papers. Heatwaves events served to reveal where social inequalities exist in the capacity of people, buildings/infrastructure, and sectors to respond effectively. Yet it is important to remember that vulnerability is not static but dynamic. Different studies, and different sectors, conceptualised and enacted the discourse on vulnerability differently.

In addition, to date, the vast majority of the research into building overheating has focused on homes. Despite research suggesting that up to 20% of homes currently experience overheating problems during an average UK summer, new houses built in line with Government housing plans do not have to factor overheating into their designs (Peacock et al., 2010; Wilson and Barton, 2018). Further, at a national level in the UK it is found that not only is there a discrepancy in the amount of heatwave research conducted in different regions of the UK but this discrepancy is also mirrored in the formulation and/or implementation of official Government policies and plans (Khare et al., 2015). Despite the UK's latest climate projections showing that heatwaves will increase in frequency, severity and duration across all UK regions, the level of research and policy development does not follow these concerns. No research met our criteria for heatwaves policy and management in Northern Ireland. This is concerning because without an evidential base for policy at best the urgency of the problem will remain low and at worst it will remain an 'invisible risk'. It therefore can be concluded that heatwaves at an international level remain for the moment an 'invisible, borderless risk'.

14.1.2 Health Information Systems: *Evaluate the trends and modelling for extreme heat*

In this thesis, when focusing on the continent of Africa (Chapter 10.1), a region that is of particular concern because of limitations to adaptive capacity (Adger et al., 2009; Russo et al., 2016), both indicators of heat stress (above 32°C and above the 90th Percentile) significantly demonstrate that a larger proportion of both the populated and land area of Africa is being exposed to more intense values of heat stress for longer in 2019 than in 2000. However, there are differences in the level of significance and the characteristics of trends for area exposed and the duration of heat stress between heat stress indicators (Zare et al., 2019). In addition, for the heatwave case studies of South Africa 2015/16 and Morocco July/August 2000, it can be suggested that, drivers of heatwaves are closely linked to the arrival of synoptic systems as well as the large-scale shifts in the background environment (e.g. El Nino events) for both of the heatwave examples (Hu et al., 2019; Russo et al., 2016, Meque, et al., 2022). It is shown in a study by Meque, et al., (2022), that different modes of El Nino lead to an intensification and probability of heatwaves occurring in the Southern region of Africa. Synoptic systems are prominent for the Moroccan heatwave with changes in the placement of the Libyan High Pressure present, due to the migration and development of Hurricane

Alberto as it travels from the Ethiopian highlands to the Atlantic Ocean, having an influencing factor on the direction of the Harmattan winds and therefore advection in the region (Filahi et al., 2015; Lavaysse et al., 2016).

In addition, this thesis presents the necessary research evidence and developments that will support the implementation of the first global heat hazard alert system, now already in pre-operations and testing at ECMWF (Chapter 7). We anticipate *thermofeel* will have a large impact on the research of heat stress, heatwaves and thermal comfort as a whole. We also expect this library to be easily extendable by the research and operational weather forecast communities, as well as those in the humanitarian sector. The library has also the potential to be commercialised and applied to the growing area of climate services (Cullmann et al., 2020; Hewitt et al., 2012) through the development of a mobile app for health services. With the right preparedness measures and communication *thermofeel* methods could save lives and build heat resilience (WMO & WHO, 2015).

14.1.3 Essential Technologies: *Develop new technologies to reduce risk to heat*

This thesis explored the difference between existing operational ERA5-HEAT code and new *thermofeel* methodologies for the UTCI (Chapter 8). It was found that there is a substantial difference between the new Gauss-Legendre integrated cossza developed as part of *thermofeel* to calculate MRT and UTCI in comparison to the operational c code currently creating the ERA5-HEAT dataset (Di Napoli et al., 2021; Di Napoli, Hogan, et al., 2020). Further, there is a substantial difference between both MRT and UTCI values when dsrp (downward solar radiation proportion) is used in the place of fdir (total sky radiation proportion) in the MRT calculation. We therefore recommend that if ERA5-HEAT is rereleased using the thermofeel methodology with fdir in the MRT calculation alongside the existing 'legacy' dataset available that the documentation indicates that differences are observed when dsrp is used in the place of fdir to be transparent with users.

This thesis also provides evidence of the relationship between the UTCI (Universal Thermal Climate Index) outputted values and those values used as inputs to the calculation. In addition, to exploring a linear model of the UTCI (Chapter 9), it has been demonstrated that a higher value of 2m temperature, mean radiant temperature, saturation vapour pressure and low wind speed lead to the highest values of the UTCI. And that, conversely, low temperature, low values of mean radiant temperature and saturation vapour pressure with high wind speeds will lead to the lowest UTCI values. In addition, 2m temperature and Mean Radiant Temperature have the strongest positive correlation with the UTCI, as well as, explaining most the variance of the UTCI. Further, a proposed UTCIsimple method is presented that only has a mean absolute error of 2.77°C less than 5°C and seen as acceptable across the testing data compared to the UTCI polynomial method. This is important as it reduces the computing capacity needed to calculate the UTCI and makes it more accessible, whilst providing an adequate proxy of the UTCI.

Further, this thesis saw the development of a new approximation of WBGT (Wet Bulb Globe Temperature) designed for gridded datasets (Chapter 10). $WBGT_{Brimicombe}$ has been demonstrated to be an accurate approximation of WBGT when compared to $WBGT_{Liljegren}$ (Kong & Huber, 2021; Liljegren et al., 2008). $WBGT_{Brimicombe}$ is within 1 heat stress category of $WBGT_{Liljegren}$, across the land surface, and mostly has anomalies of no more than ±2°C for the 3 heatwave case studies chosen. In addition, it has a strong positive correlation with $WBGT_{Liljegren}$ and the highest MAE value is 1.13°C. This shows that $WBGT_{Brimicombe}$ is a useful method for weather forecasting because it is designed for gridded datasets and has been shown to be an accurate approximation of WBGT. It is the hope that in integrating this WBGT into reanalysis data, forecasts and even climate model data, this could enhance research for example on definitions of heatwaves in terms of health outcomes and acclimatization levels, which would be highly beneficial across sectors but especially across health.

14.1.4 Service Delivery: *Consider the communication of heat risks and impacts within wider culture*

For Chapter 11 it is found that heat waves have the least amount of news media articles. This should not be a surprise given other research demonstrating the consistent underreporting of this weather hazard (Harrington and Otto, 2020; Vogel et al., 2019). It however, may be a surprise given the number of record-breaking heat waves during recent years such as the June 2021 Pacific North-West heat wave which was attributed to climate change (Sjoukje Philip et al., 2021).

How notable events or weather hazards get attention and are reported is subject to 'newsworthiness', which can also be known as the political economy between society and the media (Boykoff and Yulsman, 2013; Kitzinger, 1999). This is made up of 4 main factors: *the* *availability effect/heuristic which is if a hazard is presented as risk before it is more likely to be remembered in this manner, stories from impacted groups, geographically bound and are visually impactful* (Kitzinger, 1999; Tomlinson et al., 2011). The results of this study show that the hazards that fit the criteria the most were storms which have the most articles by quantity and wildfires that have the most articles per individual occurrence.

Attention deficit in the English Language News Media leads to a lack of investment in adaptation for some hazards, making us unprepared. In addition, this pushes us towards more precarious tipping points where adaptation becomes more of a challenge for society (Howarth and Brooks, 2017). This study's results highlight a huge reporting bias in favour of storms and wildfire in the news media. This has a material cost where storms receive more research, funding and policy than other hazards (Brimicombe et al., 2021b; Harrington and Otto, 2020; Howarth and Brooks, 2017; Vogel et al., 2019).

The number of articles on average per individual weather hazard that also considers climate change is not following the 'newsworthiness' criteria and therefore drought, wildfire and heat waves have the most articles. Therefore it can be suggested that, reporting of climate change has come about by the increasing collaboration between science (across career stages) and the media examples include Science Media Centre, The Conversation and Voice of Young Science. This comes in spite of the discourse around the role of science in both communication and policy spaces and should continue (Boykoff and Yulsman, 2013; Pielke, 2007).

In Chapter 12, it is demonstrated that extreme heat already is featured across the mainstream English language media in a number of a different of grid-group types described in the Cultural Theory of Risk framework. These are *Gilmore Girls* and *Emily in Paris* Egalitarian and Individualistic, *Bridgerton* Hierarchical and *In the Heights* Individualistic, Egalitarian and also Fatalist. This demonstrates the ease with which extreme heat and heatwaves can be incorporated into the entertainment mainstream English language media which has the potential to improve engagement with the risk of extreme heat (Thompson, 2003; Topp et al., 2019).

In addition, here it is found that *Perfect Planet* the documentary case study gives less prominence to heatwaves than other weather extremes becoming more likely with our changing climate. Prior research has found under-reporting of heatwaves and their impacts in Meteorological Reports (Brimicombe, Napoli, et al., 2021). Previous research has also suggested that better collaboration between producers, writers and science advisors could improve the communication of climate in the media (Smith et al., 2018), The content of climate change documentaries may also reflect the fields from which documentary advisors are drawn. This issue merits further research.

In Chapter 13, all the research from the thesis is brought together. It can be suggested that the main barrier to a Global Heat Early Warning system appears to be a lack of consensus, alongside key factors to its success such as defining a heatwave, vulnerability, resources, and dissemination.

In addition, historically heatwaves have not been within the remit of disaster risk reduction or meteorological agencies, being siloed to the health sector. A global-scale early warning system is necessary to counter the borderless nature of heat hazards. In addition, with the move from systematic early warning systems to an integrated, multi-hazard early warning systems approach this better fits the complex multi-sector nature of heatwaves.

Therefore, the time is now for a global heatwave early warning system. It is outlined here that in phase one this should build upon country level EWSs and be a collaboration between the World Meteorological and World Health Organisations. Next, in phase two using a OneHealth framing and consideration of a wider hazardscape other sectors should begin to collaborate.

14.2 Overall implications of this thesis

In the undertaking of the research presented in this thesis several new avenues of research that could be explored further arose. Here the limitations of this thesis and future avenues will be discussed.

14.2.1 Limitations

Each chapter has specific limitations which are discussed throughout. However, here key limitations from across the thesis will be presented. It is felt these do not detract from the answers this thesis contributes to the aims and objectives and the originality of the research, but, they do present interesting future research opportunities.

The use of heat stress indices is both a strength and limitation of this overall thesis because these indices present a way to better indicate core body temperature than air temperature alone (Ioannou et al., 2022), but conversely there are so many indices that it can be confusing from a user perceptive what information is gained from them. We consistently received reviews on work submitted for journal publication that showed confusion as to exactly what a thermal comfort index was and the benefits of using this over just temperature. This was despite significant effort to explain heat stress indexes as different from air temperature or as a 'feel like temperature'. This confusion was particularly noticeable for the Universal Thermal Climate Index (UTCI) as it is one of the newer thermal comfort indices available and is also one of the most complex as it makes use of a body model.

Impact of extreme heat was discussed in this thesis through impact reporting by EM-DAT, meteorological reports and in the English language news media. It had been the hope at the outset of this thesis design that mortality modelling for Africa would be possible. Data on a small enough temporal scale to assess the skill of heat indices for being able to predict mortality could not be obtained because of the Coronavirus pandemic. Similarly, a limitation is no new research presented on the perceptions of local communities and key stakeholders with a focus on African nations, this again was because of the challenges presented by the pandemic which made collecting such data impossible. Given this the decision was made to focus on expanding the heat stress modelling aspect of the project, which meant key impact and perception questions remain.

Skill of weather forecasting is also not presented in this thesis. The focus remains on a more technical assessment of the fundamentals of heat stress modelling and historical heat stress within reanalysis data. As an individual PhD researcher resourcing challenges led to difficulties in obtaining forecasts for multiple heat stress indices on a range of time scales in the right format, to be able to carry out an assessment of the skill of forecasts across regions and years. Before the development of *thermofeel*, the UTCI was the only thermal comfort index being forecasted on a medium-range internally within ECMWF, with data only going back to 2018. To create any new forecast data using *thermofeel* the workflow at present is still manual, and despite optimisation, run times and computing power needed even on a server outside of a high-power computer for a long-scale forecasting study were unattainable. Further, As Chapter 8, outside of the medium-range a radiation variable is missing for the extended and seasonal range forecasts to create the UTCI and WBGT, limiting to heat indexes without radiation.

14.2.2 Addressing extreme heat risk and impacts

Many interesting questions remain in fully addressing extreme heat risk and impacts. Here the key ones that come out in the body of this thesis will be discussed. First, is there one heat stress index that outperforms the others in explaining a key impact of extreme heat (i.e. mortality rates or hospital admissions)? We already know that for key body temperature indicators WBGT and the UTCI are the 'gold standard' (Ioannou et al., 2022). The added complexity for this comes from mortality models being designed for mortality curves that come from temperature alone (i.e. Vicedo-Cabrera et al., 2021). It remains unclear at the present time how these curves change when other meteorological variables are added.

Another question raised about thermal comfort indices was heat stress thresholds universal use across the globe. A recent study demonstrated that the widely stated 35°C wet bulb being the deadly temperature, a theoretical number is actually found to be a range of values dependent on climate (Vecellio et al., 2022). This thesis explored in part exposure time for the UTCI in addition to intensity in an attempt to consider acclimatization levels. However both chapters conclude that local acclimatization impact studies of heat stress indices are needed to assess the robustness of the given heat stress thresholds for being an indication of risk levels (Nazarian & Lee, 2021; Zare et al., 2019).

An early warning system can only be effective at reducing risk if communication gives the right agency and there is resilient infrastructure. Across Component 4 (Chapters 11-13) communication is at the core of the theme and key questions are raised. Extreme heat is not primarily perceived through our visual sense (Kuht & Farmery, 2021), how do all our senses contribute to extreme heat perception and likelihood to adapt? It has previously been shown that warnings with suggested adaptation measures increases an individual's agency (Heidenreich et al., 2021). However, questions remain about how different approaches for extreme heat messaging resonates with different groupings in society, or how the voice used is more likely to lead to individual adaptations in comparison to inaction. As well as, how documentaries in comparison to other mainstream media content effects perceptions of extreme heat risk would be interesting to explore, to improve communication (Smith et al., 2018; Topp et al., 2019). Although not an exhaustive list of future avenues of research, these suggestions are key to take into consideration for building an effective global heat hazard awareness system.

15. Conclusions

This chapter provides an overall summary of the main conclusions presented by each component of the thesis. Table 15.1 shows the table presented in Chapter 1, with what the main research questions per component are answered, here the answers that have been found throughout the thesis are now highlighted. One of the real strengths of the systems approach of this research is the breadth of components addressed that are key in a global heatwave early warning system. This provides a plethora of evidence towards the aim: *investigate the impact of extreme heat and policy measures and to explore the development of a global heat hazard early warning system.*

Table 15.1 The main research questions, novel findings and academic contributions presented in this thesis.

Mobilization and Governance *Assess policy prioritization and governance*			
Chapter	Research Questions	Novel Findings	Publications/ Academic Contributions
Chapter 4: Borderless Heat Stress with bordered impacts	Q: How does the area of heat stress change over this millennium and is this adequately captured by meteorological reporting? A: it is demonstrated for the first time that heat stress had grown in area since 2000 and that the impacts of heatwaves were under-reported in meteorological reports.	Heat Stress as indicated by the UTCI being shown to grow in area. Underreporting of heatwaves vs other hazards in meteorological reports.	**Brimicombe C**, Di Napoli C, Cornforth R, Pappenberger F, Petty C. and Cloke H.L., 2021a. Borderless heat hazards with bordered impacts. *Earth's Future*, https://doi.org/10.1029/2021EF002064 **[IF: 7.495, *n*=9] [CB 80%]**
Chapter 5: *Heatwaves: an invisible risk in UK policy and research*	Q: How are heatwaves presented in UK policy and what are the barriers to creating policy? A: Heatwaves are an invisible risk in UK policy and subject to sectoral silos, targets responses and social networks are the two main way that	The siloing of heatwaves to the health and building sectors within UK policy and research. The first-time heatwave policy barriers and suggested solutions had been	**Brimicombe C**, Porter J J, Di Napoli C, Pappenberger F, Cornforth R, Petty C and Cloke H L, 2021b, Heatwaves: An invisible risk in UK policy and research, *Environ. Sci. Policy* 116 1–7 Online: https://linkinghub.elsevier.com/retrieve/pii/S1462901120313782 **[IF: 5.581; *n* = 19]**

	can be used to reduce the risk of heatwaves.	presented in this manner for the UK.	
Health Information Systems *Evaluate the trends and modelling for extreme heat*			
Chapter 6: Trends in African Heatwaves	Q: How has the exposure to heat stress changed for Africa and what should forecasters look out for in heatwaves that present large impacts? A: The intensity, frequency and area of heat stress has increased for Africa since 1980, forecasters should be aware of a sudden increase in heat stress over a few days in the lead up to a heatwave peak and be aware of location specific dynamics.	The first time the UTCI as an indication of heat stress had been used at a continental scale for Africa. In, addition to the first-time area exposed to heat stress had been shown to grow using this methodology.	
Chapter 7: thermofeel: a python library for thermal comfort indices	Q: Can I create accurate thermodynamical thermal comfort models for gridded data, that is open to the research community?	The first time a python library for thermal comfort indices had been designed to work across data structures from numerical weather prediction	**Brimicombe C**, Di Napoli C, Quintino T, Pappenberger F, Cornforth R and Cloke H L, 2022b, thermofeel: a python thermal comfort indices library 2022 *Software X*, https://doi.org/10.1016/j.softx.2022.101005 **[IF: 1.959,** *n*= 6**] [CB 80%]**

	A: thermofeel which is used in ECMWF's forecasting systems whilst also providing accurate methods for gridded data and observation data for the community.	outputs to observation data.	
Essential Technologies *Develop new technologies to reduce risk to heat.*			
Chapter 8: tech memo: calculating the solar zenith angle for thermal comfort indices	Q: Can I improve the representation of Mean Radiant Temperature and thermal comfort indices in NWP services? A: By using an integral cosine of the solar zenith angle and downward solar radiation, we can improve the accuracy of MRT and subsequent thermal comfort indices in NWP services.	The creation of an accurate numerical integration method of the solar zenith angle that reduced computational time. In addition to, experiments showing for the first time for the ECMWF the difference between using downward solar radiation (dsrp) in comparison to its approximation Istar in the calculation of Mean Radiant Temperature.	**Brimicombe C**, Quintino T, Pappenberger F, Smart S, Di Napoli C and Cloke H L 2022a Technical Memorandum: The cosine of the solar zenith angle for thermal comfort indices https://doi.org/10.21957/O7PCU1X2B **[CB 80%]** *n* = 2

Chapter 9: The Development of a UTCIsimple method	Q: Can I create a less-computational expensive method for UTCI to make it more accessible? A: A UTCI linear model that is accurate can be created for gridded data on a personal computer using all the input variables.	It is possible to create a linear model for the UTCI that is accurate for gridded datasets at a global scale, but that all input variables are needed to maintain accuracy.	
Chapter 10: Wet Bulb Globe Temperature: indicating extreme heat risk on a global grid.	Q: Can I create a WBGT that is designed for gridded dataset and is accurate in comparison to the gold standard method and observations? A: The new methodology of the WBGT is as accurate as the gold standard method and is comparable in accuracy with this method for observations.	An accurate WBGT approximation was created using a new method of a Globe Temperature calculated using Mean Radiant Temperature. This is the first time this method has been used and is the first time a bespoke method for numerical weather prediction has been created for the WBGT.	**Brimicombe, C,** Lo, C.H.B., Pappenberger, F., Di Napoli, C., Maciel, P., Quintino T., Cornforth, R., and Cloke H., 2023. Wet Bulb Globe Temperature: indicating extreme heat risk on a global grid *GeoHealth* https://doi.org/10.1029/2022GH000701 **[IF: 4.60] [CB 75%]**
Service Delivery *Consider the communication of heat risks and impacts within wider culture.*			
Chapter *11: Is there a climate change*	Q: how has reporting of weather hazards in the English Language media	This is the first time an open science approach has been used to	**Brimicombe, C.** 2022. Is there a climate change reporting bias? A case study of English-language news articles, 2017-2022. *Geoscience*

reporting bias? A case study of English-language news articles, 2017–2022	changed in the last 5 years and are heatwaves under-reported? A: more weather hazards are reported now than 5 years ago and are more likely to refer to climate change. Heatwaves are under-reported.	explore the bias between weather hazards. And also the first time the relationship between climate change and weather hazards has been investigated in this way. This presents key opportunities for weather hazards reporting to be explored further such as a regional analysis.	*Communication*, *5*(3), 281–287. https://doi.org/10.5194/GC-5-281-2022 **[CB 100%]** *n = 1*
Chapter 12: the portrayal of heatwaves in popular culture	Q: How are heatwaves presented in popular culture and how can this be employed to communicate risk? A: Using a cultural theory of risk framing all grid-group typologies are presented in popular culture, with differences seen amongst media types. This could be a more novel way in our globalized society to communicate heat risk.	This scoping piece, demonstrates that heatwaves are already portrayed in a range of media, and that this can be readily investigated. A documentary case study in the form of *Perfect Planet* suggests heatwaves feature less so than other weather hazards and this should be explored further.	

Chapter 13: Towards a global heat early warning system	Q: What is needed for a robust global heat health early warning system to be developed? A: The aspects presented in this thesis and further across-sector collaboration.	The piece is the first-time barriers to a global heat early warning system have been displayed using the framework outlined by Basher *et al.,*(2006). It is hoped that policy and forecasting changes can come from this leading to a robust operational global heat early warning system being released and maintained in the near future.	

15.2 Overall Summary

This thesis has contributed original research to the fast-growing extreme heat field. Using a systems approach and an adapted framework presented for resilient health systems created by WHO it presents the investigation of the impact of extreme heat and policy measures and explores the development of a global heat hazard early warning system, has created research that will lead to an operational heat hazard early warning system, a mandate set by the joint council of the World Meteorological Organisation and World Health Organisations. It has also provided the evidence for its benefits and started to consider how communication influences perception of heat risk.

In addition, it demonstrates the need for the establishment of an international protocol for reporting heatwave impacts for international organisations and national governments. This would first allow for an internationally agree heatwave definition. It will also allow us to build an evidence base of ongoing heat impacts so that the right adaptation measures can be put in place, building resilience to heat in our changing climate.

Further, it shows that urgent improvements in reporting impacts needs to be made by meteorological organisations and the emergency disaster database EM-DAT, leading the way for robust heatwave impact reporting in the media. This is seen as a keyway to highlight the deadly risk posed by heatwaves.

Finally, despite the many important findings of this thesis, it is important to note the many other avenues of research that it also discovered and the barriers to a global heat early warning system that are still present. These barriers can be addressed as part of an operational global early warning system including which metrics, indices, and health indicators should be given priority within the system. Also, what should the trigger threshold for a heatwave be and how can this be meaningful at different scales and across sectors. As well as, understanding the best approach to warning communications and how these fits within the wider hazardscapes and societal landscape. Finally, it is important to state that effective early warning systems are only able to exist with robust infrastructure, policy and adaptation measures. These should be part of a systems approach to tackling climate change alongside EWSs. This research will help towards reducing heat impacts, so they are no longer silent killers.

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Appendices

Appendix A

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Heatwaves: An invisible risk in UK policy and research

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ABSTRACT

In 2019, a heatwave – an unusual extended period of hot weather – broke the UK's highest recorded temperature of 38.7 °C set in 2003. Of concern is that for summer 2019, this resulted in 892 excess deaths. With the intensity and frequency of UK heatwaves projected to increase, and summer temperatures predicted to be 5 °C hotter by 2070, urgent action is needed to prepare for, and adapt to, the changes now and to come. Yet it remains unclear what actions are needed and by whom. In response, a systematic literature review of UK heatwaves peer-reviewed publications, inclusive of keyword criteria (total papers returned = 183), was conducted to understand what lessons have been learnt and what needs to happen next. Our research shows that heatwaves remain largely an invisible risk in the UK. Communication over what UK residents should do, the support needed to make changes, and their capacity to enact those changes, is often lacking. In turn, there is an inherent bias where research focuses too narrowly on the health and building sectors over other critical sectors, such as agriculture. An increased amount of action and leadership is therefore necessary from the UK government to address this.

1. Introduction

In 2019, a heatwave broke the UK's highest ever recorded temperature of 38.7 °C set in 2003. Over 2 heatwaves 892 excess deaths were recorded (Public Health England, 2019). Of concern here is that the intensity, frequency, and duration of UK heatwaves are all projected to increase, and summer temperatures are predicted to be 5 °C hotter by 2070 (Lowe et al., 2018) yet the UK Government's efforts to prepare for, and adapt to, these risks has been heavily criticised for leaving the UK 'woefully unprepared' (Carrington, 2018; The Committee on Climate Change, 2017; Environmental Audit Committee, 2018; Howarth et al., 2019).

Too often the problems of heatwaves are narrowly defined as one concerned with public health alone. To date, the only tangible heatwave plan in the UK is led by the Department of Health and Social Care and is aimed primarily at healthcare service providers (Public Health England, 2018). Yet heatwaves can have other negative impacts too. For instance, they can affect 'critical national infrastructure such as transport, digital systems and water supply…' cause 'railway tracks [to buckle which] are costly to repair' and in 2010 led to economic losses of £770 million related to lost staff days (Environmental Audit Committee, 2018: 4). The risks posed by heatwaves are, importantly, not confined to a single sector but cut across different sectors in both predictable and unpredictable ways (Howarth et al., 2019). Such 'silo thinking', where an issue is only dealt with by individual sectors with little or no communication between affected sectors (c.f. Pregernig, 2014; Rogers-Hayden et al., 2011), has become politically ingrained in how the UK approaches the management of heatwaves.

In turn, the UK's research and forecasting arrangements for heatwaves are institutionally fragmented. The UK Met Office is responsible for providing meteorological and climatological data and advice to policymakers and the public nationwide. In partnership with Public

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Health England, the Met Office runs an early warning system for heatwaves from 1st June to 15th September each year (Met Office, 2020). Yet this service only covers England. Scotland, Wales and Northern Ireland receive no official warnings, and it is unclear to what extent they are covered by the National Severe Weather Warnings system (Met Office, 2020). Institutional peculiarities are found in the evidence base used to inform government policy too. As part of the UK's 2008 Climate Change Act, a risk assessment must be conducted every five years to identify which climate risks the UK faces, and therein, inform a National Adaptation Programme to tackle these risks. Whilst the first and second Climate Change Risk Assessments called for urgent action to address heatwaves (The Committee on Climate Change, 2017; DEFRA, 2018), the problem of overheating – whereby a building becomes too hot reducing comfort and productivity for those using that space – will only be addressed from 2023, too late to cover new homes built to meet the Government's housing targets of 1.5 million by 2022 (Committee on Climate Change, 2020).

Another challenge here is that there is no universal definition for what a 'heatwave' is. For instance, the World Meteorological Organization (2018: 4) defines a heatwaves as, 'A period of marked unusual hot weather (maximum, minimum and daily average temperature) over a region persisting at least three consecutive days during the warm period of the year based on local (station-based) climatological conditions, with thermal conditions recorded above given thresholds'. The UK Met Office, by contrast, defines a heatwave as a point 'when a location records a period of at least three consecutive days with maximum temperatures meeting or exceeding a heatwave temperature threshold' (McCarthy et al., 2019). Although subtle these definitions reveal competing criteria for what constitutes a heatwave: the uniqueness of the event itself vs. exceedance of a predetermined temperature threshold, which only adds to confusion when planning to manage the impact of heatwaves, especially when mortality rates can also increase from above average temperatures not just from a heatwave (Abeling, 2015). For this study, a heatwave will be defined as an unusual period of extended hot weather.

At present, research suggests that the problem faced by the UK in managing heatwaves is a political one (Environmental Audit Committee, 2018; Howarth et al., 2019). Either there is insufficient political appetite, patchiness in provision of forecasting services, or a lack of capacity to implement policies. Yet such reading pays little attention to what 'research' is being used to inform heatwave policy in the UK and why silo-thinking has taken root. To better understand how UK heatwave research has developed over the last twenty years, and importantly to assess what are the drivers, barriers and recommendations for future heatwave policy, a systematic literature review was conducted. This research seeks to pinpoint where the problem of inaction comes from and what could be done in response. To do this, the data and methods used to conduct the systematic literature review are explained in the next section, followed by the key findings, and a discussion of what those findings mean and why they are important.

2. Data and methods

To understand how UK heatwave research has developed over the last twenty years, and to assess the main drivers, barriers and recommendations for future policy, a systematic literature review was conducted (cf. Berrang-Ford et al., 2010; Porter et al., 2014; Porter and Birdi, 2018). Web of Science, and Scopus, two of the largest and most comprehensive publication index databases, were used to perform a keyword search for peer-reviewed research published between 1st January 2000 and 31st December 2019. Research published prior to 2000 was excluded because the UK's ten hottest years on record have happened in the last two decades and the frequency, intensity and duration of UK heatwaves have also increased since that point (McCarthy et al., 2019).

Systematic literature reviews offer an effective, transparent, accountable, and reproducible method for identifying, analysing and synthesising large amounts of published research (Ford et al., 2011). By making both the selection criteria and the analytical framework used explicit from the outset, biases can be reduced and more reliable conclusions reached. As noted earlier, the term 'heatwave' is understood and enacted differently across disciplines – hot spells, extreme weather events, severe heat – and therefore different keyword combinations were used to ensure the topic was comprehensively searched (see Supplementary Materials). In total, 33 keywords were used across 3 categories: (i) *topic*: heatwave identifying characteristics; (ii) *purpose*: policy and research domains; and (iii) *place*: countries within the United Kingdom. 183 publications were returned. After importing the publications to an MS Excel spreadsheet, inclusion and exclusion criterion were applied.

Only empirical, peer-reviewed, publications written in English and focusing on UK heatwave policy were analysed. Impact studies that only focused on modelling future mortality rates or temperature projections, for instance, and papers concerned with detection and attribution, were excluded. Publications that failed to address the main drivers, barriers, and recommendations for formulating and/or implementing UK heatwave policy, were also excluded. 52 journal articles fulfilled the inclusion criteria.

To ensure consistency, a qualitative scorecard was created to record key details about the retained journal articles including funding sources, disciplinary orientation, research focus, and methods used. This data helped to build a picture on 'what' research was being done, and in 'which' sector, so that linkages and gaps could be identified. A thematic analysis of the dataset was then performed whereby a ranking criterion was developed to differentiate between the high-quality, empirically robust, publications and the less rigorous studies using a grading system from one to five. A five-star paper used method(s) highly appropriate for the research question(s), included a large sample size (e.g. $>$ 200 survey subjects or 50 interview participants), and were critically and reflexively analysed. By contrast, a two-star paper or below was more exploratory in nature, with lower data points (e.g. $<$ 50 survey respondents or $<$10 interview participants), and the findings were more speculative (see Supplementary Materials).

20 journal articles (38.5 % of the retained search) scored three-stars or above and were analysed. Of these, different research designs were used such as quantitative ($n = 7$), qualitative ($n = 7$), and mixed methods ($n = 6$), and the sectors covered focused on: health ($n = 8$), building/infrastructure ($n = 6$) and behaviour/adaptation ($n = 6$).

3. Results

To date, the UK's most prominent heatwave policy is the 'Heatwave Plan for England' (see Supplementary Materials for full details). It covers England only, however ($n = 9/20$ – number of papers out of total that mentioned this policy) (Public Health England, 2018). Under the plan, responsibilities are divided between the Department of Health and Social Care, which takes the lead role in coordinating heatwaves responses across the National Health Service (NHS) and community health services, and the UK Met Office, which forecasts heatwaves and issues warnings to healthcare practitioners and Local Government (Met Office, 2020).

Our review suggests that questions remain over the effectiveness of the interventions proposed by the Heatwave Plan for England, whether these interventions are aimed at the right people, and if sufficient efforts are being made to manage heat risk in sectors beyond health Many studies praised the Heatwave Plan, for putting in place reactive measures, which are reviewed annually (Abeling, 2015; Abrahamson and Raine, 2009; Khare et al., 2015; Page et al., 2012). However, these studies also raised challenges the Heatwave Plan doesn't address, for instance, Abeling (2015: 7) suggested that the plan failed to 'consider social, environmental and technical risk dimensions', which is due to the reactive nature of the plan. Whilst Page et al. (2012) argued that the heatwave plan does not address the risks posed to mental health patients, especially those based in the community.

Several studies (n = 3/20) also referred to the important role that national climate change policies can play such as the UK's latest Climate Change Risk Assessment, which identified heatwaves and building overheating as 'high risk' (The Committee on Climate Change, 2017), and the National Adaptation Plan, which seeks to address these risks (DEFRA, 2018). Of interest here is the Climate Change Risk Assessment considers the level of heat risk to be the same for all parts of the UK. Our review, however, found that the evidence base for heatwave research varies geographically as 94 % (n = 172/183) of the returned results for the original Scopus search focused on England, and only fraction considered Wales (n = 10/183) and Scotland (n = 1/183), with Northern Ireland absent altogether (n = 0/183).

In terms of the building sector, which is responsible for designing and building new homes, office space, schools, and other properties; there is no official Government policy and/or legislation that requires overheating to be factored into new builds. Rather 'best practice' involves following the Chartered Institution of Building Services Engineers (CIBSE) thermal comfort guidance (CIBSE, 2013, 2015, 2017). Yet two-thirds of the overheating studies reviewed suggest that upwards of 20 % UK buildings exceed the maximum thermal comfort limit for a normal UK summer, without additional extreme heat, or the projected higher summer temperatures from climate change (Baborska-Narożny et al., 2017; Vellei et al., 2017).

3.1. What are the main drivers for formulating and/or implementing UK heatwave policy?

Of the 20 papers reviewed, the main drivers that influence the formulation and/or implementation of UK heatwave policy were: (i) the occurrence of a heatwave event(s); (ii) concerns about the frequency, severity and duration of heatwaves increasing due to climate change; and (iii) growing recognition of the wide range of vulnerabilities exposed by heatwaves. The vast majority of papers (80 %, n = 16/20) found that heatwaves, such as the 2003 European heatwave, were instrumental in the development of new policies and/or plans as well as research into warning systems and coping strategies.

Nearly half of the papers (40 %, n = 8/20) agreed that the growing scientific infrastructure around heatwave forecasting, particularly in relation to climate change risk assessments and projections, was also a driving force in the formulation and implementation of UK heatwave planning. It was noted that as the frequency, severity and duration of heatwaves increase, if the UK does not adapt fully and soon key sectors, including healthcare and agriculture, could fail (The Committee on Climate Change, 2017). Indeed, the UK's 2019 climate projections suggest that the 2003 heatwave will become a normal event for UK summers by 2040 (Murphy et al., 2019).

Over a third of the papers (35 %, n = 7/20) agreed that the growing recognition of vulnerabilities exposed by heatwaves played an important role in driving UK heatwave policy and/or plans. The Intergovernmental Panel on Climate Change, for instance, defines 'vulnerability' as 'the propensity or predisposition to be adversely affected' and it 'encompasses a variety of concepts and elements including sensitivity or susceptibility to harm and lack of capacity to cope and adapt' (IPCC et al., 2013, p. 128). How vulnerability is defined depends, however, on the sector. Healthcare studies (n = 9/20) identified vulnerable groups as those above the age of 65 and/or those with pre-existing medical conditions such as respiratory diseases (Abrahamson and Raine, 2009; Page et al., 2012). Infrastructure studies (n = 6/20), by contrast, focus on vulnerable as the capacity for buildings or equipment to cope with excess temperatures such as the failure of signals for the railway network (Ferranti et al., 2016, 2018; Larcom et al., 2019).

3.2. What barriers were identified to the formation and/or implementation of UK heatwave policy?

14 barriers were identified to the formulation and/or implementation of UK heatwave policy or plans. As shown in Fig. 1, the most frequent barrier cited was the perception that heatwaves are not a risk (n = 10/20). Prior to 2003, heatwaves in the UK were fairly uncommon occurring in 1976 and 1995 (see Fig. 2). This may help clarify why, as Wolf et al. (2010: 47) explains, 'long term and anticipatory responses to heat [are] perceived as largely unnecessary because of a belief that heat waves are and will remain rather uncommon in the UK'.

A quarter of the studies (25 %, n = 5/20) also commented on how UK heatwaves are 'invisible' in comparison to other extreme meteorological events (Abeling, 2015; de Bruin et al., 2016; Ferranti et al., 2018; Murtagh et al., 2019; Taylor et al., 2014). As Murtagh et al. (2019) suggests, the visual impact and newsworthiness of flood events captures public attention far more than heatwaves, in part because newspaper coverage tends to link hot weather with barbeques and other positive outdoor pursuits as opposed to there being a risk. Indeed, Taylor et al. (2014) found that UK residents believe that floods are more likely to increase due to climate change than heatwaves. Adapting our original search in Scopus to account for floods instead of heatwaves, returned 1766 results for the keyword flood compared to 68 results for the keyword heatwave, which suggests that difference in public perceptions may also be related to a research bias in favour of flood risk studies over heatwave research.

A lack of research into different areas impacted by heatwaves was also identified by a third of the studies (35 %, n = 7/20) as a barrier. Although the 2003 European heatwave has served to generate more research in the healthcare and building sectors, other at-risk sectors including transport, energy, water and food are largely ignored. Even when research is happening the focus can be somewhat narrow. For instance, much of the research from the building sector concentrates on homes, with research on other building types such as schools and offices having to play catch up (Montazami and Nicol, 2013). In turn, behaviour studies suggest that building research rarely considers the motivation and capacity of users to tackle concerns with overheating risks or the role played by mental health and pro-environmental values (Khare et al., 2015; Murtagh et al., 2019; Page et al., 2012).

The barriers outlined in this section can hinder the uptake of heatwave research in policy decision-making. A research bias in favour of floods, for instance, serves to keep heatwaves as an 'invisible' risk whilst the amount of research conducted on some sectors (e.g. healthcare, building) can skew which risks are identified and who should be responsible for dealing with them so that a form of silo thinking develops in policy debates. Indeed, the UK's latest National Adaptation Plan uses the word 'heat*' 70 times compared to 251 times for 'flood*' (DEFRA, 2018).

3.3. What solutions were proposed to improve the formulation and/or implementation of UK heatwave policy?

Just under half of the studies reviewed (40 %, n = 8/20) agreed that a key solution to managing heatwaves is through 'targeted action'. For example, where a railway signal is at-risk of failing in a heatwave, a 'targeted action' would be to replace it before this occurred (Ferranti et al., 2016, 2018). Targeted action, therefore, involves identifying, assessing, and proactively intervening in current systems to reduce, or avoid, the negative impacts associated with a heatwave. For the healthcare plan, this could involve a shift away from concentrating responsibilities in a single Government department and redistributing those responsibilities according to where heat presents a risk across Government as a whole (Oven et al., 2012).

Another main solution discussed was how to better communicate heat risks using different strategies, across different geographical scales, and aimed at different actors. This was identified through 3 separate

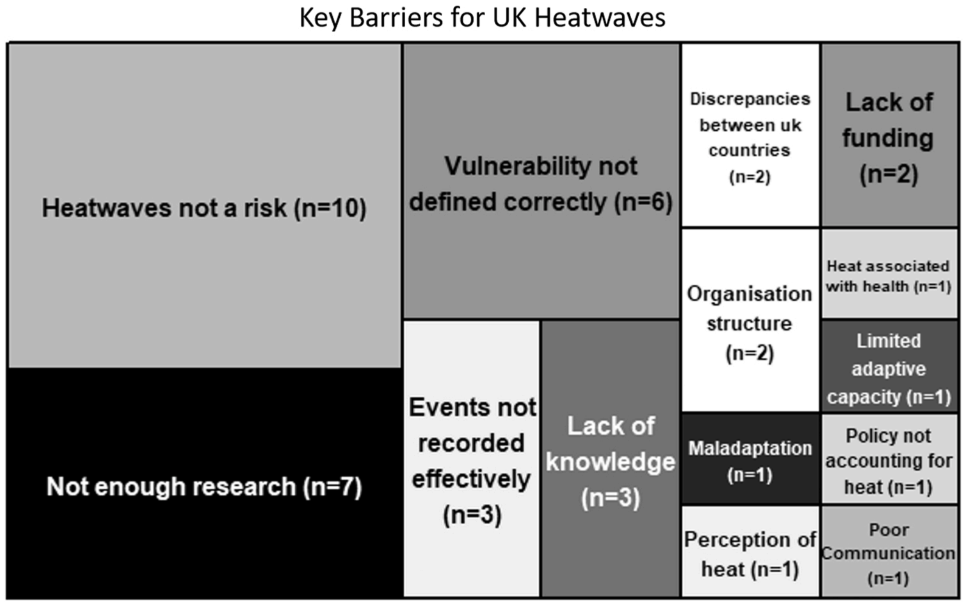

Fig. 1. Treemap visualisation of all 14 barriers identified in the dataset. The different size boxes represent the level of agreement within the dataset.

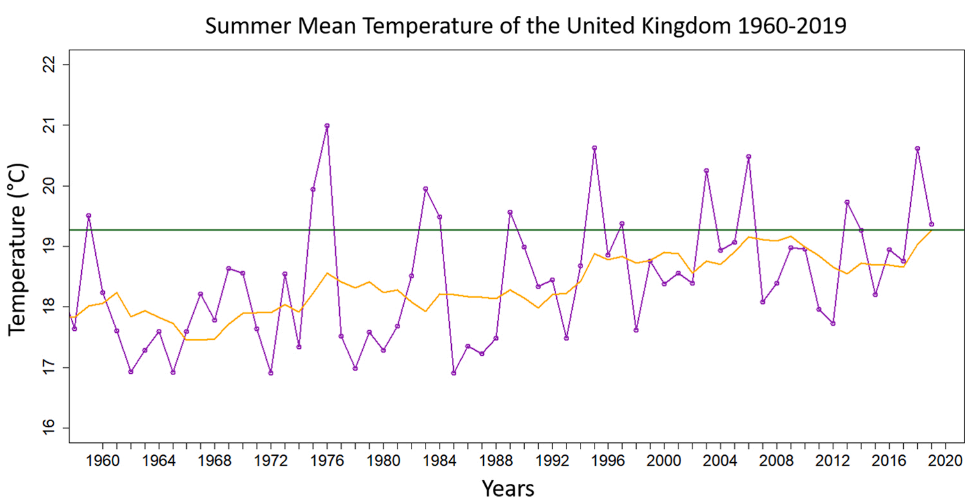

Fig. 2. Summer Mean Temperature for the UK 1960-2019. The purple line represents the trend of the summer mean temperatures from 1960 to 2019; the orange line depicts a smoothed rolling mean line of the summer mean temperatures; and the green line shows the 90th Percentile of summer mean temperatures from 1960 to 2019, purple values above this line indicate heatwaves (Met Office, 2018).

themes/scales: nationwide engagement with the population (n = 4/20), community-based engagement (n = 4/20) and the use of media (n = 3/20). Most communication solutions were proposed by research participants who were surveyed or interviewed through the studies. Abrahamson et al. (2008), for instance, reported that respondents suggested heatwaves should be incorporated in television or radio storylines, as a creative way to present the risk to a large proportion of the population. Whilst others have called on the Met Office to give heatwaves names similar to winter storms to help persuade the media, and by extension the public, of the serious risks heatwaves pose (Ward, 2019).

Furthermore, the papers reviewed agreed that more research could hold the answer to identify which sectors are at-risk, where targeted action is needed, and provide a richer and more robust evidence base to inform policymaking. One concern raised is that the UK's National Adaptation Plan seeks to empower the public to make decisions in their own interest to reduce their exposure to heat risks (Abeling, 2015; DEFRA, 2018). Yet the studies analysed suggest that the evidence base for heatwaves lacks sufficient depth to be able to inform policy on how to help people improve their adaptive capacity, drill down into the important role that social networks play in building up their resilience (Abrahamson et al., 2008; Wolf et al., 2010); or how the difference between a tenant and homeowner can limit adaptive capacities. More research was called for to better understand what solutions can be offered, and if these solutions are context specific (Baborska-Narożny et al., 2017; Murtagh et al., 2019).

4. Discussion

A major challenge faced by nation-states as well as international bodies over how best to manage heatwaves relates to a lack of evidence and inconsistencies within the evidence base that is available (e.g. geographical, sectoral). In the UK, silo thinking has taken root in the policy arena as the healthcare sector and building/infrastructure sector have been proactive in developing policies, plans and guidance, whilst other at-risk sectors are largely ignored. In turn, the research community has produced evidence to support these policy domains but again largely ignored the challenges faced by other sectors and an imbalance between heatwave and flood risk research has emerged. As a result, UK policy and research on heatwaves have worked together to produce this 'invisible risk'.

4.1. Why are there discrepancies in the reporting and analysis of extreme weather events?

Arguably the imbalance in research between floods and heatwaves is borne out of a legacy, where triggering events motivate research and policy changes, which historically has favoured the higher frequency of flood events in the UK (Met Office, 2019). With more research written about UK flooding than heatwaves, an 'availability effect' has developed. That is, the importance of something is directly related to how prevalent it is and/or how it is perceived (Khare et al., 2015). Media reporting of extreme weather events has contributed to the 'availability effect' by framing floods as a risk, and heatwaves as an opportunity (Wolf et al., 2010).

Of interest here, is that discrepancies between extreme weather events is not unique to the UK. In 2017, the European Environment Agency released its report on 'Climate Change Adaptation and Disaster Risk Reduction'. A keyword search of the document for 'flood*' and 'heat*', returned 446 and 186 mentions respectively (European Environment Agency, 2017). Despite the European Union funding research projects on extreme heat, an imbalance exists in which extreme weather events are given top billing. At the international level, reports by the OECD (Organisation for Economic Co-operation and Development) and the WMO (World Meteorological Organisation), on Climate Change Adaptation and services the word 'flood*' appears at least twice as often as the word 'heat*' (GFCS, 2016; OECD, 2018). Yet for health and climate change reports by WHO (World Health Organisation), 'heat*' does appear more frequently than 'flood*', but suggests that extreme heat remains an 'invisible risk' outside of the health sector (WHO, 2019; 2018).

4.2. Are heatwaves an 'invisible risk'?

Our review shows that, outside of a select few policy domains, yes heatwaves remain an 'invisible risk' in the UK. However, a growing body of literature is seeking to change this by broadening the scope of research into other at-risk sectors. The grey literature may offer a template for the research community to follow here. The Joseph Rowntree Foundation, for instance, has commissioned several studies on heat risks that capture the experiences of practitioners and stakeholders working and living in exposed sectors, and found that the Heatwave Plan for England is too reactive in that it focuses on coping rather than building adaptive capacity within communities (Benzie et al., 2011). Likewise, the UK's second Climate Change Risk Assessment brought together insights from researchers and practitioners to review how heat risk had been discussed across different sectors, with the findings aimed at policymakers across the full breadth of Government (The Committee on Climate Change, 2017). Such efforts reveal how the profile of heat risks can be increased via more interdisciplinary and collaborative projects, and why future research should focus on mining the grey literature to see how to accelerate the changes it calls for in both policy and research too.

4.3. Why is defining heat-related vulnerability key?

Vulnerability was a central theme throughout the reviewed papers. Heatwaves events served to reveal where social inequalities exist in the capacity of people, buildings/infrastructure, and sectors to respond effectively. Yet it is important to remember that vulnerability is not static but dynamic. Different studies, and different sectors, conceptualised and enacted the discourse on vulnerability differently. Whereas for healthcare professionals 'vulnerability' concerns the ability of 'people' to adapt and respond, for building/infrastructure researchers 'vulnerability' concerns the 'physical apparatus' that allows everyday life to function (Curtis et al., 2017; Larcom et al., 2019; Murtagh et al., 2019; Page et al., 2012; Wolf and McGregor, 2013). One solution made in the review was that the Health and Social Care Act 2012 could be updated to include consideration for climate change, and particularly heat risk, as this would help mainstream the need to address vulnerabilities across all policy areas in Government (Rauken et al., 2015). This has also been highlighted in the grey literature (see Benzie et al., 2011; Royal Society et al., 2014).

4.4. What action is needed on overheating in buildings and at work?

To date, the vast majority of the research into building overheating has focused on homes. Despite research suggesting that up to 20 % of homes currently experience overheating problems during an average UK summer, new houses built in line with Government housing plans do not have to factor overheating into their designs (Peacock et al., 2010; Wilson and Barton, 2018). Moreover, the UK Government's own research has already found that new homes do overheat, but no policy action has been taken (MHCLG, 2019). New legislation on building standards is needed as 'best practice' guidance is not working (CIBSE, 2013, 2015; 2017).

It is also surprising the main research has been on homes given that – outside of a global pandemic – people come into contact with a wide variety of building types in their everyday lives. A growing body of literature is seeking to addresses the problem of overheating in other buildings such as hospitals, schools and offices (The Committee on Climate Change, 2017; Montazami and Nicol, 2013). But there is currently no 'maximum' safe working temperature under the UK's Workplace (Health, Safety and Welfare) Regulations 1992, despite there being a 'minimum' safe working temperature. This needs to be urgently addressed as exposure to extreme heat can be a contributory factor to a range of health conditions (Glaser et al., 2016) as well as impact upon productivity.

4.5. Is there a geography to UK heatwave research?

Yes, not only does a discrepancy exist in the amount of heatwave research conducted in different regions of the UK but this discrepancy is also mirrored in the formulation and/or implementation of official Government policies and plans (Khare et al., 2015). England is the only region of the UK that has a heatwave plan, and it focuses only on health (Met Office, 2020). Despite the UK's latest climate projections showing that heatwave will increase in frequency, severity and duration across all UK regions, the level of research and policy development does not follow these concerns. No research met our criteria for heatwaves policy and management in Northern Ireland. This is concerning because without an evidential base for policy at best the urgency of the problem will remain low and at worst it will remain an 'invisible risk'.

This result may be related to legacy as heatwave events have historically been rare in the UK and institutional fragmentation introduced through devolution – where each country controls how they are governed and the policy they prioritise – has impeded centralised planning and action This is important because heatwaves do not observe administrative boundaries: they are borderless. Yet the creation of the Heatwave Health Plan for England speaks to this inconsistency as only some sectors, and some places, prepare for and adapt to heat risks. Historically heatwaves spread across wide areas, for example the European Heatwave in 2003, and the Russian Heatwave in 2010. But it is key that all guidance on heat is developed to avoid patchiness in provision and response (e.g. WMO and WHO, 2015).

5. Conclusion

Despite scholars highlighting the importance of planning for, and adapting to, the impacts of heatwaves in the UK (Environmental Audit Committee, 2018; Howarth et al., 2019; Public Health England, 2014), our research shows that the evidence base available to decision-makers is limited. Where evidence does exist, it is accompanied by a research bias. That is, the vast majority of studies focus on health risks or infrastructure. Other at-risk sectors, such as transport, energy, water and food, which are just as important to the functioning of our everyday lives receive considerably less attention. Risks posed by heatwaves are rarely limited to a single sector but cut across different sectors in both predictable and unpredictable ways. Efforts to formulate, and in turn, implement heatwave policies can encounter problems as Government departments have different mandates, priorities, and influence, and as a result, institutional responsibilities become fragmented and/or deferred (Environmental Audit Committee, 2018).

Our research also found that the heatwave evidence base varies geographically. Nearly all the studies focus on England, with Scotland and Wales receiving only a small amount of attention and Northern Ireland ignored altogether. Likewise, the official Government policy and/or plan for managing heatwaves focuses on just England. Yet heatwaves do not observe administrative boundaries. Without a rich, robust and diverse evidence base, the risk of maladaptation and poor coping strategies could increase on a regional basis. A major concern, therefore, is that heatwaves become an 'invisible risk' for policymakers. A lack of evidence, and inconsistencies within that evidence base, can serve to deprioritise the seriousness of heatwave risks and the urgency of policy action. For instance, 892 excess deaths were attributed to the UK's 2019 heatwaves whereas 11 deaths were ascribed to floods in the same year yet the evidence base and managerial resources for heatwaves is tiny in comparison to flood risk.

Unless the problem of 'silo thinking' in the way in which Government policy is formulated and/or implemented is urgently addressed, and the research community broadens the scope of studies to consider other at-risk sectors, the connections between those sectors, and actively seeks to fill gaps in the knowledge base between regions, then heatwaves will remain at worst an 'invisible risk' amongst policymakers or at best a niche debate between healthcare and building professionals. Answers on how to tackle these challenges may already exist but require more interdisciplinary thinking and commitment. Future research should focus on bringing insights from practitioners, local communities, and the grey literature together with scholarly research to provide a fully rounded picture on heatwave research so that policymakers can be better informed and supported when making decisions.

CRediT authorship contribution statement

Chloe Brimicombe: Conceptualization, Formal analysis, Investigation, Resources, Writing - original draft, Visualization. **James J. Porter:** Conceptualization, Methodology, Validation, Writing - review & editing. **Claudia Di Napoli:** Resources, Writing - review & editing. **Florian Pappenberger:** Writing - review & editing. **Rosalind Cornforth:** Writing - review & editing. **Celia Petty:** Writing - review & editing. **Hannah L. Cloke:** Supervision, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.envsci.2020.10.021.

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AGU ADVANCING EARTH AND SPACE SCIENCE

Earth's Future

RESEARCH ARTICLE

10.1029/2021EF002064

Key Points:

- In the Northern Hemisphere, heat stress during the month of August is growing in area and is larger during a heatwave
- Heat stress area increase is greater over the populated land surface than the total land surface during August
- Impacts of Heatwaves are not sufficiency captured by international meteorological organization reports and emergency events impacts database

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Borderless Heat Hazards With Bordered Impacts

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Abstract

Heatwaves are increasing in frequency, duration, and intensity due to climate change. They are associated with high mortality rates and cross-sectional impacts including a reduction in crop yield and power outages. Here we demonstrate that there are large deficiencies in reporting of heatwave impacts in international disasters databases, international organization reports, and climate bulletins. We characterize the distribution of heat stress across the world focusing on August in the Northern Hemisphere, when notably heatwaves have taken place (i.e., 2003, 2010, and 2020) for the last 20 years using the ERA5-HEAT reanalysis of the Universal Thermal Comfort Index and establish heat stress has grown larger in extent, more so during a heatwave. Comparison of heat stress against the emergency events impacts database and climate reports reveals underreporting of heatwave-related impacts. This work suggests an internationally agreed protocol should be put in place for impact reporting by organizations and national government, facilitating implementation of preparedness measures, and early warning systems.

Plain Language Summary

Heat extremes are increasing in frequency, duration, and intensity due to climate change. Their impacts include a rise in death rates, a decrease in how much of a crop is produced and power outages. Here we show that there is a lack of reporting of impacts in international organization reports, international disaster databases. Further, heat stress, an impact of heat extremes is characterized using an index that is human-centric. With a focus on August and the Northern Hemisphere, we show that heat stress has grown in extent and is presenting a growing risk to more of the population over this millennium. This work suggests that organizations and national governments should come together to agree a protocol for how to best report heat impacts, so that we can be better prepared for them.

1. Introduction

Heatwaves are increasing in frequency, duration, and intensity due to climate change (Perkins-Kirkpatrick & Gibson, 2017; Russo et al., 2017; Vogel et al., 2019), and they occur over large areas often coinciding with other natural hazards such as wildfires and droughts (Sutanto et al., 2020; Vogel et al., 2019). Heatwaves are as impactful as other hazards, such as floods, but reporting their characteristics and impacts, as well as understand their risk is challenging because they are an invisible physical phenomenon (Brimicombe et al., 2021). They are also considered to be widely underreported in official databases, reports, and in news media (Harrington & Otto, 2020; Khare et al., 2015). However, robust reporting is essential not only for communicating the risk of heatwaves, but also to develop effective policy and action (Harrington & Otto, 2020; Howarth et al., 2019; Kitzinger, 1999).

Heatwaves can be considered the most deadly meteorological hazard (World Meteorological Organization, 2019), responsible for the death of more than 70,000 and 55,000 people globally in 2003 and 2010, respectively (Robine et al., 2008; Schubert et al., 2011). Heatwaves have other health risks such as increased morbidity (Watts et al., 2019). In addition, they also cause cross-sectional risks including decreasing crop yields (Abass et al., 2018; Vercillo et al., 2020), putting a strain on power grids (Larcom et al., 2019), reducing productivity of laborers (Oppermann et al., 2017), and impacting economic activity (Kotz et al., 2021).

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Heatwave morbidity and mortality arise due to heat stress on the human body (Campbell et al., 2018), which can be defined as "*the build-up of body heat generated either internally by muscle use or externally by the environment*" (McGregor & Vanos, 2018). There is currently a lack of understanding of the exact nature of heat stress from a human thermal comfort perspective during heatwaves, how this has changed through time and how exposure to heat stress conditions might be changing. Existing heatwave research at a international level focuses only on temperature (Perkins-Kirkpatrick & Gibson, 2017; Vogel et al., 2019) and does not provide the necessary analysis on heat stress thus failing to answer recent calls for inclusion of physiological responses when assessing heat exposure and vulnerability (Nazarian & Lee, 2020; Vanos et al., 2020).

In this study, we provide quantitative evidence of the areas of the world that are exposed to heat stress with a focus on the Northern Hemisphere. We use the ERA5-HEAT reanalysis (Di Napoli et al., 2020) of the Universal Thermal Climate Index (UTCI) (Di Napoli et al., 2018, 2019). We analyze the change in heat stress extent for the month of August, a notable month for heatwaves since 2000 for both total land area and populated land area as well as consider to what extent exposure to heat stress conditions is growing. We compare these measures of heat stress to reported heatwave impacts to assess deficiencies in the reporting of these natural hazards. Using the heatwaves of August 2003, 2010, and 2020 notable for their intensity and impacts (Robine et al., 2008; Schubert et al., 2011), we compare ERA5-HEAT UTCI to heatwave impacts reported in the emergency events database (EM-DAT) international disasters database, international organization reports, and climate bulletins (Achberger et al., 2011; Copernicus Climate Change Service, 2021; CRED, 2020a; World Meteorological Organization, 2021).

We consider heatwaves to be borderless, unconstrained by the geography of the physical and human landscape. However, disaster reporting is severely constrained by national and institutional geographic boundaries. This work aims to demonstrate the extent of heat stress from heatwaves, to what extent heat stress is becoming an increasing hazard and demonstrate whether impacts are captured in reporting. Such evidence can be used to establish an internationally agreed protocol in order to provide robust global heat impact reporting by organizations and national governments. This in turn will provide the evidence to facilitate the implementation of preparedness measures and early warning systems for heat on a global scale.

2. Methods

2.1. ERA5-HEAT Universal Thermal Climate Index (UTCI) Reanalysis

Heat stress is assessed using the ERA5-HEAT reanalysis (https://doi.org/10.24381/cds.553b7518) which is freely accessible on the Copernicus Climate Data Store (Di Napoli et al., 2020). We use the 0.25° × 0.25° gridded Universal Thermal Climate Index (UTCI) from ERA5-HEAT at an hourly time step. The UTCI is shown to be a useful indicator of heatwaves and heat stress by studies in many countries (Di Napoli et al., 2018; Guigma et al., 2020; Pappenberger et al., 2015; Urban et al., 2021) and models the response of the human body to the outside thermal environment in terms of 2 m air temperature, mean radiant temperature, relative humidity, and 10 m wind speed (Bröde et al., 2012; Di Napoli et al., 2020). It is worth noting that although the UTCI has the units °C, it is not the same as temperature and provides an indication of the average human body response to different thermal environments (Jendritzky et al., 2012).

We calculate the monthly mean of the daily maximum UTCI for August 2003, 2010, and 2020 as well as the climatological of this for the UTCI for the 1981–2010 period. The latter is then used to calculate anomalies of the UTCI (°C) for the aforementioned months. Further, number of exposure hours to heat stress above 26°C is additionally calculated for the months (Nazarian & Lee, 2021). We focus on the Northern Hemisphere, the region with the largest area of land mass and the largest proportion of the global population (Chambers, 2020) and August was chosen because it historically has experienced notable heatwaves in both the Northern Hemisphere during the summer and the tropics where heat extremes do occur throughout the year (Perkins-Kirkpatrick & Gibson, 2017; Russo et al., 2016).

2.2. Reporting Global Heatwaves

We undertake a two-part review of reported heatwave information. First, we analyze the international natural disaster database EM-DAT for the August 2003, 2010, and 2020 heatwaves. Emergency Events Database

(EM-DAT) is a leading international disaster database run by the Center on the Epidemiology of Disasters (CRED) since 1988 (CRED, 2020a) and data are used in reports by the UN (Cullmann et al., 2020; World Meteorological Organization, 2019). A disaster is included in EM-DAT if it meets this definition "*as a situation or event which overwhelms local capacity, necessitating a request to the national or international level for external assistance, or is recognized as such by a multilateral agency or by at least two sources, such as national, regional or international assistance groups and the media*" (CRED, 2020b). Furthermore, a disaster is included if it is reported to kill more than 10 people or/and 100 or more people are affected or/and call for international assistance/declaration of a state of emergency (CRED, 2020b).

Second, we investigate how the August 2003, 2010, and 2020 heatwaves were reported in three major international climate reports by meteorological organizations, these reports inform on trends and extremes of the global or European climate on an annual basis. These are the American Meteorological Society State of the Climate reports (Achberger et al., 2011; American Meteorological Society, 2004), World Meteorological Organization reports (World Meteorological Organization 2004, 2011) and the Copernicus State of the Climate for Europe (Copernicus Climate Change Service, 2021). Other international reports are not included as they are written for a different year, for example, The State of the Climate in Africa is only for 2019 (World Meteorological Organization, 2020). In addition, they are not included if they do not specifically mention heatwaves (i.e., National Centers for Environmental Information, 2020).

2.3. Heat Stress Area

We assess heat stress area in two ways. The first makes use of the 26°C UTCI threshold, which, once exceeded, indicates thermal levels at which an individual would experience heat stress, ranging from moderate (26°C–32°C UTCI) to extreme (above 46°C UTCI). The second uses values above a 5°C UTCI anomaly compared to the heat stress climatology for August from 1981 to 2010. In both cases, we use gridded spatial data to create binary maps approach is used (Vitolo et al., 2019) with grid cells over the threshold set equal to 1, 0 otherwise.

As exposure to heatwaves is known to be greater in more populated areas (Chambers, 2020; Watts et al., 2017), the gridded data is first masked to land area, excluding Antarctica, and then also masked to populated land area using grid cells with a population count of over 0 from the Land Scan data set for 2000–2019 provided by the Oak Ridge National Laboratory (Dobson et al., 2000; Vijayaraj et al., 2007), with 2020 being masked to 2019 population count. All grid cells are then summed, allowing for proportions to be calculated. All calculations are carried out using Rstudio.

3. Results

3.1. International Heat Stress Characteristics From ERA5-HEAT

In each of the heatwave events considered in this study heat stress occurs between the latitudes of 50° north and 40° south (Figure 1, left panels). The maximum value for heat stress occurs in the Sahara and Arabian Peninsula, where the UTCI reaches a maximum value of 54°C which exceeds the extreme heat stress threshold of 46°C UTCI. Countries impacted include Algeria, Tunisia and Mauritania in North Africa and Oman, United Arab Emirates, and Saudi Arabia on the Arabian Peninsula. Further, there are high levels of heat stress in the average maximum values for August extending over much of the globe. This is across Europe including Spain, Croatia, and Germany; parts of Asia including Bangladesh, Vietnam, parts of India, and China; the Americas including parts of North America, Brazil, and Ecuador; and Northern Australia.

The anomaly of the UTCI with respect to the 1981–2010 climatology locates the centers of heat stress for August 2020, 2010, and 2003 (Figure 1, central panels). For August 2003 and 2020, above-average heat is centered on Russia and Siberia. During August 2010, the main heat stress hotspot is situated over Russia. In all three heatwaves, hotspots are also evident in the USA and Europe, but the anomalies are spatially different for these regions in each event. For example, in 2010 in the USA the hotspot is the east coast, during 2003 it is central and during 2020 it is the west coast.

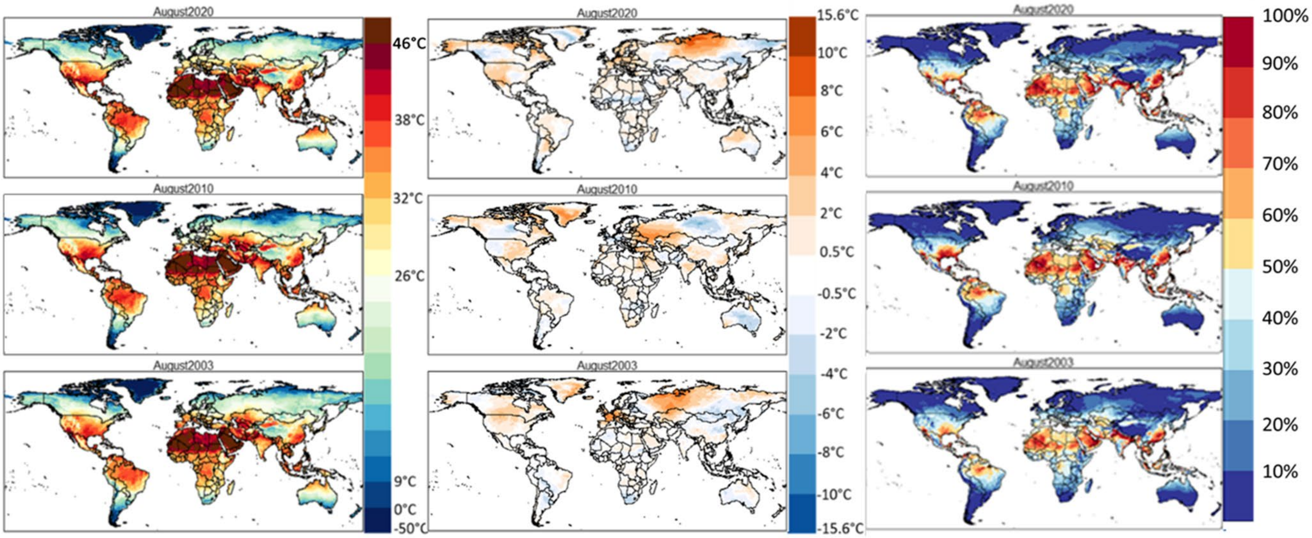

Figure 1. Universal Thermal Comfort Index (UTCI) monthly mean of the daily maxima (left), corresponding anomalies with respect to climatology (center), percentage time that hourly UTCI is over heat stress threshold (26°C) (right) from August 2020, 2010, and 2003 heatwaves.

In addition, the regions that are experiencing the highest intensity heat stress (Figure 1, left panels) are also experiencing the longest exposure time to above heat stress values (Figure 1, right panels). For example, North West Africa is experiencing exposure times of at least 80% in all three heatwaves. Europe sees a lower exposure time of up to 20% during all three heatwaves, but a larger heat stress anomaly (Figure 1, central panels).

3.2. Changes in Heat Stress During August

Populated areas have greater exposure to maxima in heat stress than the total global land mass (Figure 2). Over half of the populated land area has been exposed to heat stress levels in the month of August, every year since 2000. Seventy-four percent of the populated land area of the world was exposed to heat stress levels above 26°C UTCI in 2020 (Figure 2b). Peaks in data over the heat threshold are consistent with heatwave years. They are also consistent with El Niño years (e.g., 2003, 2006, 2007, 2013, 2018, and 2020). This suggests that heat stress area is larger during heatwaves.

There is an increasing trend in UTCI maxima anomalies of more than 5°C UTCI when compared to the 1981–2010 climatology (panel a) and maxima UTCI over the heat stress threshold of 26°C UTCI (panel b). The trend is stronger for the populated land area than for the overall land area, showing that the increase in heat stress is greater in areas which are populated. Peaks in the UTCI maximum anomalies are also consistent with years where a heatwave is also occurring (e.g., 2003, 2006, 2010, 2013, 2016, 2019, and 2020), but capture slightly different years to the above threshold method.

3.3. Evaluating Deficiencies in Heatwave Impact Reporting

The meteorological organization reports and EM-DAT do not capture the impacts to the extent we see heat stress (Figure 1). Notable differences can be seen for parts of North Africa including Tunisia and Mauritania; Asia including Vietnam and the Americas including Brazil and Ecuador.

During August 2020, a heatwave had the largest extent on record, covering 74% of the populated land surface, and extreme heat stress conditions are observed in the African Sahel and Arabian Peninsula with parts of Europe, Asia, the Americas and Northern Australia experiencing moderate to high heat stress levels (Figure 2b). Evidence of heatwaves for 2020 in EM-DAT is limited with only Belgium, France, the Netherlands, and the UK included. Our research shows a discrepancy between reports and countries experiencing heat stress.

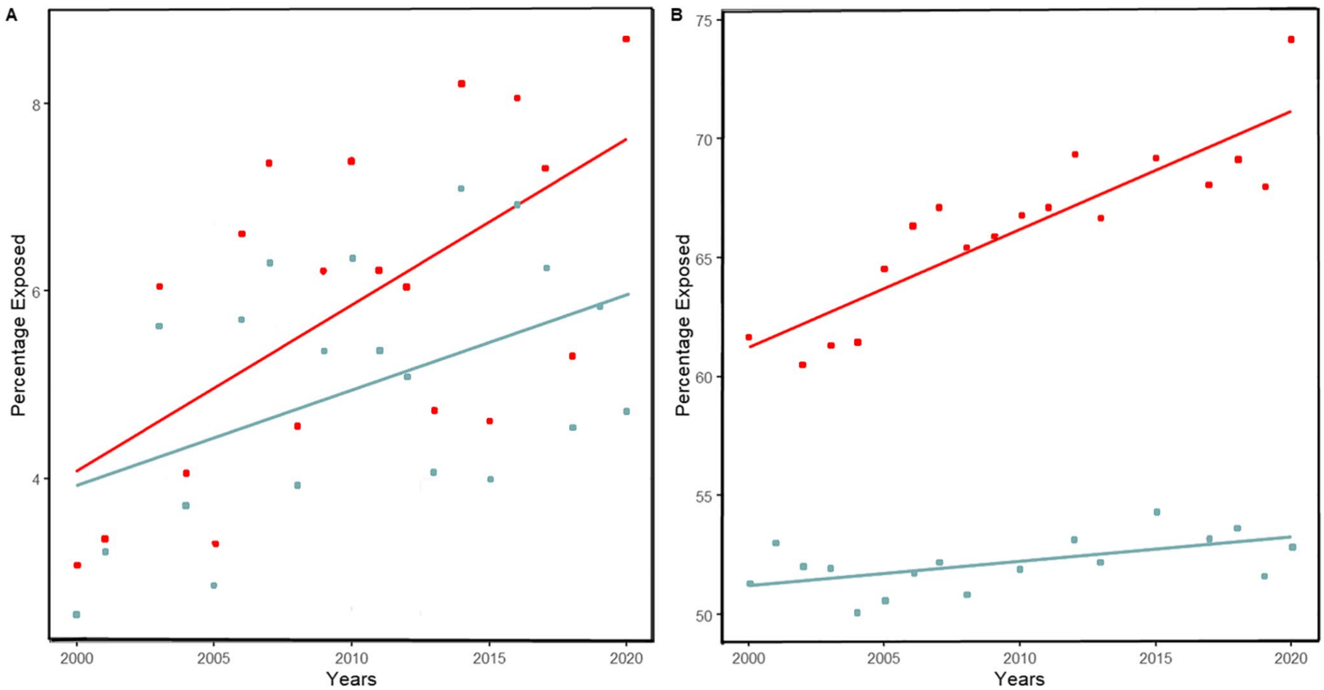

Figure 2. Percentage of land area exposed to heat stress values from 2000 to 2020, Red/Top: Proportion of populated land area as defined by LandScanTM (2000–2019) (Dobson et al., 2000; Vijayaraj et al., 2007), Blue/Bottom: Proportion of total land mass. Panel (a) uses values over a 5°C anomaly compared to August 1981–2020, Panel (b) uses maximum values over the 26°C UTCI heat stress threshold.

The World Meteorology Organization *State of the Climate* report for 2020 discusses heatwaves in a section with droughts and wildfires. It simply lists temperature records from heatwaves and mentions the regions of Europe, the US and some of Asia (Japan and Hong Kong) (World Meteorological Organization, 2021). The *European State of the Climate* has a specific session for heat stress despite showing evidence of heat stress they consider the overall summer not "unusually warm," with no long lived heatwaves and only short ones which broke a few temperature records (Copernicus Climate Change Service, 2021). In another section they state how it "was not remarkable" despite stating the "length of the period of with tropical temperatures was exceptional" stretching over a large area (Copernicus Climate Change Service, 2021). Figure 1 demonstrates how the exposure time to heat stress is similar in Europe for August 2020 in comparison to August 2003, while the anomalies in heat stress are slightly lower. In addition, Figure 1 shows many countries from North Africa (e.g., Morocco) and the African Sahel (e.g., Mauritania and Chad), as well as the West Coast of America, experiencing heat stress but these do not feature in English Language reports. In both the international meteorological organization reports currently available no impacts are reported.

The comparison between our heat stress data and reports allows us to show what the real-life impacts of heat stress are. However, it is limited with no English language reports for Algeria, Tunisia in North Africa and Mauritania in the African Sahel and Oman and Saudi Arabia on the Arabian Peninsula and the Americas including parts of North America, Brazil, and Ecuador, despite these areas experiencing high levels of heat stress in August 2020 (Figure 1) and is indicative of underreporting.

In August 2010, 67% of the populated land surface was exposed to heat stress levels (Figure 2b). Extreme heat was experienced again in the African Sahel and Arabian Peninsula. With parts of Europe, Asia, the Americas, and Northern Australia experiencing moderate to high heat stress levels (Figure 1). The evidence is stark for 2010 from EM-DAT, with only Brazil, India, Japan, and Russo listed as experiencing heatwaves (CRED, 2020a). Our results show during 2010 countries exposed to heat stress also included many North African countries (e.g., Tunisia, Algeria, and Libya), the Central USA and the Middle East (e.g., Jordan and Israel). The American Meteorological Society *The State of the Climate* (Achberger et al., 2011) and the World Meteorological Organization *The State of the Global Climate* (World Meteorological Organization, 2011) reports only make reference to heatwaves condition and excess mortality in Europe for 2010.

There are overall less reported impacts for 2010 in comparison to 2020. We again see a discrepancy from different reporting sources, there were no English language reports indicating heat stress impacts for North Africa, the Middle East or Latin America that were found in our systematic search.

A similar picture to that of August 2020 and 2010 is observed for August 2003. In August 2003, 62% of the populated land surface was exposed to heat stress levels (Figure 2b). Extreme heat was experienced again in the Sahara and Arabian Peninsula with parts of Europe, Asia, the Americas, and Northern Australia experiencing moderate to high heat stress levels (Figure 1). For EM-DAT anytime in 2003 the only countries listed are 15 in Europe, four countries of Bangladesh, India, Japan, and Pakistan in Asia and only Algeria in Africa (CRED, 2020a). Our results show (Figure 1) countries experiencing heat stress during 2003 included many countries in North Africa (e.g., Morocco, Tunisia, and Libya) during 2003, as well as Canada and the Eastern US and Asia and the Middle East (e.g., UAE, China, and Japan).

The American Meteorological Society *State of the Climate* reports (American Meteorological Society, 2004) and the World Meteorological Organization *The State of the Global Climate* (World Meteorological Organization, 2004) reports only make reference to heatwaves and excess mortality in only Europe, India, and Pakistan for 2003.

Overall, reports allow us to observe what the impacts of high, moderate, and extreme heat stress are. But, there is a huge discrepancy between regions experiencing heat stress and reporting impacts, leading to a lack of evidence of the impacts of heatwaves and heat stress.

4. Discussion

4.1. Heat Stress Expanding Is Exposing a Larger Proportion of the Population to a Risk

Our results demonstrate that heat stress is borderless, covering a large proportion of the total land mass during an August heatwave. In addition, during a heatwave the population exposed to the risk of heat stress is increasing and as such populations are experiencing a rise in baseline levels of mortality and morbidity more often during August. Moreover, with an increase in nations with an aging population this risk is greater, as those over 65 are especially vulnerable to heat illnesses and mortality (Arbuthnott & Hajat, 2017; Chambers, 2020; Kovats & Hajat, 2008; WMO & WHO, 2015). We also show how regions with the highest heat stress levels also have the highest exposure time which is an important element when considering heat morbidity and indicates less time to recover from heat exposure(Chambers, 2020; WMO & WHO, 2015).

In addition, this study presents evidence that heat stress area has grown since the millennium in the month of August (Figure 2), which is consistent with trends seen in temperature and extreme heat by other studies (Chambers, 2020; Perkins-Kirkpatrick & Gibson, 2017; Vogel et al., 2019; Watts et al., 2018). This provides evidence for the need of a global heat hazard alert system, as heat is not simply impacting one area at a time but many regions simultaneously, even when only considering August as we present here. However, we note that above the 26°C UTCI heat stress threshold is not experienced the same everywhere due to climate and acclimatization, which should be explored further and is only an indication of when one could start experiencing heat stress (Di Napoli et al., 2018; Nazarian et al., 2019).

4.2. Europe Receives the Most Attention

Furthermore, the results of this study show that when a heatwave exposes a large proportion of the total land mass to heat stress conditions, Europe is the focus of attention. For EM-DAT 20 out of the 28 countries featured are in Europe. Europe is also the most mentioned continent for international meteorological reports, featuring for all the heatwaves considered. Interestingly for Europe in 2020 there is a slight contradiction between sources the *European State of the Climate* (Copernicus Climate Change Service, 2021) is not considering this as long lived or remarkable, whereas the World Meteorological Organization *State of the Climate* (World Meteorological Organization, 2021) consider it for this region as "significant." This demonstrates the need even in regions with the most attention the need for an international heatwave reporting protocol, which would prevent this confusing situation from occurring.

We provide evidence of the scale of the discrepancies in reporting of heatwaves with no reports considered mentioning Latin America and at most two mentioning Africa. These regions are in part in the tropics where heatwaves can occur all year. One reason is because the main language spoken in these areas is often not English. Other reasons behind areas globally where heatwaves are not reported can be complex, and includes the country is in a state of conflict, there is not the political will or there is not the funding for this to take place, for example, the political economy of hazards and disasters (Fankhauser & McDermott, 2014; Neumayer et al., 2014). This has led to a lack of evidence of what the impact of heatwaves and heat stress are, further supporting the need for a heatwave reporting protocol.

4.3. Influential Data

In comparison, EM-DAT is an influential database, being used by the UN in not only World Meteorological Organization reports (World Meteorological Organization, 2004, 2011) but also in Disaster Risk Management reports (Cullmann et al., 2020). In literature, it is often presented that EM-DAT has a bias on what disasters are recorded (Ceola et al., 2014; Gall et al., 2009; Fankhauser & McDermott, 2014). In reality, EM-DAT is the most reliable source of information on disasters (Cullmann et al., 2020) but is subject to the same challenges that are faced by all in recording and assessing heatwave impacts, where there is huge discrepancies between countries reporting (CRED, 2020c). In addition, because of the lack of attention and evidence heatwaves often are not perceived as a risk by international agencies and national governments leading to impacts going unknown and in some regions the situation is such that resources to report do not exist (Brimicombe et al., 2021; Harrington & Otto, 2020). Through the availability bias we are more likely to recognize a heatwave as a risk if it has previously been presented as such (Wolf et al., 2010). EM-DAT are aware of these discrepancies and are making good progress in addressing these (CRED, 2020c).

5. Conclusion

In summary, this study shows for the first time with a focus on notable August heatwaves and the Northern Hemisphere that heat stress is growing in area and is larger during the month of August. It also demonstrates how heatwaves are borderless not constrained by political boundaries and that impacts are not adequately reported—a deficiency in risk reporting. To start solving the discrepancies presented here between heat stress exposure and impact reports we offer three suggestions to address these aimed at building the evidence base that is currently lacking, and putting in place the robust adaptation measures needed.

These are: *First, the establishment of an international protocol for reporting heatwave impacts for international organizations and national governments*. This will allow us to build an evidence base of ongoing heat impacts so that the right adaptation measures can be put in place, building resilience to heat in our changing climate. *Second, improve recording in EM-DAT and make it clear in all reports that it has discrepancies being addressed*. This will prevent the potential perception amongst those that work in natural hazards that heatwaves present less of a risk than other hazards such as storms and flooding. It in addition will support the first suggestion, by building an evidence base. *Third, implement a Global Heat Hazard Alert System*. This would follow guidelines set out in the joint report by the World Health Organization and World Meteorological Organization (WMO & WHO, 2015). This should be similar to GloFAS implemented and maintained by ECMWF for flooding (Alfieri et al., 2013; Emerton et al., 2016) and would inform countries when the risk to heat stress is highest. As well as, indicating when a country and international organization should be putting extra preparedness measures in place, but also when to expect an increase in impacts. In addition, we suggest that it should in some way include acclimatization, which was not the focus here and is an important aspect that needs further research. By investing in such measures, we can improve resilience to heatwaves, which are increasing in frequency, duration, intensity, and area as a result of climate change.

Data Availability Statement

ERA5-HEAT, provided by ECMWF is freely accessible here: https://doi.org/10.24381/cds.553b7518 (Di Napoli et al., 2020). The Oak Ridge National Laboratory LandScanTM population count data set from 2000 to 2019 are freely available to those in educational organizations or the US Federal Government (Dobson et al., 2000; Vijayaraj et al., 2007).

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Thermofeel: A python thermal comfort indices library

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A B S T R A C T

Here the development of the python library *thermofeel* is described. *thermofeel* was developed so that prominent internationally used thermal indices (i.e. Universal Thermal Climate Index and Wet Bulb Globe Temperature) could be implemented into operational weather forecasting systems (i.e. the European Centre for Medium Range Weather Forecasts) whilst also adhering to open research practices. This library will be of benefit to many sectors including meteorology, sport, health and social care, hygiene, agriculture and building. In addition, it could be used in heat early warning systems which, with the right preparedness measures, has the potential to save lives from thermal extremes.

Code metadata

Current code version	*1.2.0*
Permanent link to code/repository used of this code version	https://github.com/ElsevierSoftwareX/SOFTX-D-21-00124
Legal Code License	*Apache License version 2*
Code versioning system used	*Git*
Software code languages, tools, and services used	*Python*
Compilation requirements, operating environments & dependencies	*Linux and IOS operating systems for some methods indicated in documentation*
If available Link to developer documentation/manual	https://thermofeel.readthedocs.io/en/latest/?
Support email for questions	servicedesk@ecmwf.int

1. Motivation and significance

Extreme heat is an increasing killer hazard and research around heatwaves and heat stress is growing [1–4]. However, there is not a universal definition of heatwaves and this has led to the use of many different heat indices by studies globally [5]. In addition, cold weather continues to cause excess mortality and causes challenges for infrastructure for example Winter in Texas 2021 [6]. Key indices include wet bulb globe temperature [7,8] and the biometerological method of the Universal Thermal Climate Index (UTCI) which brings together meteorological parameters and a body model providing a human centric heat index [9,10].

To date there is no comprehensive library that brings together the most prominent thermal indices, with only **pythermalcomfort** [11] existing for a small selection of indoor thermal comfort indexes, **comfort** [12] not being maintained and undocumented and **ladybug-comfort** [13] which is not developed specifically for numerical weather prediction and does not provide the same methods as *thermofeel*. This makes it difficult to incorporate thermal comfort indices into numerical weather prediction services as well as to adhere to open science best practices, such as reproducibility and transparency, that are widely being adopted [14].

The development of thermofeel as a python library was chosen due to the popularity of the language for scientific applications,

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Nomenclature

t2 m	2 m temperature (K)
td	dew point temperature (K)
va	wind speed at 10 metres height (m/s)
rh	relative humidity (%)
svp/e_hPa	saturation vapour pressure (hPa)
mrt	mean radiant temperature (K)
mrtgt	mean radiant temperature from globe temperature (K)
ssrd	surface solar radiation downwards (J/m^2)
ssr	surface net solar radiation (J/m^2)
fdir	total sky direct solar radiation (J/m^2)
strd	surface thermal radiation downwards (J/m^2)
strr	surface net thermal radiation (J/m^2)
lat	latitude
lon	longitude
y	year
m	month
d	day
h	hour
tbegin	time step beginning
tend	time step end
cossza	cosine of the solar zenith angle (°)
utci	universal thermal climate index (°C)
wbt	wet bulb temperature (°C)
bgt	globe temperature (°C)
wbgt	wet bulb globe temperature (°C)
wbgts	wet bulb globe temperature simple/approximation (°C)
hi	heat index (°C)
net	normal effective temperature (°C)
C	Celsius
K	Kelvin
m	metres
J	Joules
Pa	pascal

usually with faster run-time on a given system than that of R, a comparable language [15]. It also has a range of free learning courses associated with it, making it easier to learn than other common scientific languages such as C, C++ or Fortran [16]. In addition, it has a constantly growing catalogue of libraries that aid testing and documentation but complement the methods presented in *thermofeel* [17].

thermofeel allows the user to reproduce the methods used in the development of the ERA-5 HEAT dataset which provides historical world-wide data records for mean radiant temperature and universal thermal climate index [10]. In addition, it extends this dataset by giving users methods to easily calculate the most prominent heat indexes, with a current focus on outdoor thermal comfort. Users can use the methods on a range of different data types by making use of existing python libraries.

Most notably this library presents the first operational method of calculating the wet bulb globe temperature from mean radiant temperature [18,19]. Furthermore, *thermofeel* is developed by the European Centre for Medium Range Weather Forecasts (ECMWF) following well established development procedures for time-critical operational software and contains methods that are currently being tested and integrated into ECMWF's weather forecasting product generation systems.

2. Software description

2.1. Software architecture

The library thermofeel contains a main module with the calculation methods and a helper module which is called in the background for auxiliary functions. The functional design of this library allows for easier maintenance and, since each calculation method is implemented as a *pure function* guaranteeing no side-effects, the library can be easily used in parallel and concurrent environments such as Dask [20]. Moreover, this also allows each calculation method to simultaneously support scalars and numpy arrays as input, performing the calculations elementwise where appropriate and thus returning a compatible result (scalar or arrays) as output. This design was intentional to ease the integration with ECMWF's parallel computing environment. This library was developed and tested on the Linux and Mac OSX operating systems, and we believe it is fully compatible with any POSIX system supporting Python 3.

2.2. Software functionalities

thermofeel provides methods to calculate the most prominent indices which currently focuses on outdoor thermal comfort. Ahead we discuss the methods and present some of the relevant literature describing them in more detail, with more depth provided in the *thermofeel* documentation (https://thermofeel.readthedocs.io/en/latest/?). Table 1 shows the different thermofeel index calculation methods

2.3. Software exceptions and validation

We filter the data as is indicated by the original method documentation where appropriate. For example, the UTCI is set to −9999 when its input parameters – temperature, wind speed, relative humidity and mean radiant temperature – fall outside specific validity ranges [10]. In addition, adjustments are calculated for set thresholds for solar zenith angle integrated and heat index adjusted.

2.4. Software validation

The thermofeel library also contains unit tests for all provided calculation methods and based on the pytest library. The inputs for the tests are based upon the average hourly data from ERA5 reanalysis [31] for the 2nd November 1996 and the 2nd August 2003. An example of the inputs can be seen in Table 2 and the outputs in Table 3. We implemented further tests on some methods, e.g. on the cosine of the solar zenith angle method, and these can be found on the software repository.

3. Illustrative examples

To test how a user might apply the methods presented in Section 2.2, Table 1 to meteorological data, we produced visual maps of all the indices using data from ERA-5 [31] reanalysis for 06UTC on the 8th June 2020 which is shown in Fig. 1. These figures can be easily produced from our library and the existing **netCDF4, matplotlib** and **cartopy** libraries using source code 1. We also provide examples using other python libraries developed by ECMWF such as magics and eccodes these can be seen in the GitHub examples directory (https://github.com/ecmwf-projects/thermofeel/tree/master/examples).

Table 1
Showing thermofeel index calculation methods.

Name	Function	Description	Reference
Solar declination angle	solar_declination_angle(jd,h)	Returns declination angle in degrees and time correction in hours	
Relative humidity	calculate_relative_humidity_ percent(t2 m,td)	Returns relative humidity as a percentage	
Saturation vapour pressure	calculate_saturation_vapour_ pressure(t2 m)	Returns relative humidity as water vapour pressure units hPa	
Cosine of the solar zenith angle instant	calculate_cos_solar_zenith_ angle(lat,lon,y,m,d,h)	Returns the cosine of the solar zenith angle which is used to calculate mean radiant temperature	[21]
Cosine of the solar zenith angle integrated	calculate_cos_solar_zenith_angle_ integrated(lat,lon,y,m,d,h,tbegin,tend,intervals_ per_hour=1, integration_order=3,):	Returns the cosine of the solar zenith angle which is needed to calculate mean radiant temperature from solar radiation, based upon an integration over forecast steps	[21]
Mean radiant temperature	calculate_mean_radiant_ temperature(ssrd, ssr, fdir, strd, strr, cossza)	Returns mean radiant temperature (mrt) in kelvin, incidence of radiation on the body which is used in the utci and wbgt calculations	[22]
Universal Thermal Climate Index (UTCI)	calculate_utci(t2 m, va, mrt, ehPa)	Returns the biometeorology index the universal thermal climate index (utci) in °C	[9,10]
Wet bulb globe temperature simple	calculate_wbgts(t2 m)	Returns an approximation of wet bulb globe temperature known as wet bulb globe temperature simple in this library °C	[23]
Wet bulb temperature	calculate_wbt(t2 m,rh)	Returns wet bulb temperature calculated using an empirical expression from temperature and relative humidity percent	[24]
Globe temperature	calculate_bgt(t2 m, mrt, va)	Returns globe temperature calculated from temperature mean radiant temperature and 10 metre wind speed in °C (Method not tested for windows operating system)	[18,19]
Wet bulb globe temperature	calculate_wbgt(t2 m,mrt,va,td)	Returns wbgt using the wet bulb temperature and globe temperature methods as components into the wbgt equation	[25]
Mean radiant temperature from globe temperature	calculate_mrt_from_bgt(t2 m, bgt, va)	Returns mean radiant temperature using the inverse method to calculate_bgt in °C	[18,19]
Humidex	calculate_humidex(t2 m, td)	Returns humidex a heat index that incorporates relative humidity with temperature in °C	[26]
Normal Effective Temperature (NET)	calculate_net_effective_temperature(t2 m, rh, va)	Returns normal effective temperature (NET) which is a model of how a human responds to meteorological parameters in °C	[27]
Apparent temperature	calculate_apparent_ temperature(t2 m,rh,va):	Returns apparent temperature a heat index modelled on wet bulb globe temperature in °C	[28]
Wind chill	calculate_wind_chill(t2 m,rh,va)	Returns wind chill is designed to emulate how cold it feels in a very windy environment in °C	[29]
Heat index simplified	calculate_heat_index_simplified(t2 m, rh=None)	Returns heat index simplified the original method for heat index in °C	[30]
Heat index adjusted	calculate_heat_index_adjusted(t2 m, td)	Returns heat index that is adjusted between different thresholds to be more accurate in the tropics in °C	[30]

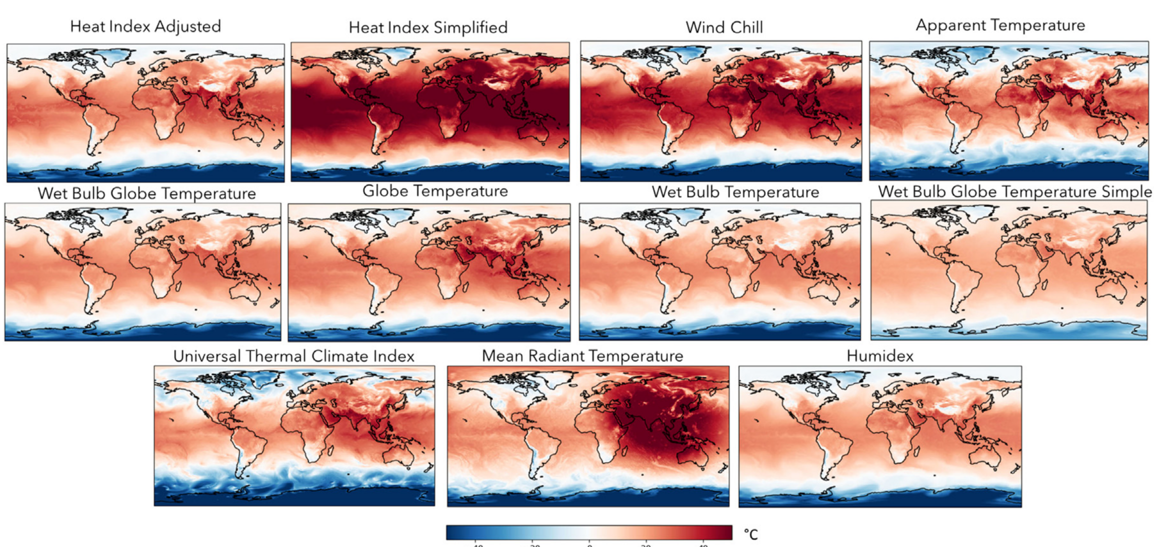

Fig. 1. Global maps of thermal indexes for 06UTC on the 8th June 2020 as described in Section 2.2, Table 1.

In addition, in Fig. 2, we present two approaches to calculating the cosine of the solar zenith angle [21]. A method which is integrated over forecast steps and is specialised for a forecasting system with a beginning and end time, where radiation values are

Table 2
The test variable values for thermofeel.

t2m K	td K	va m/s	mrt K	ssrd W/m^2	ssr W/m^2	fdir W/m^2	strd W/m^2	strr W/m^2	cossza °
310	280	2.00	300	604146	471818	374150	1061213	−182697	0.5
300	290	0.02	310	604135	467182	377084	1061000	−183218	0.5
277	273	0.59	286	607954	464531	383763	1061090	−184536	0.5
277	273	0.59	286	613806	463360	391216	1061362	−186295	0.5
277	273.	0.60	286	619349	462326	398038	1062483	−187558	0.5
277	273	0.59	286	626611	463422	406661	1063639	−189544	0.5
277	273	0.59	286	634958	465688	416602	1064458	−192353	0.5
277	273	0.59	287	638089	463850	418866	1066043	−194661	0.5
277	273	0.59	287	640019	462945	42167	1066746	−196444	0.5

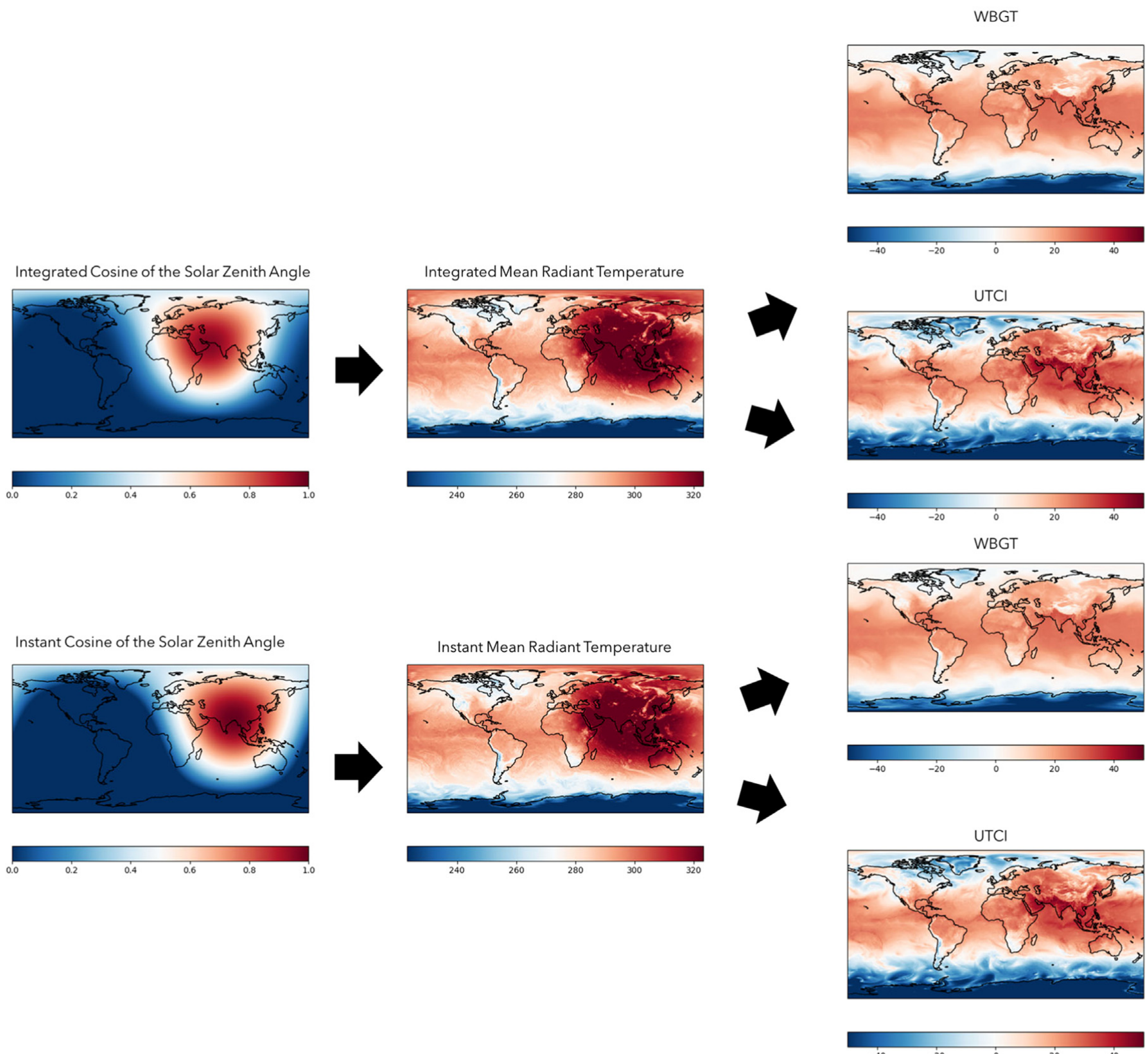

Fig. 2. Methods for using the two cosine of the solar zenith angle calculations.

accumulations, as well as an instantaneous method which only needs the UTC (Universal Time Zone) hour to calculate the cosine of solar zenith angle. Cosine of the solar zenith angle is a key component of mean radiant temperature [22] which is used to calculate the thermal indexes the UTCI and WBGT [10,19].

The difference between these two approaches (mean value) is tiny at 1×10^{-8} for the UTCI and 2×10^{-9} WBGT final output, and this allows for an accurate cosine solar zenith angle to be calculated with a simpler method that requires less parameters.

Source Code 1: Showing an example of the methods for 06UTC on the 8th June 2020, run on a Linux operating system.

4. Impact

Heat stress is a growing impact of climate change, with heatwaves increasing in intensity, frequency and duration [1]. In addition, cold stress is continuing to have an impact [32]. It is therefore important to have a robust set of methods to aid research and the development of early warning systems in this field [33]. We anticipate *thermofeel* will have a large impact on the research of heat stress, heatwaves and thermal comfort as a whole. It allows for open science practices [14] to be more readily applied to the extreme thermal research area in a way not available before. We also expect this library to be easily extendable

Table 3
The test outputs for thermofeel calculated using the inputs from Table 2.

rhp %	svp hPa	Heat index °C	Heat index adjusted °C	Humidex °C	mrt K	net °C	utci °C	wbgt °C	wbgts °C	Wind chill °C
15.93	62.31	68.27	34.59	31.82	286.04	40.75	33.50	35.61	26.72	60.09
54.31	35.37	52.14	27.53	23.12	286.11	31.49	29.93	25.78	19.99	50.75
74.75	8.19	16.82	2.51	1.07	286.29	3.41	8.63	3.27	6.02	9.30
74.77	8.20	16.86	2.53	1.09	286.54	3.43	8.64	3.29	6.03	9.32
74.74	8.23	16.93	2.58	1.14	286.81	3.50	8.76	3.34	6.06	9.41
74.47	8.27	17.07	2.67	1.21	287.11	3.60	8.93	3.42	6.11	9.56
74.32	8.31	17.17	2.73	1.27	287.42	3.68	9.10	3.48	6.15	9.66
73.80	8.40	17.40	2.88	1.40	287.70	3.85	9.28	3.63	6.23	9.90
73.41	8.44	17.53	2.95	1.47	287.85	3.94	9.37	3.71	6.28	10.01

by the research and operational weather forecast communities, as well as those in the humanitarian sector.

In addition, it allows for easy integration of thermal comfort indexes into operational weather forecasting. Further, we envision that cross-sectional users will benefit from our library, from researchers and operational meteorologists [10] to health professionals [5] and those in engineering and urban planning [34].

Thermofeel calculation methods are being tested and integrated into the operational weather forecasting systems at ECMWF. On a global scale this will be the first time these methods will be forecasted, and lead to practical applications. For example, with the right preparedness measures *thermofeel* methods could save lives and build heat resilience [33]. The library has also the potential to be commercialised and applied to the growing area of climate services [35,36] through the development of a mobile app for health services.

5. Conclusions

Here we have set out the key information of the python library *thermofeel*. This library has been designed so that thermal indexes can easily be incorporated into numerical weather prediction and operational forecasting systems. In addition, it adheres to open source development and robust operational testing and acceptance procedures. We have produced comprehensive documentation and provided examples of how to use this library to further aid users. We envision that this library will be of benefit to a wide range of users across sectors and could aid in the further development of early warning systems for thermal extremes.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Technical Memo

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Calculating the Cosine of the Solar Zenith Angle for Thermal Comfort Indices

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Abstract:

The cosine of the solar zenith angle (cossza) is a key component in Mean Radiant Temperature (MRT). Mean Radiant Temperature is used in the calculation of the Universal Thermal Climate Index (UTCI) and can be used in the calculation of Globe Temperature a component of the Wet Bulb Globe Temperature (WBGT), both of which are important thermal comfort and heat stress indices. It has previously been demonstrated that in numerical weather prediction services cossza should be integrated over a time step for the most accurate results. Here, we present the comparison of the operational cossza being used to create ERA5-HEAT, an instantaneous approach and a Gauss-Legendre Integration cossza. We further calculate MRT and UTCI for the ERA5-HEAT method and the methodology in the *thermofeel* library and see discrepancies in the approaches of on average -1.5K for MRT and -0.42K for UTCI. We suggest that the methodology in the *thermofeel* library supersedes the operational c code and is published alongside the existing ERA5-HEAT dataset in addition to forecast data being published, for users to make their own comparisons and extend this data's usefulness. We also suggest that a sensitivity analysis of the UTCI is carried out to aid better understanding of this thermal comfort index.

Introduction

The cosine of the solar zenith angle (cossza) is the angle between the sun's rays and the vertical (Aktaş & Kirçiçek, 2021). It is a key component in the calculation of mean radiant temperature (MRT), (Di Napoli et al., 2020; Vanos et al., 2021) which is used to calculate other thermal and heat indexes such as the Universal Thermal Climate Index (UTCI) (Fiala et al., 2012; Di Napoli et al., 2021) and the Globe Temperature component of Wet Bulb Globe Temperature (WBGT) (De Dear, 1987; Guo et al., 2018). In addition, MRT has been shown to be a better predictor of mortality than air temperature (Ta) which is one of the main impacts of extreme heat (Thorsson et al., 2014).

Each heat index has its benefits and limitations for modelling human thermal comfort. It has been shown for operation forecasts (i.e ECMWF) the most accurate version of cossza is a numerical integration over a forecast time step (Hogan & Hirahara, 2016). Different approaches to provide a cossza over a time step can be employed. These include integration methods as well as a simpler instant cossza.

Here we provide an overview of the current operational method for using cossza. Cossza is part of the ERA5-HEAT dataset (Di Napoli et al., 2021). We further compare this to an instantaneous method and a Gauss-Legendre Quadrature approximation of an integral, available as part of the new python thermal comfort library *thermofeel (Brimicombe, et al.,* *2021, 2022)*. This allows us to make recommendations for both *thermofeel* (Brimicombe, et al., 2021, 2022) and ERA5-HEAT (Di Napoli et al., 2021).

Methods

To calculate the cossza there are a number of different approaches that can be taken because an instantaneous cossza (hereafter instant) is required for the exact recorded time of the observation. Whereas using numerical weather prediction services leads to the requirement to calculate the integrated average cossza over a time step period, to have an accurate cossza. As such *thermofeel* provides both an instant cossza and an integrated cossza.

Instant cossza

Instant cossza is the simplest approach to calculating a cossza, it is calculated using equation 1 and 2 (Hogan & Hirahara, 2015, 2016). It involves the solar declination angle which is the angle between the equator and the center of the earth the center of the sun. In addition, it involves the local solar time.

$$\mu_0 = \sin\delta \sin\phi + \cos\delta \cos\phi \cos h$$

[1]

δ is the solar declination angle and ϕ is latitude, h is the local hour angle.

$$h = T + \lambda + \pi$$

[2]

T is local solar time and λ is longitude.

Integrated cossza

Integrated cossza is the method currently used in operations at ECMWF to calculate the ERA5-HEAT dataset it can be summarized by equation 3 (Hogan & Hirahara, 2015, 2016). It also takes into account sunrise and sunset when the value of cossza reduces to zero.

$$\overline{\mu_{0m}} = \sin\delta \sin\phi + \frac{\cos\delta \cos\phi\,(\sin h_{max} - \sin h_{min})}{h_{max} - h_{min}}$$

[3]

δ is the solar declination angle and ϕ is latitude, h_{max} is the end time of a time step and h_{min} is the beginning time of the time step.

Gauss-Legendre Quadrature integrated cossza

An accurate way to reduce the cost to a computer, in terms of computational power and time taken of integrating a cossza is to use an approximate numerical integration method and apply it to an instant cossza. Empirical experiments were carried out to compare Gauss-Legendre Quadrature to a Simpsons integral rule and Gauss-Legendre Quadrature chosen because it incurs in less redundant calculations when called over multiple time steps, since it does not evaluate the function at the interval boundaries(Zienkiewicz et al., 2005; Babolian et al., 2005; Goldstein, 1965). The Gauss-Legendre Quadrature is outlined in equation 4 where f(x) is equation 1 and visually in figure 1. ξ is the i-th coordinate of interval boundaries at which the function for cossza instant is evaluated and ω is the i-th weight factor for the numerical integral corresponding to the i-th coordinate.

$$\int_{h_{min}}^{h_{max}} f(x)dx \approx \frac{h_{max} - h_{min}}{2} \sum_{i=1}^{n} \omega_i f\left(\frac{h_{max} - h_{min}}{2} \xi_i + \frac{h_{min} + h_{max}}{2}\right)$$

[4]

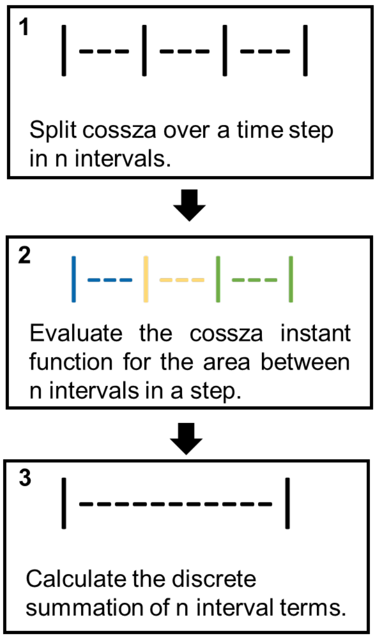

Figure 1: a schematic outlining the steps (1 to 3) taken to calculate a discrete summation integrated cossza using the instant cossza method (I.e., the distinct colours in step 2) in combination with the Gauss-Legendre quadrature approximation.

Mean Radiant Temperature

The mean radiant temperature can be defined as the incidence of radiation on a body. For a numerical weather prediction service, it requires 5 input radiations (surface-solar-radiation-downwards, surface net solar radiation, total sky direct solar radiation at surface, surface thermal radiation downwards, surface net thermal radiation) in addition to the cosine of the solar zenith angle (cossza). The full methodology for mean radiant temperature is available in Di Napoli et al., 2020 and is summarized in table 1 and equations 5 and 6.

$$MRT^* = \frac{1}{\sigma}\left\{f_a L_{surf}^{dn} + f_a L_{surf}^{up}\left[\frac{a_{ir}}{\varepsilon_p} + \left(f_a S_{surf}^{dn,diffuse} + f_a S_{surf}^{up} + f_p I^*\right)\right]\right\}^{0.25}$$

[5]

$$f_p = 0.308\cos\left(\gamma\left(\frac{0.998-\gamma^2}{50000}\right)\right)$$

[6]

Table 1: The radiation variables that are used in the calculation of the MRT in Equations 5 and 6. Table 1 from Di Napoli et al., 2020

Name	Symbol/Equation
Surface solar radiation downwards	Sdnsurf=Sdn,directsurf+Sdn,diffusesurfSsurfdn=Ssurfdn,direct+Ssurfdn,diffuse
Surface net solar radiation	Snetsurf = Sdnsurf − SupsurfSsurfnet=Ssurfdn−Ssurfup
Direct solar radiation at the surface	Sdn,directsurfSsurfdn,direct
Surface thermal radiation downwards	Ldnsurf Lsurfdn
Surface net thermal radiation	Lnetsurf=Ldnsurf−Lupsurf

A key component of Mean radiant Temperature is known as Istar this is defined as "*radiation intensity of the Sun on a surface perpendicular to the incident radiation direction*" (Di Napoli et al, 2020) in the current operational code this is calculated using equation 7. Where Direct Solar Radiation (dsrp) is available I* is equal to this variable.

$$I* = fdir\ /\ cossza\ (where\ cossza\ >\ 0.01)$$

[7]

Universal Thermal Climate Index

The UTCI is a bio-thermal comfort index which makes use of the meteorological parameters of 2m temperature, water vapour pressure, 10m wind speed and mean radiant temperature and a body model it is estimated by a 6-order polynomial which is summarized by equations 9 and 10 (Bröde et al., 2012; Fiala et al., 2012; Di Napoli et al., 2021).

$$UTCI(Ta, Tr, Va, Pa) = Ta + Offset(Ta, Tr, Va, Pa)$$

[9]

Where Ta= air temperature, Tr= mean radiant temperature, Va= wind speed Pa= water vapour pressure

$$Pa = Ps \times \frac{\varphi}{100}$$

[10]

Where Ps = Saturation Vapour Pressure and φ= relative humidity percent.

Results

The implementation of the integrated cossza (figure 2a) visually is different from the other cossza methods implemented, being clipped at the top of the parabola for the 42^{nd} time step after the initial date of 21 May 2021.The difference between the integrated cossza and the Gauss-Legendre cossza is at most ±0.1° (Figure 2d).The instant cossza has the largest area with complete darkness indicated by 0° values in (figure 2c). In addition, visually the instant cossza covers a slightly different area than the integrated approaches (figure 2c). This is because it is for the instant time at the 42^{nd} time step whereas the integrations are the average of step 39^{th} to 42^{nd}. Further, both the integrated cossza (figure 2a) and the Gauss-Legendre cossza (figure 2b) have a small gradient than the instant cossza (figure 2c) which can be seen in the color gradient in figure 2. This allows for sunset and sunrise to be considered more accurately because there is a greater range in cossza values between maximum sun and darkness.

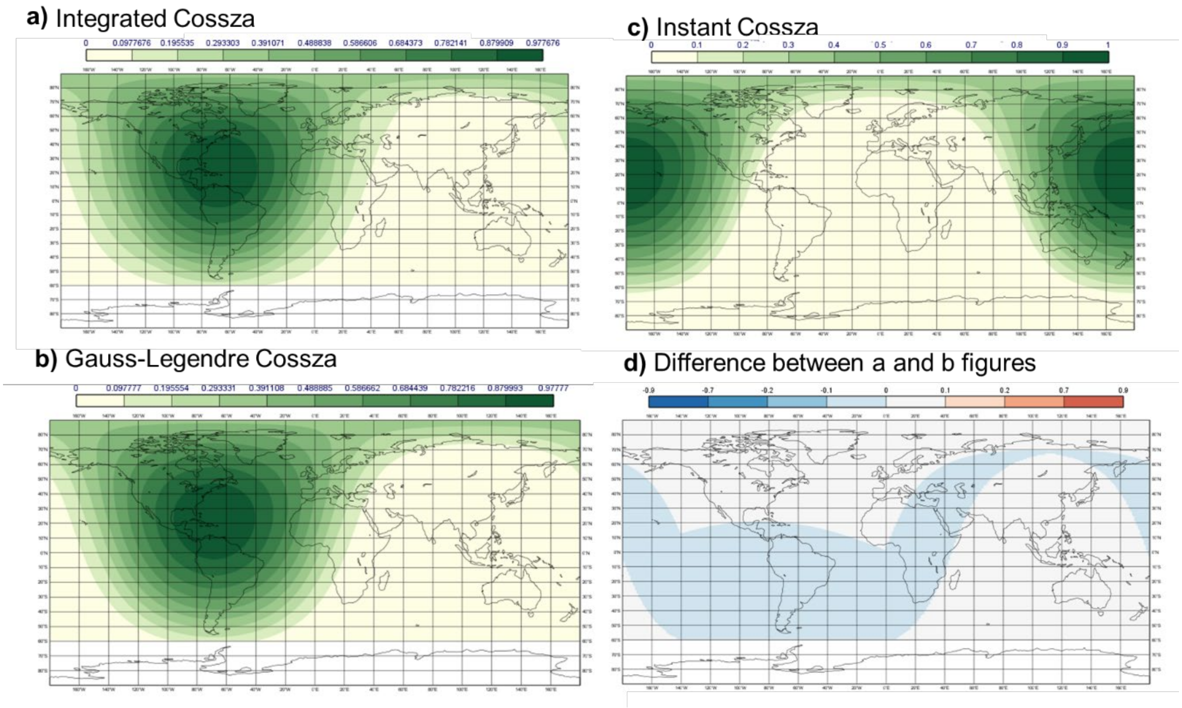

Figure 2: Showing the difference cossza approaches for 42hr lead time from 21 May on a 3 hour time step, a) the current operational (integrated) cossza for ERA5-HEAT calculated in the c coding language, b)an average of an gaussian integration of the instant cossza for a time step, c) an Instant cossza for a given hour and d) the difference between parts a and b of this figure.

The biggest difference is more than +10K between the operational MRT (figure 3a) and the Gauss-Legendre method (figure 3b) employed by *thermofeel* to calculate MRT in the area surrounding North America (120W,20W,20S,60N) for the 42nd step after an initial date of 21 May 2021 around where the continent is experiencing it's maximum cossza value (figure 3c). Whilst there are up to -5K anomalies evident for North America (figure 3c). Notably the current operational calculation of MRT does not consider the continent of Antarctica (figure 3a) and as such this is cropped out in all output plots.

In addition, considering the medium range forecast for the initial date 21 May 2021 00UTC, the maximum positive anomaly is 19K. In comparison, the largest negative anomaly is -28K. However, the difference in the mean anomaly over all time steps is -1.5K. This demonstrates that the difference in the methods is more evident in the extremes of the distribution of MRT.

In comparison, the biggest difference for the UTCI mirrors the patterns seen for the MRT. There is around a +5K difference between the operational UTCI (figure 4a) and the *thermofeel* Gauss-Legendre UTCI (figure 4b) in areas around North America, where cossza is at its maximum (figure 4c). Whilst there is a -10K anomaly where cossza is at its maximum (figure 4c). When considering the medium range forecast for the initial date 21 May 2021 00UTC, the maximum positive anomaly is 6.6K, whereas the mean anomaly is -0.42K.

In addition, there is a noticeable difference between both MRT and UTCI values (figures 5 and 6) when dsrp is present in the calculation of MRT using *thermofeel* in comparison to when it is approximated using fdir and cossza (equation 7). The biggest difference is in Greenland at up to +17K for MRT (figure 5c) and +6K for the UTCI (figure 6c). For MRT at the 42nd time step after an initial date of 27 July 2021 the mean anomaly between the approaches is +2K, whilst the min is 0K and the max +17K. In comparison the mean anomaly at the same time step for UTCI is 0.62K, the min is also 0K and the max anomaly is 6.5K.

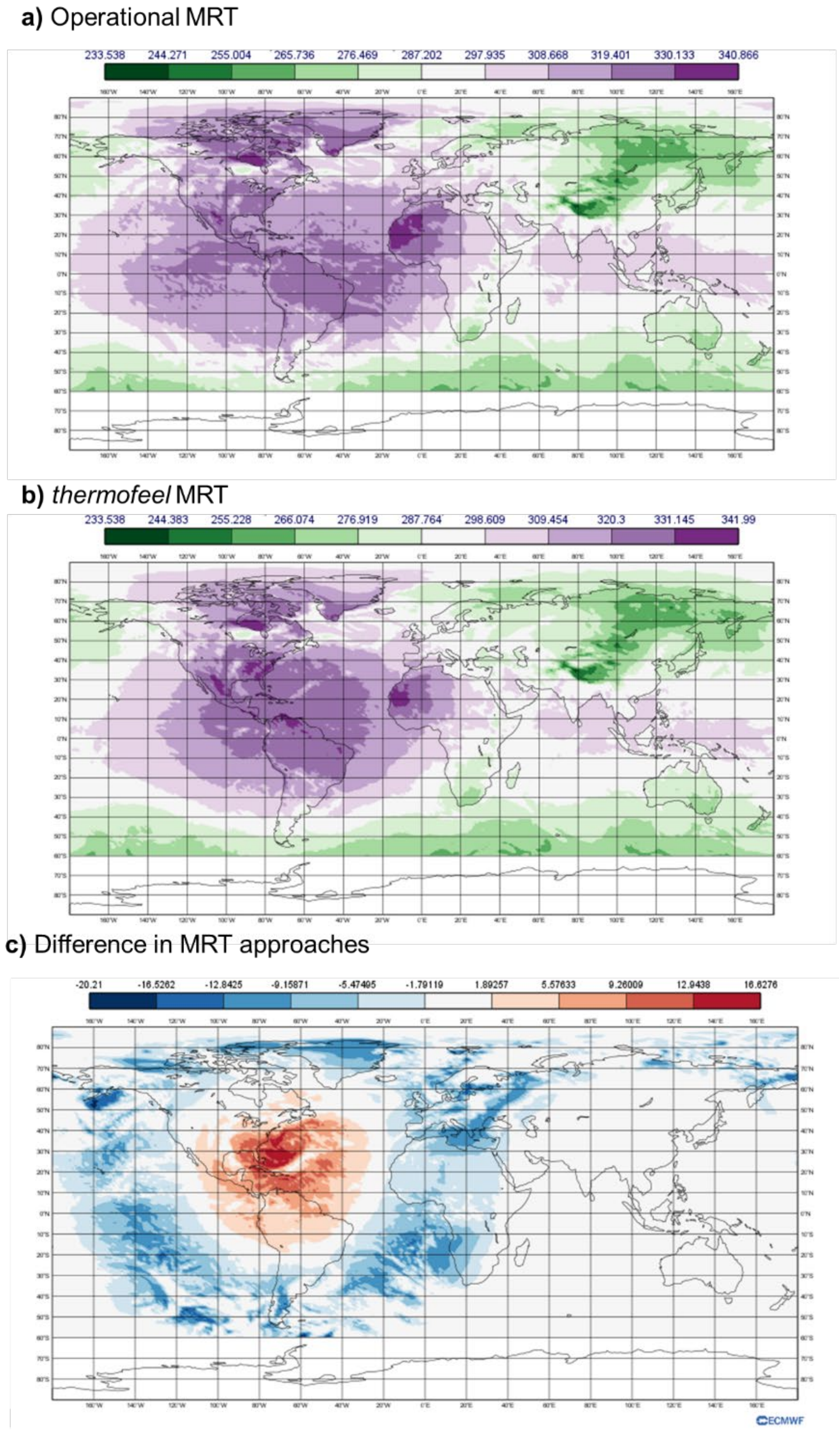

Figure 3: the operational c mean radiant temperature (top), the thermofeel mean radiant temperature (middle) and the anomaly plot of the approaches (bottom). For the 42nd step after the initial date 21 May 2021 at 00UTC.

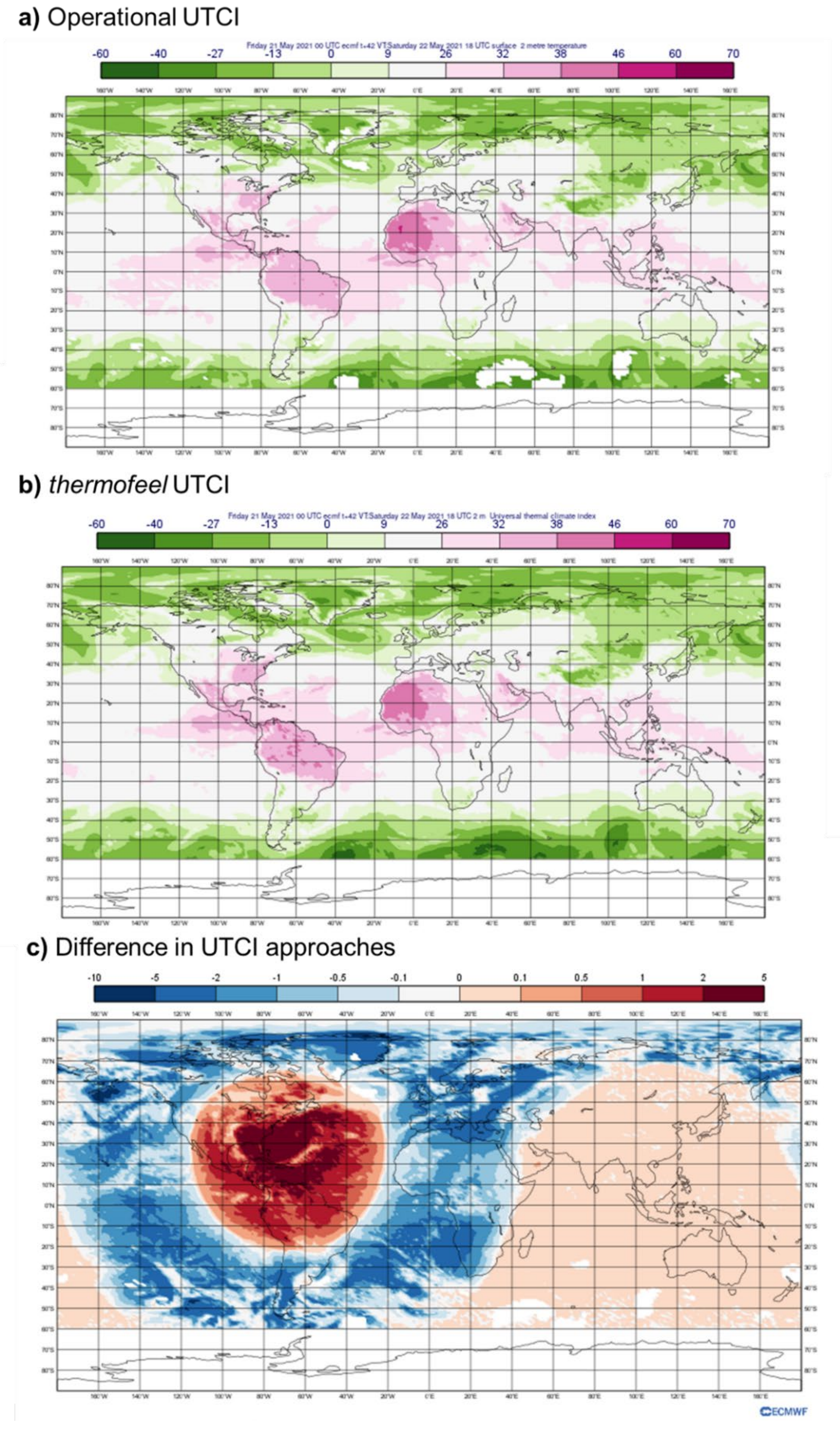

Figure 4: the operational c universal thermal climate index(top), the thermofeel universal thermal climate index (middle) and the anomaly plot of the approaches (bottom). For the 42nd step after the initial date 21 May 2021 at 00UTC.

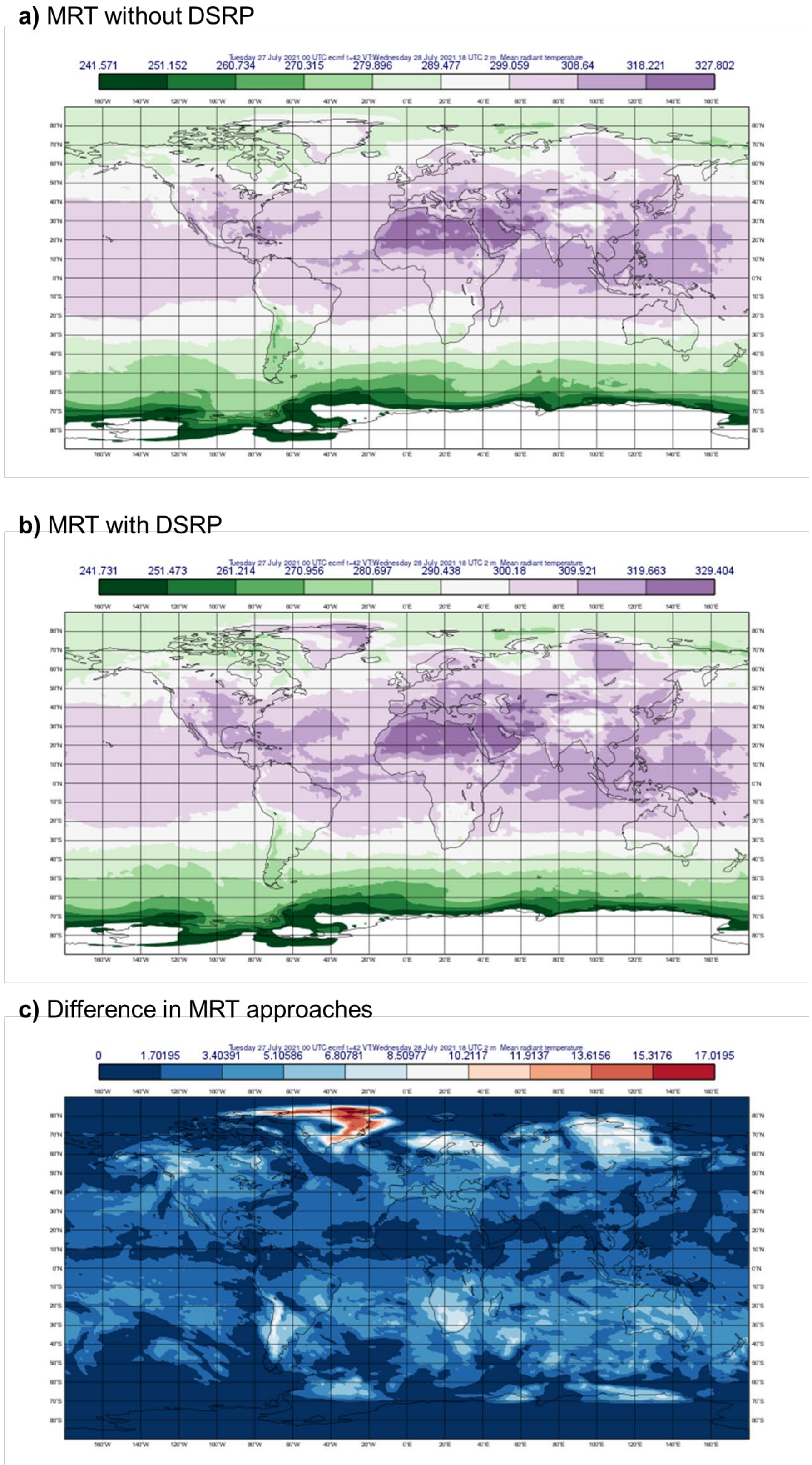

Figure 5: thermofeel MRT without dsrp(top), the thermofeel mean radiant temperature with dsrp (middle) and the anomaly plot of the approaches (bottom). For the 42nd step after the initial date 27 July 2021 at 00UTC.

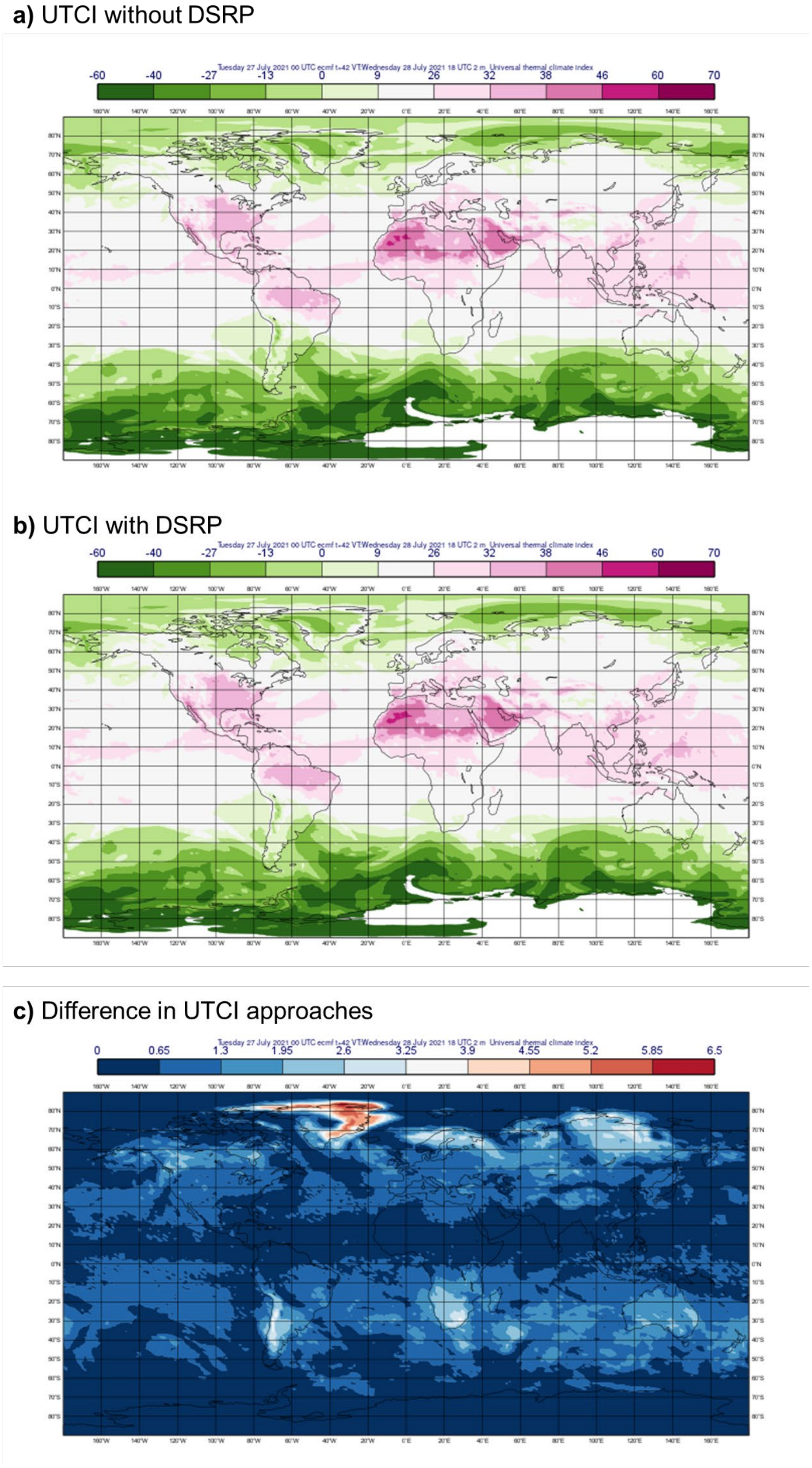

Figure 6: thermofeel UTCI from MRT without dsrp(top), the thermofeel UTCI from MRT with dsrp (middle) and the anomaly plot of the approaches (bottom). For the 42nd step after the initial date 27 July 2021 at 00UTC.

Discussion

We recommend that the Gauss-Legendre integrated cossza and the thermofeel methodology supersedes the operational c code used to calculate the ERA5-HEAT dataset. This is because the thermofeel method removes the clipping at the top of the parabola that is present in the c code (figure 2).

There is a substantial difference between the Gauss-Legendre integrated cossza employed in the thermofeel methodology to calculate MRT and UTCI in comparison to the operational c code currently creating the ERA5-HEAT dataset (Brimicombe et al., 2022; Di Napoli et al., 2021). This is more so evident in the extremes of the distribution of both UTCI and MRT. This suggests that the ERA5-HEAT dataset may be underestimating heat stress values while overestimating cold stress values, which could have implications for the health sector who can use heat stress forecasts to make lifesaving decisions (Blazejczyk et al., 2012; Jendritzky & Tinz, 2009; Di Napoli et al., 2019; Urban et al., 2021). The biggest difference is observed around where cossza is at its maximum (figure 3 and 4). However, the observed differences are larger when the step duration is bigger, and therefore the magnitude of error is less at 1 hour time step (i.e., ERA-5) in comparison to a 6 hourly forecast time step (i.e., after a 144-step). Further, there is a substantial difference between both MRT and UTCI values when dsrp is used in the place of fdir in the MRT calculation (equation 6 and 7).

We therefore recommend that if ERA5-HEAT is rereleased using the thermofeel methodology with fdir in the MRT calculation alongside the existing 'legacy' dataset available that the documentation indicates that differences are observed when dsrp is used in the place of fdir to be transparent with users. We recommend that the full forecast data is released as calculated using fdir for MRT using thermofeel to aid with decisions that are increasingly being made about thermal comfort conditions as a beta forecast and urge that dsrp be released in IFS (on all lead times) as a priority (Brimicombe et al., 2021, 2022).

In the ERA5-HEAT dataset Antarctica is currently cropped out and this is because of the many missing values that occur in this region (Di Napoli et al., 2021). We recommend that when the data is rereleased using the methodology introduced using the thermofeel library that Antarctica remains part of the dataset and that missing values and anomalous values are assigned as such, this is of benefit because it demonstrates to users that Antarctica does exist within the dataset but is often outside the range of the UTCI method (Bröde et al., 2012).

In addition, the UTCI and its components would benefit from a sensitivity analysis. We know that the windy and extreme cold conditions of Antarctica are outside the remit of the UTCI method, and previously it has been demonstrated that high MRT and low wind speeds lead to a higher UTCI values (Pappenberger et al., 2015), but, there is current understanding of which combination of the meteorological components of the UTCI (2m Air Temperature, MRT, Saturation Vapour Pressure and Wind Speed), lead to its hottest and coldest values. Such an analysis would allow us to better understand this thermal comfort index.

In addition, we suggest that the saturation vapour pressure method over ice is investigated in the calculation of saturation vapour pressure, a key component of the UTCI (Bröde et al., 2012; Hardy, 1998; Di Napoli et al., 2021). Currently the methodology for water saturation water vapour pressure is used universally, whereas for colder regions where ice is present on the ground the optimum approach is slightly different (Hardy, 1998). This could be useful as it could make the values for Antarctica within the range of the UTCI method and allow cold stress to be considered, which is currently not always possible.

Conclusion

We have demonstrated that the *thermofeel* methodology for calculating the variables of cossza, mrt and utci should supersede the operational c code that creates the ERA5-HEAT dataset. We recommend that it is used to create an ERA5-HEAT version 2 beta and is published alongside the legacy dataset, allowing for users to make their own comparisons as well as, the full forecast dataset as beta. In addition, we urge that dsrp is made operational in IFS so that a more accurate MRT can be calculated for the forecasts from *thermofeel*. In addition, we recommend that Antarctica is no longer cropped from the dataset, allowing users to recognize where data is missing and where it is present. Further, we recommend a sensitivity analysis of the UTCI is carried out to improve understanding of what combinations of the meteorological components lead to the highest and lowest values. Finally, the saturation vapour pressure over ice should be explored for the continent of Antarctica. Overall, the method introduced in *thermofeel* will allow for ERA5-HEAT to be readily expanded to operational forecasts and other thermal comfort indices, benefitting many users of ECMWF data.

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Is there a climate change reporting bias? A case study of English-language news articles, 2017–2022

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Abstract. How weather hazards are communicated by the media is important. Which risks are understood, prioritized and acted upon can be influenced by the level of attention they receive. The presented work investigates whether or not the number of weather hazard news articles has increased since 2017, which weather hazards received the most attention in the news articles, and how often climate change was discussed in relation to weather hazards in these news articles. The methods used are advanced searches of Google and the Emergency Disaster Database (EM-DAT) for media articles considering weather hazards – specifically floods, heat waves, wildfires, storms and droughts – between 2017 and 2022. Results suggest that storms are more likely to be reported than any other climate risk, though wildfires generate more news articles per event. Bias in reporting needs to be addressed and is important, because it can exacerbate unpreparedness.

1 Introduction

The Intergovernmental Panel on Climate Change's AR6 report demonstrates that storms, flooding, heat waves, wildfires and droughts have been increasing in intensity and frequency with climate change (IPCC, 2021). Since 2017, there have been a number of notable weather events: the Pacific typhoon season in 2018, the European floods in 2021, and the Mediterranean heat wave and wildfires in 2021 (Gao et al., 2020; Kreienkamp et al., 2021; Philip et al., 2021; Sullivan, 2021).

Communication of a risk does not always lead to the risk being understood (Porter and Evans, 2020); however, the media is a key actor in communicating climate change and has a moral obligation to highlight the risks of extreme weather and what action is needed (Boykoff and Yulsman, 2013; Kitzinger, 1999). In addition, it has been found that the media gives more attention to sensationalist views on climate change instead of to the consensus view (Meah, 2019; Petersen et al., 2019).

Research demonstrates that the bias in reporting hazards and climate change leads to deficits in attention and material resources (i.e. not fully recognizing or addressing the risk) (Brimicombe et al., 2021a; Howarth and Brooks, 2017). In comparison, it has been found that when more visual hazards such as floods and storms (Wilby and Vaughan, 2011) are used to demonstrate climate change risk – also known as objectifying climate change – there is an improved understanding of climate risk (Höijer, 2010).

Reported here for the first time, this study uses open science principles (Armeni et al., 2021; Nosek et al., 2015) alongside the advanced search tools provided by Google and the Emergency Disaster Database (EM-DAT) (CRED, 2020) to examine how weather hazards are mentioned in news articles published between 2017 and 2022. The aim is to understand: (1) whether or not the number of articles focused on weather hazards has increased since 2017; (2) which weather hazards receive the most attention; and (3) how often climate change is discussed in relation to those weather hazards.

2 Methods and data

All the methods and data chosen for this study are in keeping with open data and open science. Open data is where the research results are reproducible and transparent, whilst open science is a term given to the removal of the barriers to sharing any kind of output (Armeni et al., 2021).

2.1 Advanced Google search

An advanced Google search of the news category was carried out for the period of 1 January 2017 to 1 January 2022. Google was chosen, as it has the most comprehensive results in comparison to other search engines (i.e. Bing) and tools to assist with advanced searches. The search involved two stages: first, a search for all news articles in the relevant period containing the keywords "flood", "heat wave", "wildfire", "storm" and "drought" was conducted; second, this search criterion was repeated with the keywords "climate change" (Brimicombe et al., 2021b). Each term was assessed to consider whether it captured the most articles – for example, using "heat wave" not "heatwave" and "climate change" not "climate crisis" or "global warming". Each hazard was evaluated separately and their results compared, with duplicated results not included. Articles that mention more than one weather hazard were counted twice.

To counter any overestimates that occur where articles are not discussing a weather hazard but are using the term to describe something else, the approach taken is to look at the first 100 article headlines and to remove articles not discussing a weather hazard to give a better estimate of the true number of news articles. Examples included articles discussing "Goal droughts", "NFL Storm" and "the single *Heat Waves* from the band Glass Animals". Then, this proportion of articles was removed from the overall total, giving a new overall count of articles. For example, for the keyword "storms" in 2017, the initial search returned 6.31 million articles, but 21 out of the first 100 were not about the weather hazard, so 4.98 million articles were counted for storms.

Limitations in this method do remain, as it can still capture articles not explicitly about weather hazards; however, this is limited by the proportional approach taken. In addition, it is only likely to capture the English news media and will give a slightly different number of articles between users. As such, it is recommended that further, in-depth research should be carried out looking at news media sentiment.

2.2 EM-DAT hazard reporting

To supplement the findings of the advanced Google search, another source of data is used that is in keeping with open science: the Emergency Events Disaster Database (EM-DAT) EM-DAT is the leading international disaster database; it contains details of over 22 000 mass disasters that have occurred worldwide since 1900 and is compiled from a range of sources, including UN agencies and non-governmental organizations (NGOs) (CRED, 2020). This provides an overview of the number of weather hazards that have occurred every year for the last 5 years. This then allows for an assessment of how many articles have been written on average about each weather hazard. Figure 1 shows a count of the weather hazards included in EM-DAT that are considered by this study and that have occurred every year from 2017 to 2021 (CRED, 2020).

The limitations of this method are that there are biases in how hazards in this database are reported and that there is an underreporting of hazards by this database (Brimicombe et al., 2021a; Gall et al., 2009). In addition, this database only includes hazards that are considered a disaster, where an agency declares a state of emergency, or where it is reported that over 100 people have been affected (CRED, 2020). However, it remains the most comprehensive source of reported weather hazards (Brimicombe et al., 2021a; Gall et al., 2009).

3 Results

3.1 Has the number of weather hazard news articles increased since 2017?

Between 2017 and 2022, there has been an increase in the number of English-language news media articles for all weather hazards, amounting to more than 142 million articles over the last 5 years. In 2021, 28.1 million articles were about storms, whereas 169 000 articles were about heat waves (Fig. 2). Of interest, only 0.7 % of all news articles mentioned climate change and weather hazards together. The results for the number of articles mirror those for overall news articles written.

3.2 Which weather hazards receive the most attention in news articles?

The results in Sect. 3.1 change when the number of articles is considered as a proportion of the number of weather hazards reported in CRED (2020, their Table 1). The approach taken here is to aggregate the totals per hazard for the last 5 years to reduce the influence of the underreporting bias in EM-DAT. Figure 3 is another representation of the reporting bias introduced by EM-DAT, where the total costs for each hazard each year are shown. No losses are attributed to heat waves. The results for total damages mirror those for the total number of articles written. It can therefore be suggested that articles are more likely to be written for hazards that have the biggest financial losses associated with them.

Overall, for each individual weather hazard (total number of articles for all hazards in Fig. 2/total number of reported hazards in Fig. 1), 89 000 articles were written on average; however, the picture for each hazard varies widely – for example, one storm could have 10 times more articles written about it than another. A future study on this would be beneficial. On average, per wildfire (total number of articles about wildfires/total number of reported wildfires), there have been a total of 175 000 articles written in the last 5 years (Fig. 4). The weather hazard with the least number of articles per weather hazard occurrence over the last 5 years is heat waves, with an average of 12 000 articles (Fig. 4).

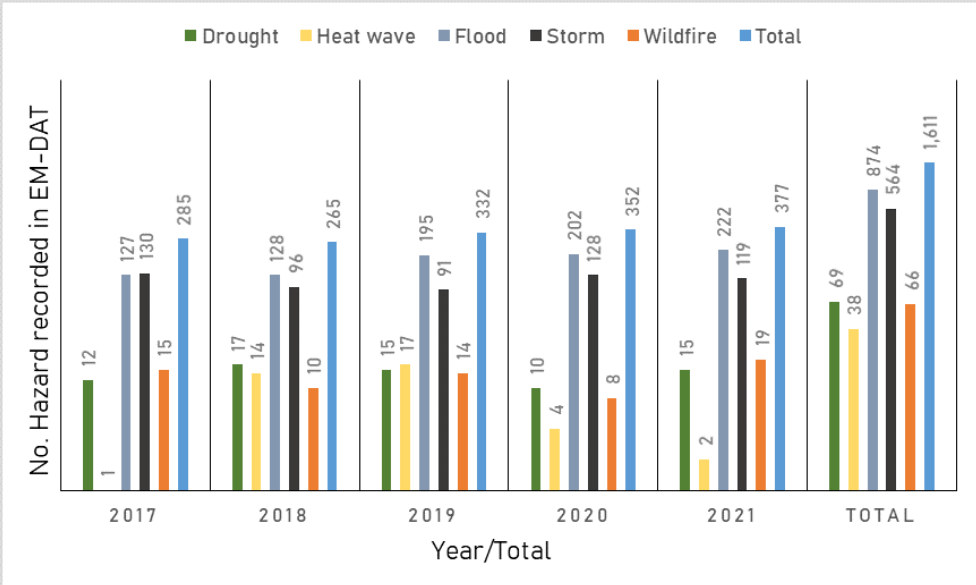

Figure 1. The total number of disasters reported per weather hazard for the last 5 years, as reported in EM-DAT (CRED, 2020).

3.3 How often is climate change discussed in relation to weather hazards in these news articles?

Overall, for each individual weather hazard, an average of 650 articles that also consider climate change were written (total number of articles including climate change in Fig. 2/total number of hazards reported in Fig. 1). The hazard with the most articles written is drought – on average, per drought, there have been 3 000 articles written in the last 5 years (Fig. 4). The weather hazard with the least number of articles written per weather hazard occurrence over the last 5 years is floods, with an average of 200 articles (Fig. 4).

4 Discussion

4.1 Why are some hazards discussed by English-language news media more?

Heat waves have the least amount of news media articles. This should not be of surprise, given other research demonstrating the consistent underreporting of this weather hazard (Harrington and Otto, 2020; Vogel et al., 2019). It may, however, be of surprise, given the number of record-breaking heat waves during recent years, such as the June 2021 Pacific North-West heat wave, which was attributed to climate change (Philip et al., 2021).

How notable events or weather hazards get attention and are reported is subject to “newsworthiness”, which is the political economy between society and the media (Boykoff and Yulsman, 2013; Kitzinger, 1999). This newsworthiness is made up of four main factors: the availability effect or heuristic, which is when a hazard is presented as a risk before it is likely to be remembered in this manner; stories from impacted groups; whether or not the hazard is geographically bound; and whether or not a hazard is visually impactful (Kitzinger, 1999; Tomlinson et al., 2011). The results of this study show that the hazards that fit these criteria the most were storms, which have the most articles by quantity, and wildfires, which at have the most articles per individual occurrence.

4.2 How does English-language news media discuss climate change and hazards?

Per individual weather hazard, on average, the articles that also consider climate change do not comply with the newsworthiness criteria outlined above; therefore droughts, wildfires and heat waves have the most articles. Instead, the media can be suggested to follow the science where it is seen these hazards are easier to attribute to climate change than floods or storms (Ciavarella et al., 2020; Kreienkamp et al., 2021). While the media does have a moral obligation and plays a key role in communicating climate risk, how science, the public and those in positions of power communicate climate change has an influence on what is portrayed by the media (Boykoff and Yulsman, 2013; van der Hel et al., 2018; Howarth and Anderson, 2019).

Therefore, it could be suggested that this reporting of climate change has come about through the increasing collaboration between science (across career stages) and the media. Examples of this collaboration include Science Media Centre (https://www.sciencemediacentre.org/, last access: 23 January 2022), The Conversation (https://theconversation.com/uk, last access: 23 January 2022) and Voice of Young Science (https://senseaboutscience.org/what-we-are-doing/voys/, last access: 23 January 2022).

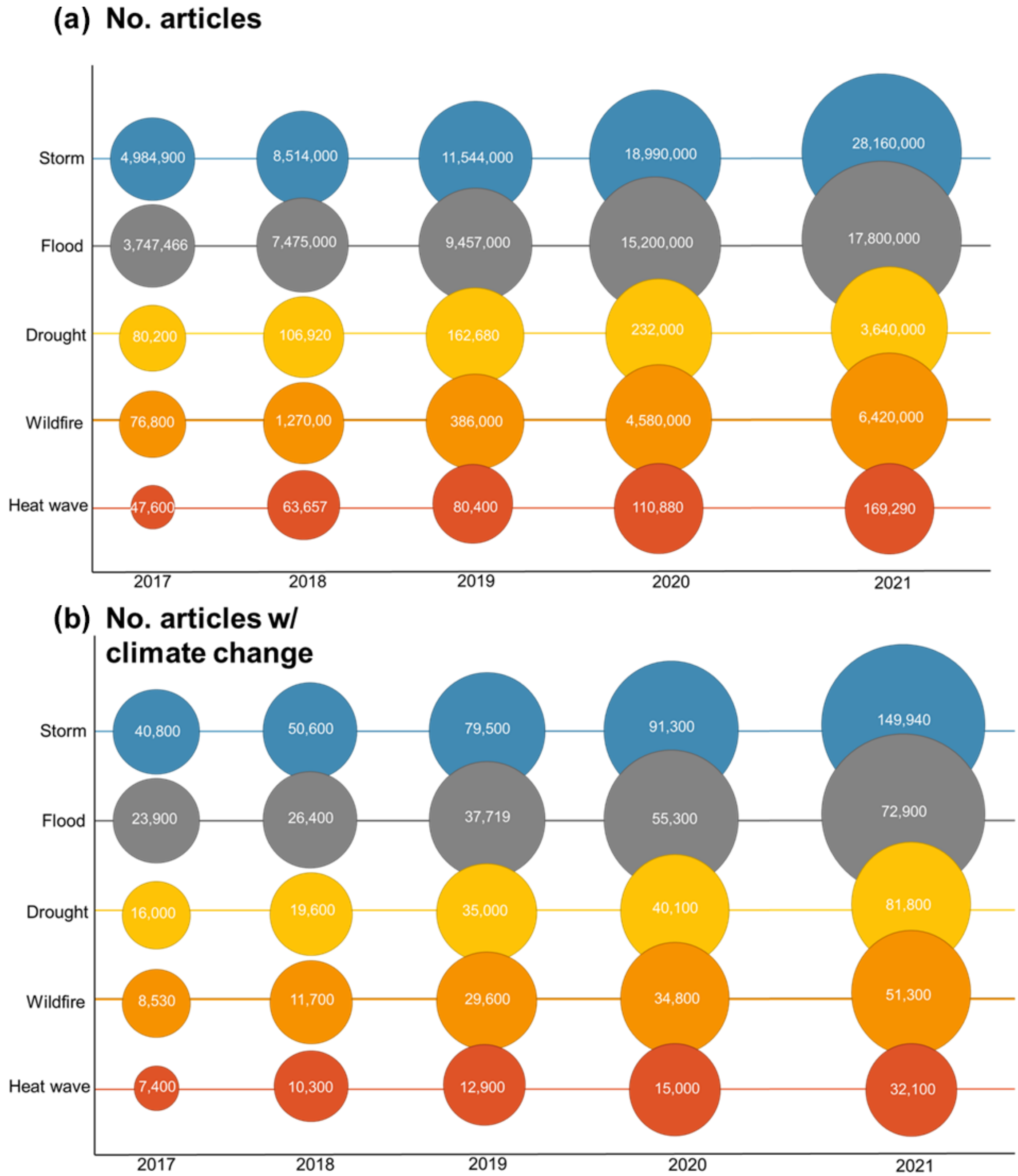

Figure 2. Number of articles per hazard per year for 2017 to 2022; **(a)** indicates overall article numbers, while **(b)** indicates only articles that contain weather hazards and climate change as their subject.

This comes in spite of the discourse around the role of science in both communication and policy spaces (Boykoff and Yulsman, 2013; Pielke, 2007).

4.3 Why is consistent reporting important?

The attention deficit in English-language news media leads to a lack of investment in adaptation for some hazards, making us unprepared. In addition, this pushes us towards more precarious tipping points, where adaptation becomes more of a challenge for society (Howarth and Brooks, 2017). This study's results highlight a huge reporting bias in favour of storms and wildfires in the news media. This has a material cost, where storms receive more research, funding and policy than other hazards (Brimicombe et al., 2021b; Harrington and Otto, 2020; Howarth and Brooks, 2017; Vogel et al., 2019).

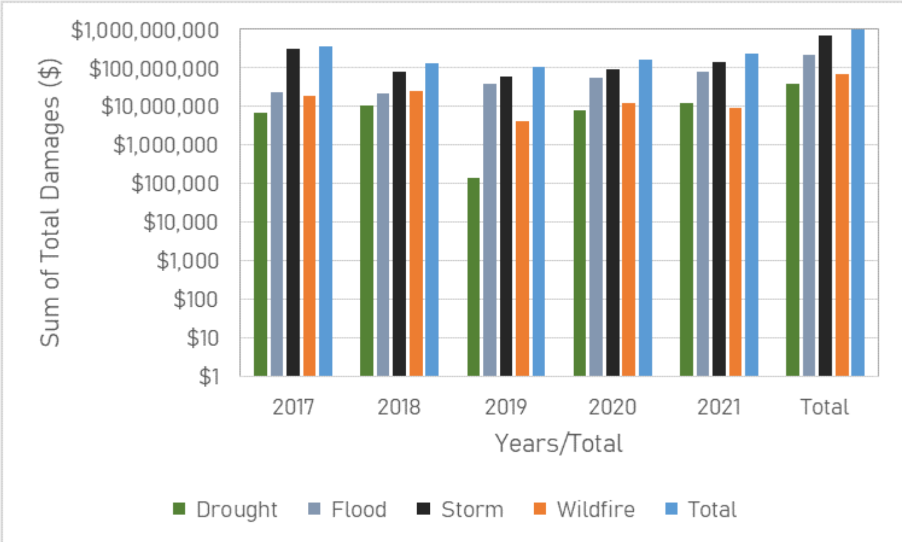

Figure 3. Sum of Total Damages for each hazard per year as reported by EM-DAT, heat wave cannot be seen as no damages are recorded (CRED, 2020).

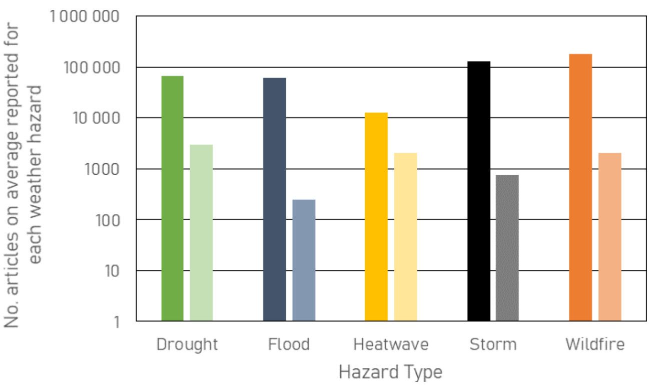

Figure 4. The average number of articles per individual hazard category for the last 5 years. Dark colour is total number of articles and light colour is articles including climate change. (Number of articles in Fig. 2a or b/total recorded hazards for each hazard type in Fig. 1.)

However, despite ranking second in terms of the overall number of articles, per individual occurrence, floods have the least number of articles. This could be an indication that there is a larger range in the number of articles written per flood (i.e. one flood has 1 million articles, but another only has 1 000 articles); this is something that should be explored further in a news media sentiment study, with particular focus given to geographical bias.

4.4 What does using an open science approach demonstrate?

This study uses advanced Google search trends to show the bias that is apparent in English-language news media surrounding weather hazards and climate change. This is not the most robust method to carry out a study of this kind; however it is the most accessible. For example, long-scale newspaper databases are not free to access.

Using an open science approach highlights the transparency surrounding the reporting bias (Armeni et al., 2021). This is a positive, because it means that it is easy to track improvements and changes in reporting. Bias reduces the ability of reporting as a tool to reduce hazard risk, and highlighting it is the first step in changing the narrative (Brimicombe et al., 2021a, b).

5 Conclusion

There is a bias in terms of which weather hazards English-language news media report on and a bias in terms of which weather hazards are linked to climate change. This is important, because in terms of material cost, some hazards generate more investment than others. This leads to underpreparedness for specific hazards as a result of underreporting regarding their impacts. Reporting is a key way that we can improve communication, and it plays a part in avoiding societal tipping points. This study suggests that greater collaboration between scientists (across career stages) and the English-language news media is key to improving reporting overall and to continue to grow the reporting of the risks of weather hazards and their intrinsic links with climate change.

Data availability. All data is available via advanced Google searches and the EM-DAT database (https://www.emdat.be/, last access: 15 June 2020; CRED, 2020).

Competing interests. The author has declared that there are no competing interests.

Ethical statement. Ethics approval and informed consent were not sought; this study does not deal with sensitive data or human participants.

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GeoHealth

RESEARCH ARTICLE

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Wet Bulb Globe Temperature: Indicating Extreme Heat Risk on a Global Grid

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Key Points:

- We create an accurate method for calculating Wet Bulb Globe Temperature (WBGT) using Mean Radiant Temperature termed $\mathrm{WBGT}_{\mathrm{Brimicombe}}$
- It is found that $\mathrm{WBGT}_{\mathrm{amsc87}}$ also known as WBGTsimple is not an accurate approximation of WBGT
- $\mathrm{WBGT}_{\mathrm{Brimicombe}}$ can assist with robust heat stress standards across sectors including in public and occupational health

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Abstract The Wet Bulb Globe Temperature (WBGT) is an international standard heat index used by the health, industrial, sports, and climate sectors to assess thermal comfort during heat extremes. Observations of its components, the globe and the wet bulb temperature (WBT), are however sparse. Therefore WBGT is difficult to derive, making it common to rely on approximations, such as the ones developed by Liljegren et al. (2008, https://doi.org/10.1080/15459620802310770, $\mathrm{WBGT}_{\mathrm{Liljegren}}$) and by the American College of Sports Medicine ($\mathrm{WBGT}_{\mathrm{ACSM87}}$). In this study, a global data set is created by implementing an updated WBGT method using ECMWF ERA5 gridded meteorological variables and is evaluated against existing WBGT methods. The new method, $\mathrm{WBGT}_{\mathrm{Brimicombe}}$, uses globe temperature calculated using mean radiant temperature and is found to be accurate in comparison to $\mathrm{WBGT}_{\mathrm{Liljegren}}$ across three heatwave case studies. In addition, it is found that $\mathrm{WBGT}_{\mathrm{ACSM87}}$ is not an adequate approximation of WBGT. Our new method is a candidate for a global forecasting early warning system.

Plain Language Summary The Wet Bulb Globe Temperature (WBGT) is an international standard for how we measure the effect of heat on the human body. It is used across sectors in health, industry, sports, and climate to calculate how we feel and how our body responds during heat extremes. Its calculation has historically relied on globe thermometer and wet bulb temperature observations, which are however not widely available. This has made WBGT difficult to calculate and meant approximations have been created. Here we formulate a new WBGT method that can be used with global gridded data that are freely available and we compare it against other methods in common use. We find that our method is accurate when compared to the existing gold standard WBGT method.

1. Introduction

The Wet Bulb Globe Temperature (WBGT) is an International Standards Organisation (ISO) approved metric of heat stress in humans (Int Org Standard, 2017). Heat stress is caused by the build-up of body heat either as a result of exertion and/or exposure to the external environment (air temperature humidity, solar radiation, wind speed etc.) (D'Ambrosio Alfano et al., 2014; Ioannou et al., 2022; Jacklitsch et al., 2016; McGregor & Vanos, 2018; Parsons, 2006). WBGT was originally developed in the 1950s as part of a campaign to lower the risk of heat disorders during the training of US Army and Marine troops (Minard, 1961).

The WBGT has many applications and is used widely in many research areas such as the occupational and public health sectors. In addition, it is used in the sports and exercise field, industrial hygiene and in climate change research and is one of the most popular heat stress indices (Heo et al., 2019; Kjellstrom et al., 2009; Lemke & Kjellstrom, 2012; Lucas et al., 2014; Racinais et al., 2015).

The WBGT (°C) is defined by three environmental variables via the following equation (Minard, 1961):

$$\mathrm{WBGT} = 0.7T_{\mathrm{w}} + 0.2T_{\mathrm{g}} + 0.1T_{\mathrm{a}} \tag{1}$$

where T_{a} is 2 m air temperature (i.e., dry bulb temperature, in °C), T_{g} is globe thermometer temperature (°C), and T_{w} is natural wet bulb thermometer temperature (°C).

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Whereas 2 m air temperature is easily measurable, observations of globe thermometer and wet bulb thermometer temperatures are often sparse (Budd, 2008; D'Ambrosio Alfano et al., 2014). Consequently, it has been historically challenging to calculate WBGT from Equation 1 and it is instead common to rely on approximations. These include the approximation from the American College of Sports Medicine (termed $\text{WBGT}_{\text{ACSM87}}$), which is a linear model of the WBGT (American college of sports medicine, 1987), and the approximation by Liljegren and colleagues (termed $\text{WBGT}_{\text{Liljegren}}$), which is a more complex approximation based on the fundamentals of heat transfer (Liljegren et al., 2008).

In this study, we compare a new approach to approximate WBGT (termed $\text{WBGT}_{\text{Brimicombe}}$) with $\text{WBGT}_{\text{ACSM87}}$ and $\text{WBGT}_{\text{Liljegren}}$. Our approach is novel in calculating WBGT from gridded data using the variable of mean radiant temperature and is designed for operational forecasting systems. Comparisons are performed globally by using the ERA5 hourly global gridded reanalysis from the European Centre for Medium-Range Weather Forecasts (ECMWF), Observation data from the World Radiation Monitoring Center–Baseline Surface Radiation Network (Driemel et al., 2018) and are here discussed within the context of three heatwave case studies (India and Pakistan in July 2003, the Western Sahel in March 2013 and Australia in December 2019).

2. Method

2.1. Brimicombe WBGT Approximation ($\text{WBGT}_{\text{Brimicombe}}$)

This new approach to approximate WBGT has been developed for numerical weather prediction post-processing as it takes an optimized approach to the calculation of WBGT by removing the need for iterative loops. We calculate globe temperature using an adapted version of the original Bedford and Warner equation, making use of mean radiant temperature, a measurement of incidence of radiation on a body which is appropriate for indoor or outdoor use depending on given inputs (Bedford & Warner, 1934; De Dear, 1987; Guo et al., 2018; Thorsson et al., 2007; Vanos et al., 2021).

Here Equation 2 is used to solve for globe temperature as the subject because the ERA5 reanalysis data contains the variables of 2 m air temperature (T_a), 10-m wind speed (v_a), and mean radiant temperature (T_{MRT}). All temperatures are in Kelvin; 10-m wind speed was found to be within ±1°C of an approximated 2 m wind speed which used the method found in Spangler et al. (2022) and therefore is used (not shown). The code to compute this is available as part of thermofeel: https://doi.org/10.21957/mp6v-fd16 (Brimicombe et al., 2021; Brimicombe, Di Napole et al., 2022)

$$T_{\text{MRT}} = \sqrt[4]{{T_g}^4 + \frac{h_{cg}}{\varepsilon \times D^{0.4}} \times \left(T_g - T_a\right)} \tag{2}$$

In Equation 2, h_{cg} is the mean convection coefficient and is calculated using Equation 3. This is an additional correction from the original method and reduces the impact weighting of high wind speeds on the outputted globe temperature (De Dear, 1987; Guo et al., 2018).

$$h_{cg} = 1.1 \times 10^8 \times {v_a}^{0.6} \tag{3}$$

To calculate the wet bulb temperature (WBT), a theoretical method by Stull (2011) is used and is shown in Equation 4, where T_a is 2 m air temperature in °C and RH is relative humidity in percent. This method is valid between −20°C and 50°C and between 5% and 99% humidity, which are the ranges the method is optimized for and with which it has been used in previous studies (Freychet et al., 2020; Heo et al., 2019; Raymond et al., 2017). In addition, this method provided a test case, an expected value for a given set of inputs, which allowed validation of the calculated value (Stull, 2011).

$$\begin{aligned} T_w = T_a \tan^{-1}&(0.151977(\text{RH} + 8.313659)^{1/2}) \\ &+\tan^{-1}(T_a + \text{RH}) \\ &-\tan^{-1}(\text{RH} - 1.676331) + 0.00391838(\text{RH})^{3/2} \\ &\times\tan^{-1}(0.023101 \times \text{RH}) - 4.686035 \end{aligned} \tag{4}$$

Once calculated, the globe temperature and WBT along with 2 m air temperature are used in Equation 1 to provide the $\text{WBGT}_{\text{Brimicombe}}$.approximation.

2.2. Liljegren WBGT Approximation ($WBGT_{Liljegren}$)

$WBGT_{Liljegren}$ can be considered a existing "gold standard" benchmark WBGT value as it is widely considered the most accurate WBGT approximation available (Kjellstrom et al., 2009; Kong & Huber, 2021; Liljegren et al., 2008). To obtain $WBGT_{Liljegren}$, WBT is calculated as per Equation 5 and globe temperature is calculated as per Equation 6 which are then used in Equation 1. Specifically, WBT is calculated as

$$T_w = T_a - \mathrm{Nu} \times \mathrm{Sh} \times \left(\frac{\mathrm{Pr}}{\mathrm{Sc}}\right)^a \left(\frac{e_w - e_a}{P - e_w}\right) + \frac{\Delta F_{net}}{A_h} \tag{5}$$

where Nu is the Nusselt number, Sh is the Sherwood Number, Pr is the Prandtl number, and Sc is the Schmidt number and $\left(\frac{e_w - e_a}{P - e_w}\right)$ is the change in saturation water vapor transfer between the hygrometer wick and its surroundings. $\frac{\Delta F_{net}}{A_h}$ is the net radiative heat flux divided by the convective heat transfer coefficient. Full details can be seen in (Liljegren et al., 2008). Globe temperature is calculated as

$$T_g^4 = \frac{1}{2}(1 + \varepsilon_a)T_a^4 - \frac{h}{\varepsilon_g \sigma}(T_g - T_a) + \frac{\mathrm{ssrd}}{2\varepsilon_g \sigma}(1 - \alpha_g)\left[1 + \left(\frac{1}{2\cos\theta}\right)\mathrm{dsrp} + \alpha_{sfc}\right] \tag{6}$$

where the $\frac{h}{\varepsilon_g \sigma}(T_g - T_a)$ and $\frac{S}{2\varepsilon_g \sigma}(1 - \alpha_g)$ terms denote the energy gain from diffuse downwards and direct downward solar radiation respectively. dsrp is the projected area and α_{sfc} is the reflected solar radiation and ssrd is downward solar radiation. Full details can be seen in Liljegren et al. (2008) . Here data for $WBGT_{Liljegren}$ is provided by Kong and Huber (2021), instead of calculation using the HEAT-SHIELD methodology, because the method presented by Kong and Huber appears to be more robust and closer to the original methodology (Casanueva, 2017).

2.3. American College of Sports Medicine WBGT Approximation ($WBGT_{ACSM87}$)

The $WBGT_{ACSM87}$ (American college of sports medicine, 1987) was also calculated (Equation 7) as it continues to appear widely in literature, despite it being known to have large bias (Chen et al., 2019; Grundstein & Cooper, 2018; Kong & Huber, 2021). $WBGT_{ACSM87}$ is calculated from 2 m air temperature and saturation water vapor pressure (e) as:

$$WBGT_{ACSM87} = 0.567 \times T_a + 0.393 \times e + 3.94 \tag{7}$$

2.4. Methodological Difference Between $WBGT_{Brimicombe}$ and $WBGT_{Liljegren}$

Several methodological differences between our new WBGT approximation and the existing "gold standard" WBGT approximation are present (Brimicombe, Di Napoli et al., 2022; Liljegren et al., 2008).

One key variable that is necessary in the calculation of T_g (both in Equations 2 and 6) is the cosine of the solar zenith angle. In previous studies it is found that radiation in the Liljegren T_g methodology has inaccuracies at sunrise and sunset due to the method used to calculate this variable (Kong & Huber, 2022; Lemke & Kjellstrom, 2012). These inaccuracies are known to become greater in a numerical weather prediction service time step (a period of several hours) (Brimicombe, Quintino, et al., 2022; Hogan & Hirahara, 2016). For the Brimicombe T_g methodology this does not occur because a specially designed cosine of the solar zenith angle is implemented (Brimicombe, Di Napoli et al., 2022; Brimicombe, Quintino, et al., 2022).

Another difference is in the number of radiation input variables used to calculate T_g in the Liljegren methodology. In this only 2 radiation components are used (Liljegren et al., 2008) in comparison to the 5 that calculate T_{MRT} (please refer to: Di Napoli et al., 2020) which goes on to calculate the Brimicombe T_g. Equation 2, which expresses mean radiant temperature T_{MRT} as a function of T_g and T_a, is comparable to the heat balance expressed in Bedford and Warner (1934), therefore relating mean radiant temperature to the temperature of surrounding surfaces. Similarly, Equation 2 can also be rearranged in order of $T_g{}^4$, where many comparable terms to Equation 6 are identifiable.

In the Liljegren T_w methodology a psychrometric WBT is calculated using fundamentals of mass transfer. In addition a key input of saturation water vapor pressure is calculated differently over ice and water (and the land

Table 1
Heat Stress Thresholds for Wet Bulb Globe Temperature and Recommended Labor Legal Definitions of Workloads for an Average Period of Work

WBGT (°C)	Recommended maximum workload	Approximated work/rest cycles (minutes)	Category
>33	Resting	Rest	5
30–33	Light	15/45	4
28–30	Moderate	30/30	3
25–28	Heavy	30/15	2
23–25	Very heavy	45/15	1
<23	No recommendations	No recommendations	0

Note. Adapted from Jacklitsch et al. (2016).

surface) as in Hardy (1998). In comparison, in the Brimicombe T_w methodology an empirical theoretical WBT is calculated (Stull, 2011). As previously mentioned, this computationally removes the need for iterative loops, which are onerous to run for a gridded data set. In addition, the saturation water vapor pressure method is only for over water (and the land surface) in contrast to being over either water or ice, given that WBGT is a human heat stress index. How these methodological differences introduce errors will be explored within this study.

2.5. WBGT Approximation Comparisons

To compare the WBGT approximations, this study uses variables available as part of the ERA5 and ERA5-HEAT gridded reanalysis data sets produced by ECMWF on a 0.25° × 0.25° grid at an hourly time step (Di Napoli et al., 2021; Hersbach et al., 2020). ERA5 was chosen for this study as a state-of-the-art gridded reanalysis data set; it is an ideal data set to test out a new gridded based methodology and has the added benefit of outputting the mean radiant temperature variable (the incidence of radiation on the body). ERA5 and ERA5-HEAT variables of 2 m air temperature, 2 m dew point temperature, 10 m wind speed and mean radiant temperature are used in the relevant equations to calculate $WBGT_{Brimicombe}$ and $WBGT_{ACSM87}$. $WBGT_{Liljegren}$ is also calculated using ERA5 reanalysis data. There are known limitations of ERA5; these include inaccuracies at higher elevations (Brunamonti et al., 2019; Senyunzi et al., 2020).

The approximations are calculated and compared for three past heatwaves on dates where heat stress is known to have occurred. One affected India and Pakistan in July 2003, another the Western Sahel in March 2013 and another Australia in December 2019 (CRED, 2020). In addition, this study also considers the full global gridded data sets of WBGT values including those below a heat stress threshold.

The gridded ERA5 reanalysis output for $WBGT_{Brimicombe}$ is compared to the observed $WBGT_{Brimicombe}$ calculated using data from the Tateno TAT (36.1°N, 140°E) and Nya Långenäs NYA (78.9°N, 11°E) stations from the World Radiation Monitoring Center–Baseline Surface Radiation Network (WRMC–BSRN, Driemel et al., 2018) for Daily Maximum WBGT for July 2003 and March 2013. In addition, for March 2013 the Stull WBT method is compared to the Davies-Jones method (available at: https://github.com/smartlixx/WetBulb/blob/master/WetBulb.py) (Davies-Jones, 2008; Stull, 2011). We are constrained by the available observation data.

The comparison between the three approximations uses the observed WBGT thresholds set out by the ISO (Jacklitsch et al., 2016; Table 1). According to ISO, which considers heat stress by reference to recommended lifting and hard labor workloads, 33°C is known as a critical health threshold for WBGT (Heo et al., 2019).

$WBGT_{ACSM87}$ and $WBGT_{Brimicombe}$ are compared against the existing gold standard approximation of $WBGT_{Liljegren}$ in two ways. The first is through evaluation of the spatial anomaly in WBGT values. $WBGT_{Liljegren}$ is subtracted from the corresponding $WBGT_{ACSM87}$ or $WBGT_{Brimicombe}$ values. Second, is a correlation between $WBGT_{Liljegren}$ and the other WBGT approximations is assessed together with the mean absolute error (MAE). In addition the sensitivity of the outputted $WBGT_{Brimicombe}$ and $WBGT_{Liljegren}$ approximations to key input variables is assessed.

3. Results

3.1. Gridded Outputs of WBGT for the Three Heatwaves

In July 2003, the highest values of $WBGT_{Liljegren}$ are over 33°C for the border of northern India and Pakistan, which is indicative of extreme heat stress in category 5 (Figure 1, left column). This pattern is well matched by $WBGT_{Brimicombe}$. The lowest values for both of these WBGT approximations are over the Himalayas bordering the north-east of India, indicating no heat stress. $WBGT_{ACSM87}$ has lower heat stress values and only reaches 33°C, category 4.

In March 2013, the highest values of $WBGT_{Liljegren}$ are over 33°C and are indicative of extreme heat stress (category 5) for the north of Ghana and Nigeria (Figure 1, middle column). This pattern is broadly matched by

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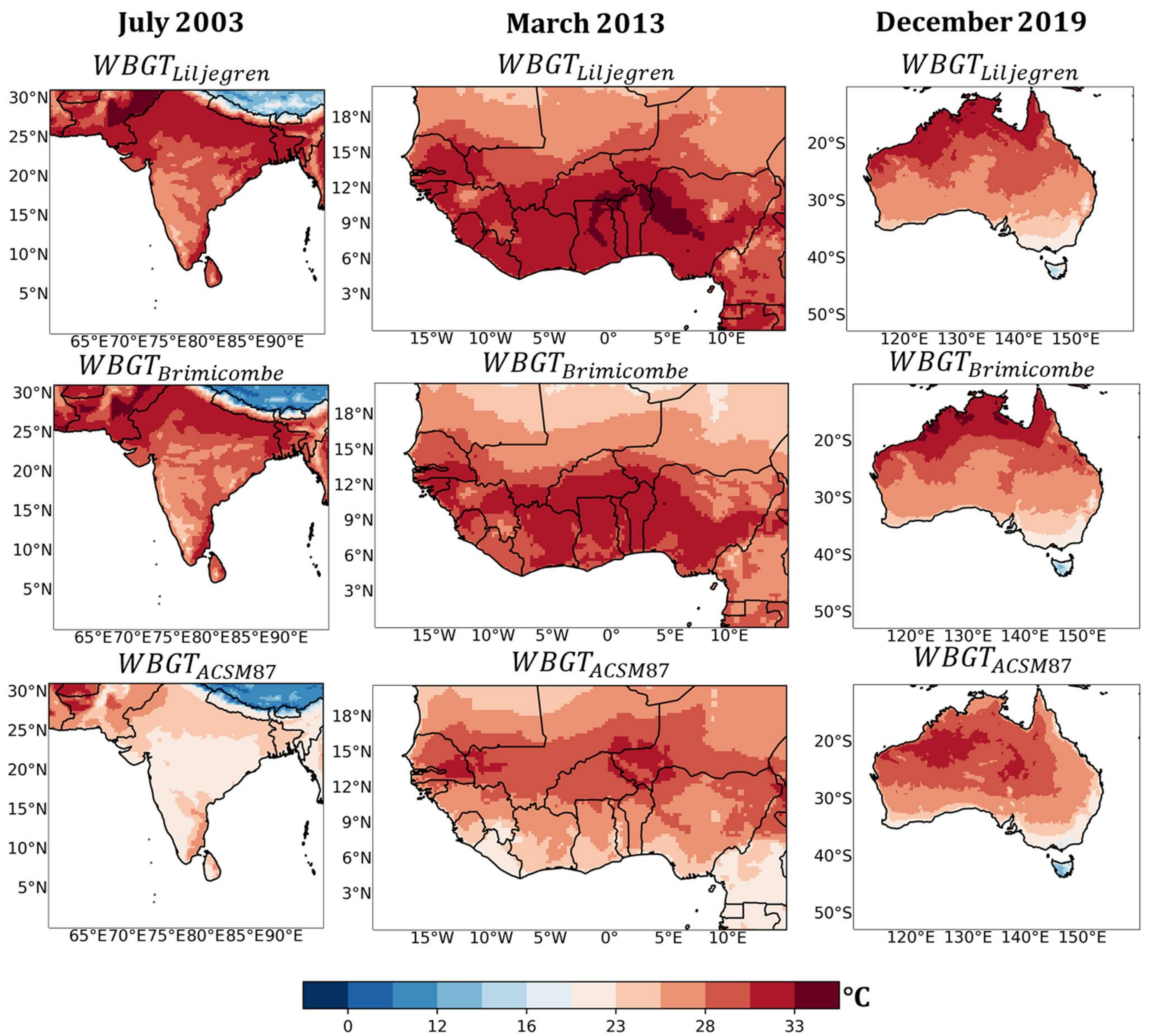

Figure 1. Heat stress calculated via $WBGT_{Liljegren}$, $WBGT_{Brimicombe}$, and $WBGT_{ACSM87}$. Monthly mean of daily maximum Wet Bulb Globe Temperature heat stress (left to right) for the heatwaves that affected India and Pakistan in July 2003, the Western Sahel in March 2013, and Australia in December 2019. Sea area has been masked.

$WBGT_{Brimicombe}$ although the extreme region of heat stress has slightly lower values. Similarly to the July 2003 heatwave, $WBGT_{ACSM87}$ has much lower values than the other approximations and only reaches at the maximum up to 33°C (category 4) in one small area. The pattern of heat stress is not well captured and $WBGT_{ACSM87}$ is consistently at least two heat stress categories lower than $WBGT_{Liljegren}$ and $WBGT_{Brimicombe}$ over the whole region.

For the heatwave of December 2019 in Australia, there are strikingly similar heat stress patterns for $WBGT_{Liljegren}$ and $WBGT_{Brimicombe}$ (Figure 1, right column). $WBGT_{ACSM87}$ also performs better for this heatwave than for the July 2003 and March 2013 heatwaves and heat stress values are close to those of $WBGT_{Liljegren}$. However, $WBGT_{ACSM87}$ again does not capture the same shape of the areas under heat stress.

These similarities and differences can also be seen clearly at the global scale for each heatwave (Figure 2). $WBGT_{Liljegren}$ and $WBGT_{Brimicombe}$ values are similar worldwide in each of the 3 months considered (Figure 2), particularly focusing on parts of North Africa, southern Asia and Australia. It is however noteworthy that $WBGT_{Brimicombe}$ does not always capture the highest heat stress category indicated by $WBGT_{Liljegren}$ in South

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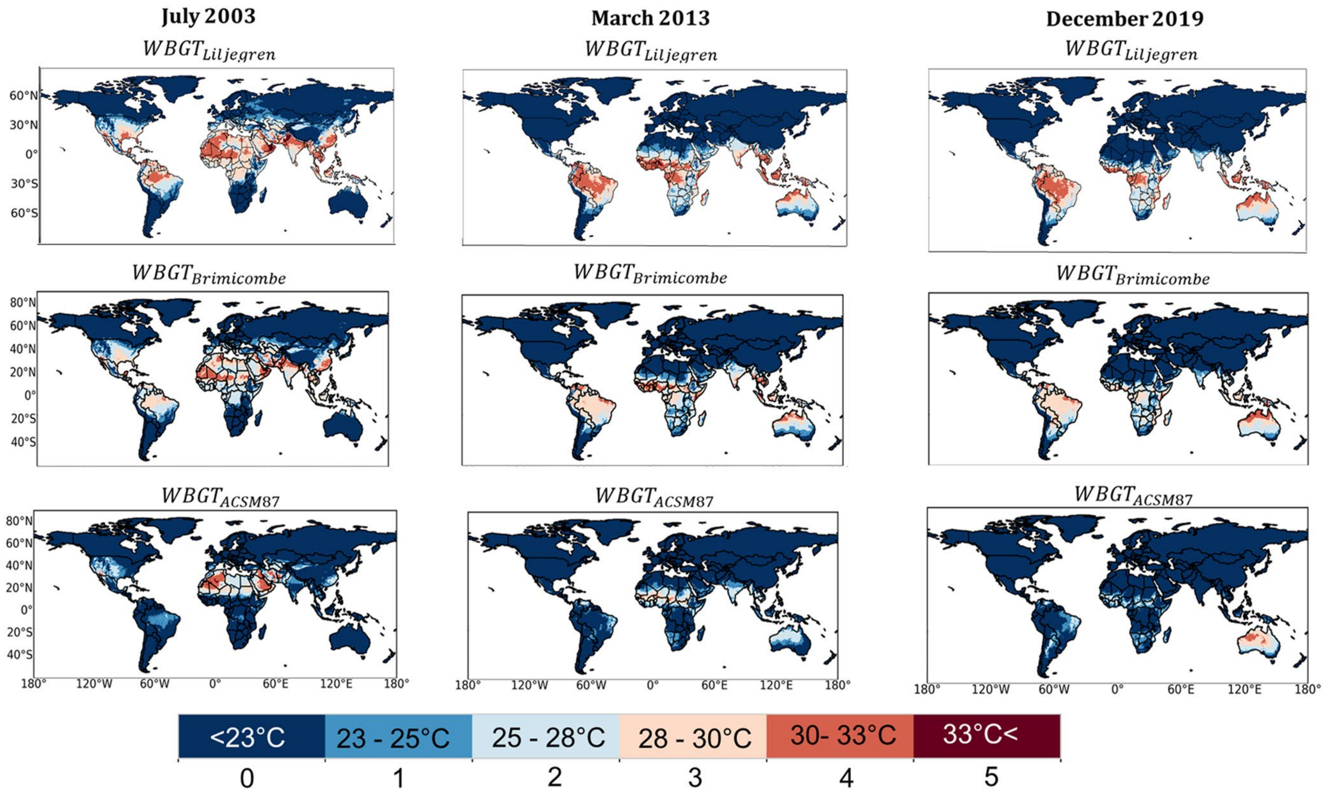

Figure 2. Categorical heat stress calculated via $WBGT_{Brimicombe}$, $WBGT_{ACSM87}$, and $WBGT_{Liljegren}$. Monthly mean of daily maximum Wet Bulb Globe Temperature (WBGT) heat stress (left to right) for the heatwaves of July 2003, March 2013, and December 2019. Categories refer to the different levels of WBGT as indicated in Table 1. Sea area has been masked.

America (Figure 2). $WBGT_{ACSM87}$ is very different from the other approximations on a global scale. It consistently has heat stress values that are too low, sometimes three heat stress categories lower, and only captures the heat stress in some parts of Australia.

3.2. WBGT Approximations Anomalies

Overall, the anomalies between $WBGT_{Liljegren}$ and $WBGT_{Brimicombe}$ are small, with negative anomalies indicating where $WBGT_{Liljegren}$ has higher values than $WBGT_{Brimicombe}$, the term anomaly is used to denote deviations of WBGT approximations in comparison to the current gold standard $WBGT_{Liljegren}$. In July 2003, $WBGT_{Liljegren}$ has higher values than $WBGT_{Brimicombe}$ across most of the land surface (Figure 3, left column). In addition, anomalies can be seen to be no more or less than ±2°C, except in Greenland which has anomalies of up to −4°C. In comparison, March 2013 has a similar pattern where anomalies can be seen to not be more or less than ±2°C between $WBGT_{Liljegren}$ and $WBGT_{Brimicombe}$ (Figure 3, middle column). However, for March 2013, more of the northern hemisphere has anomalies of −4°C, for example, in Canada and Siberia colder regions. Fewer regions experience anomalies of −4°C for December 2019, with this only present in the Himalaya into Tibet and the Canadian Rockies regions of higher elevation (Figure 3, right column). Overall across each of the three case studies, most of the land surface has anomalies of only ±2°C between $WBGT_{Liljegren}$ and $WBGT_{Brimicombe}$.

For $WBGT_{Liljegren}$ in comparison to $WBGT_{ACSM87}$ averaging across all years for the southern hemisphere, $WBGT_{Liljegren}$ have values higher than $WBGT_{ACSM87}$ by 4°C. In contrast, for the March 2013 and December 2019 heatwaves, the northern hemisphere has anomalies of +4°C. Anomalies are less in the Sahara desert and Australia. For the July 2003 heatwave, anomalies match with those seen in the Southern hemisphere of −4°C.

3.3. WBGT Approximations Correlations

Across both $WBGT_{ACSM87}$ and $WBGT_{Brimicombe}$ there is a strong linear correlation to $WBGT_{Liljegren}$ (Figure 4). $WBGT_{Brimicombe}$ has smaller MAE values across all three case studies than $WBGT_{ACSM87}$, with the smallest value

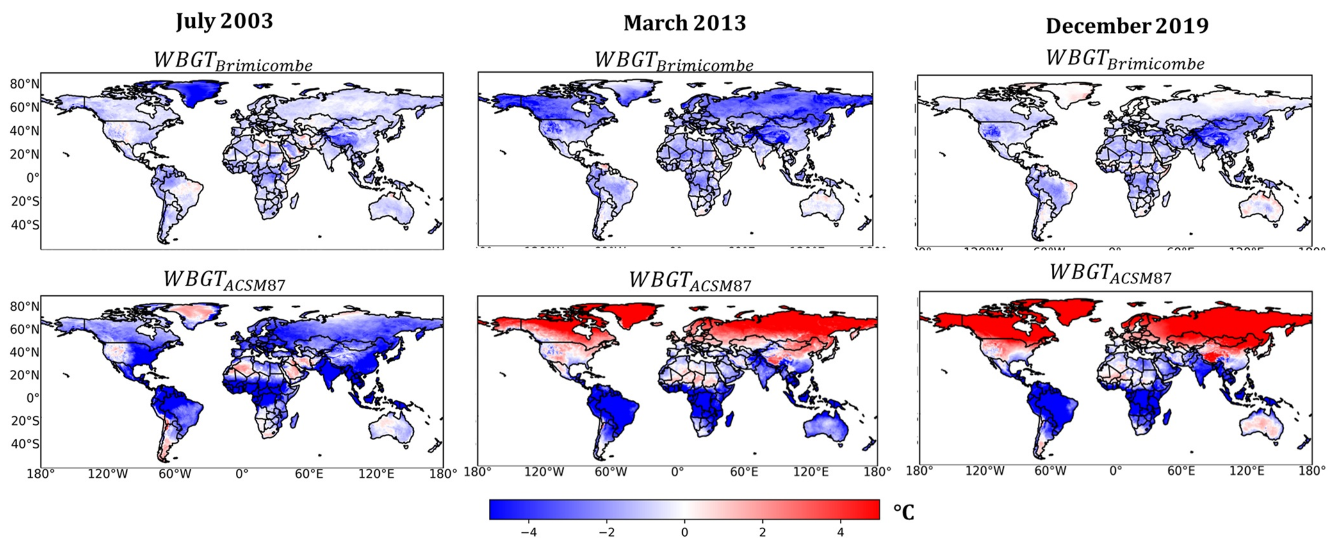

Figure 3. The monthly mean of the daily maxima anomalies of $WBGT_{Brimicombe}$ and $WBGT_{ACSM87}$ in comparison to $WBGT_{Liljegren}$ for the three heatwaves considered by this study for July 2003, March 2013, and December 2019. Negative values are where $WBGT_{Liljegren}$ has higher values than the other approximations.

being 0.76°C, being on average smaller for values about the heat stress threshold. $WBGT_{ACSM87}$ MAE values are large and range between 3.39°C and 5.51°C across the three case studies but are significantly smaller above the heat stress threshold ranging from 2.87°C to 3.11°C. $WBGT_{Brimicombe}$ heat stress values (above 23°C, category 1 onwards) have a stronger linear relationship than across the whole distribution. In comparison, $WBGT_{ACSM87}$ has a bigger spread in the cluster of points than $WBGT_{Brimicombe}$ over the whole distribution.

3.4. WBGT Approximation Differences

It has already been demonstrated that $WBGT_{ACSM87}$ differs significantly from the other WBGT approximations presented. Therefore, here the sensitivity of only $WBGT_{Liljegren}$ and $WBGT_{Brimicombe}$ to key input variables is shown in more depth. Figure 5 demonstrates that broadly for both $WBGT_{Liljegren}$ and $WBGT_{Brimicombe}$ high solar radiation, temperature, humidity with low wind speeds lead to the highest WBGT values. In Figure 5 similarly to Figure 4 a bifurcation is seen for 2 m temperature (Figure 4) and somewhat for dew point temperature (Figure 4)

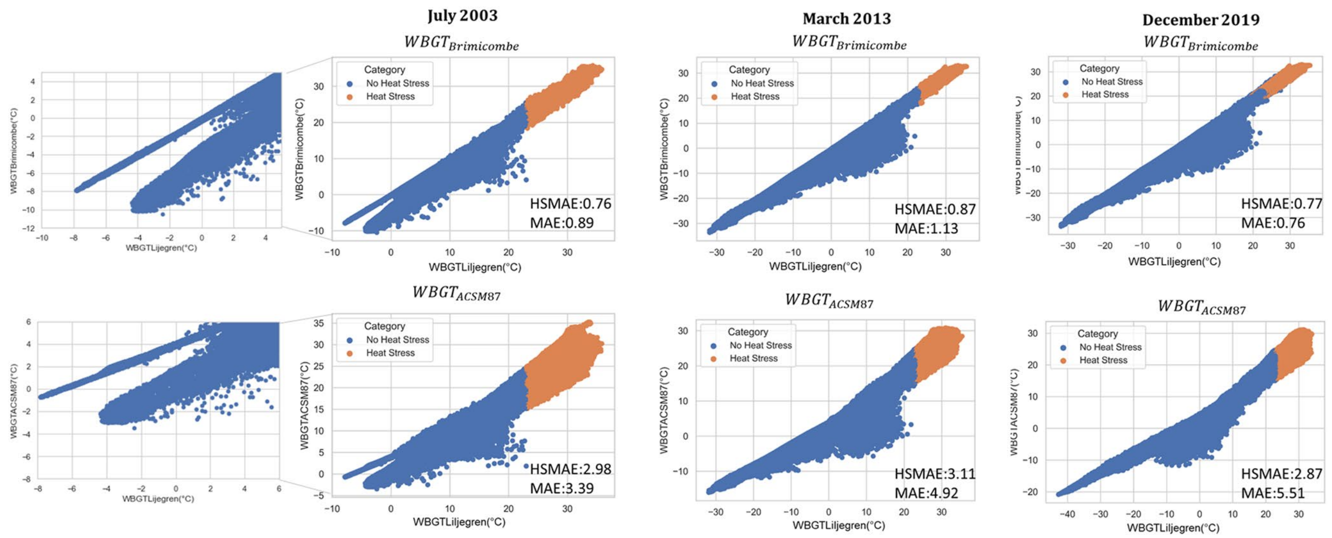

Figure 4. Global Grid Spatial Domain Correlation plots of $WBGT_{Brimicombe}$ and $WBGT_{ACSM87}$ in comparison to $WBGT_{Liljegren}$ (orange indicated heat stress, i.e., Wet Bulb Globe Temperature values above 23°C). The mean absolute error (°C) for all points and just the heat stress points is indicated in each plot for the three heatwaves considered by this study (July 2003, March 2013, and December 2019).

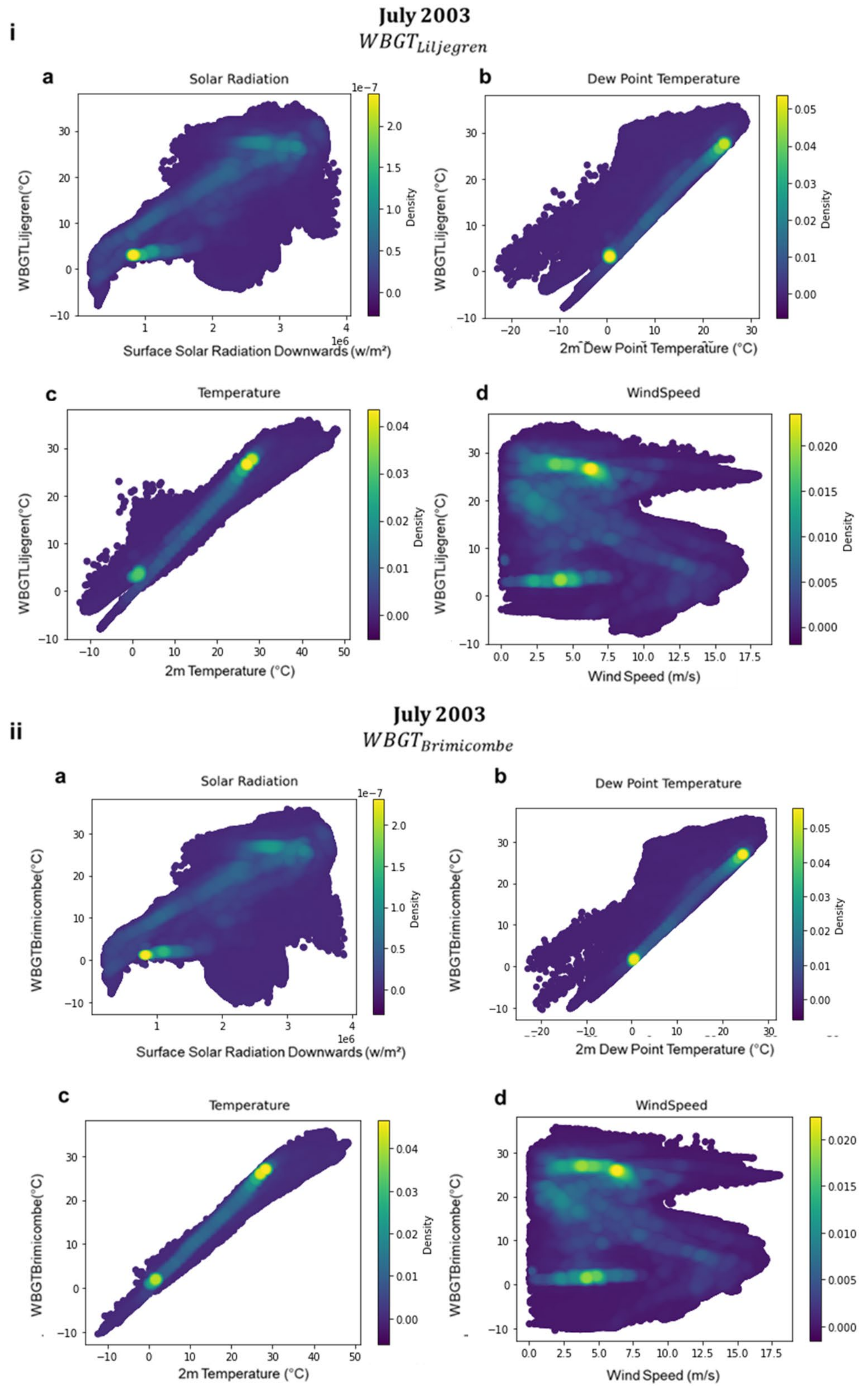

Figure 5. Global Grid Spatial Domain of the sensitivity of the output Wet Bulb Globe Temperature (WBGT) approximations with input variables for the July 2003 heatwave where (i) is $WBGT_{Liljegren}$ and (ii) is $WBGT_{Brimicombe}$ and where (a) is surface solar radiation downwards, (b) is 2 m dew point temperature, (c) is 2 m temperature, and (d) is 10 m wind speed. Input variables shown are those that are input to both WBGT approximations. Color shading denotes density of points. A similar relationship is observed for the other two heatwaves (not shown).

with the outputted $WBGT_{Liljegren}$. This confirms the trend is due to the $WBGT_{Liljegren}$ Saturation Water Vapor pressure method (Figure 4). As suggested in Section 2.4 this discrepancy comes from the difference in the Tw methodology, specifically from how saturation vapor pressure is calculated.

The sensitivity of $WBGT_{Liljegren}$ and $WBGT_{Brimicombe}$ is highly similar for solar radiation and wind speed and can be suggested to provide further evidence that Equations 2 and 6 are comparable. This is despite the potential discrepancies that were suggested in Section 2.3. This should be explored further to inform more about the inter-dependencies of the different types of radiation. Further we find that WBGT does not have a dynamical response to wind similar to previous findings and this can be suggested to be a limitation of the heat stress index (Foster et al., 2022).

3.5. $WBGT_{Brimicombe}$ Observations Comparisons

$WBGT_{Brimicombe}$ for reanalysis data performs robustly in comparison to $WBGT_{Liljegren}$ it also performs accurately compared to $WBGT_{Brimicombe}$ observed (Figure 6). $WBGT_{Brimicombe}$ has R^2 values between its ERA5 values and observation values of between 0.56 and 1 (Figures 6b–6e). It performs better for the TAT station (Tateno) situated in Japan, where WBGT values are higher than the NYA (Nya Långenäs) station situated in the Artic circle in Svalbard overall. MAE values range from 0.97°C to 5.06°C (Figures 6b–6e). The R^2 and error values are comparable with those seen between observed MRT and ERA5 MRT in Di Napoli et al. (2020).

In addition, when evaluating the Stull method in comparison to the Davies-Jones method to calculate WBT for March 2013 in the observed data small differences are observed (Table 2). The biggest MAE value is 1.43°C in WBT for NYA decreasing to 1 C in WBGT. The least significant R^2 value is 0.61 for WBT for TAT. It therefore can be suggested that using Stull in comparison to Davies-Jones makes no substantial difference in the resulting WBGT.

4. Discussion

4.1. Why Another WBGT Approximation?

We demonstrate that $WBGT_{Brimicombe}$ is a useful approximation of WBGT. As discussed in Section 2.4 and supported by the results in Section 3.4, $WBGT_{Brimicombe}$ is a beneficial method to use in the place of $WBGT_{Liljegren}$ for gridded data sets and numerical weather prediction services. Comparisons between $WBGT_{Brimicombe}$ and $WBGT_{Liljegren}$ show only small differences (a difference of 1 heat stress category and a MAE of between 0.76°C and 1.13°C) across the case studies considered. $WBGT_{Brimicombe}$ reanalysis has at most an MAE value of 5°C in comparison to it being observed (Figure 6). $WBGT_{Brimicombe}$ performs with the least accuracy in cold climates such as Greenland and at higher altitudes such as the Tibetan Plateau, regions that are not highly populated and are cold which is outside the scope of a heat stress index (Figure 3). As such, it has been shown with confidence that $WBGT_{Brimicombe}$ can be considered an accurate approximation of WBGT (Figures 1–6).

There are many approaches to calculating the WBGT and these derive from the fact that measurements from globe and wet bulb thermometers are not widely available (Dally et al., 2018; Lemke & Kjellstrom, 2012; Lima et al., 2021; Orlov et al., 2020; Yengoh & Ardö, 2020). Unless measurements come from these instruments and provide all the input parameters required in Equation 1, all approaches to calculate the WBGT are approximations, which are wide ranging in accuracy, a wide scale observation study, in terms of both weather and physiological observations would therefore be beneficial. This research, however, clearly demonstrates that the approximation by the American college of sports medicine, $WBGT_{ACSM87}$, is not an accurate indication of WBGT and recommends that it is not used for a like-for-like approximation. This finding is in agreement with current literature on the topic (Chen et al., 2019; Grundstein & Cooper, 2018; Kong & Huber, 2021; Lemke & Kjellstrom, 2012; Lima et al., 2021; Orlov et al., 2020; Yengoh & Ardö, 2020).

Previous research has suggested that the approximation by Davies-Jones (2008) is a more accurate approximation of natural WBT than the approximation by Stull (Buzan et al., 2015). However, the results presented here demonstrate the accuracy of the $WBGT_{Brimicombe}$ results and the similar sensitivity of this approximation using Stull (2011) in comparison to $WBGT_{Liljegren}$ and observed calculations of $WBGT_{Brimicombe}$. Further, for observation data it has been shown by this study that there is no more than a 1°C MAE between a WBGT output using Davies-Jones (2008) in comparison to Stull (2011). In addition, and of particularly practical relevance, the approximation by Stull (2011) is not iterative and therefore easier to use and more readily scalable than the Davies-Jones approximation. $WBGT_{Brimicombe}$ was developed for gridded data sets from numerical weather

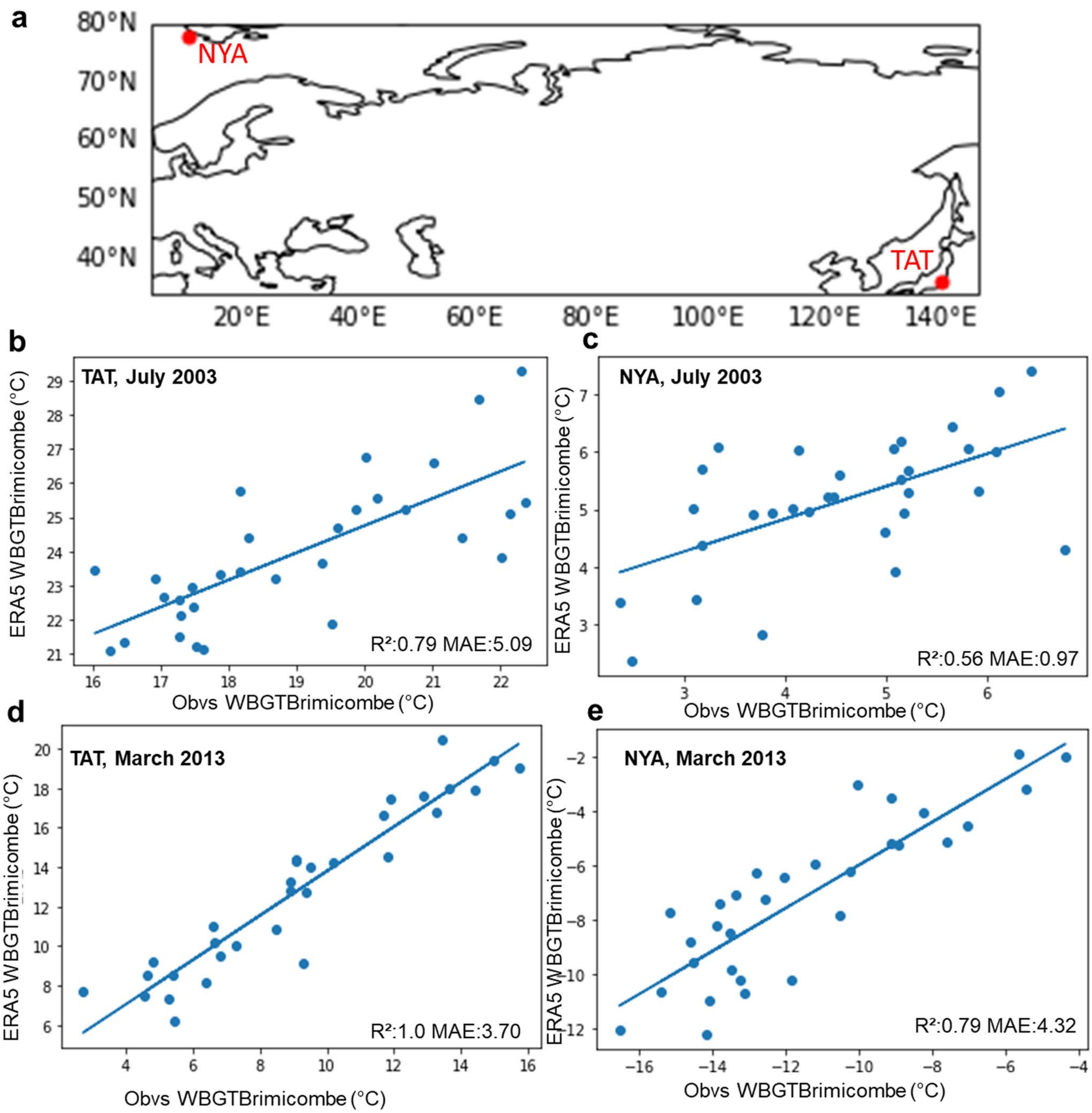

Figure 6. (a) The location of the observation stations NYA and TAT from the Baseline Surface Radiation Network data set to calculate observed Wet Bulb Globe Temperature using the method in thermofeel termed $WBGT_{Brimicombe}$. (b–e) The linear relationship, R^2 and mean absolute error values for (b) TAT Daily Max July 2003, (c) NYA Daily Max July 2003, (d) TAT Daily Max March 2013, and (e) NYA Daily Max March 2013.

prediction data sets and is as accurate as $WBGT_{Liljegren}$ whilst removing the need for complicated iterative convergence methods that can practically take a long time to run and are not readily designed for gridded data. Given all of this evidence it is unnecessary to assess Davies-Jones further by this study.

4.2. How Useful Are Set Thresholds for WBGT?

$WBGT_{ACSM87}$ was found to be significantly lower than $WBGT_{Liljegren}$ for heat stress categories and overall is not an accurate indication of WBGT heat stress risk (as per Kong and Huber (2021)). This could be of particular

Table 2
The Mean Absolute Error and R^2 Values Between Stull Wet Bulb Temperature (WBT) and Davies-Jones WBT and When They Are Subsequently Used to Calculate Wet Bulb Globe Temperature for Two Sets of Observations Taken During March 2013

	Wet bulb temperature		*Wet bulb globe temperature*	
Station	Mean absolute error	R^2	Mean absolute error	R^2
TAT 2013	0.808	0.611	0.56	0.81
NYA 2013	1.431	0.898	1	0.94

disadvantage to the health sector where thresholds are often used to identify life-threatening conditions or to recommend heat-suitable workloads (Budd, 2008; Chen et al., 2019; Jendritzky et al., 2012; Zare et al., 2019).

In this study, it is demonstrated that $WBGT_{Brimicombe}$ can use the same thresholds to indicate heat stress as $WBGT_{Liljegren}$ with these being meaningful values for hazard preparedness. The deliberate decision is taken to use heat stress categories for WBGT as set out by Jacklitsch et al. (2016), where the highest value of 33°C has been shown to be a critical level for heat stress illnesses and to correlate with an increase in hospital admissions and mortality (Cheng et al., 2019). Many studies assessing heat stress and extreme heat are now making use of percentiles compared to a climate (Guigma et al., 2020; Heo et al., 2019) or a standard deviation compared to average conditions (Harrington & Otto, 2020). Whilst we acknowledge that heat indexes and their studies, as the present one, often still do not take into account acclimatization and that 26°C will not be experienced the same by someone in the UK in comparison to Australia (Buzan & Huber, 2020; Nazarian & Lee, 2021), we see the categorical approach as fundamental to heat hazard preparedness. We support more research into acclimatization and how to best model this with heat stress thresholds and health outcomes in mind.

4.3. The Use of WBGT in Weather Forecasting

The WBGT is widely used across sectors. Our approach to the WBGT has been validated in its component parts, namely in the globe thermometer temperature and the wet bulb thermometer temperature (De Dear, 1987; Guo et al., 2018; Stull, 2011). It has been demonstrated for the first time (Section 3.4) that the T_g method of $WBGT_{Brimicombe}$ and $WBGT_{Liljegren}$ are comparable. Going forward this could be used to inform more about radiation. In addition, it is designed for easy integration into operational weather prediction outputs and for use with gridded data sets, with a view to forecast heat stress and heatwaves on a global scale (Brimicombe, Di Napoli et al., 2022).

The ISO status of the WBGT makes it stand out as a heat index that is worth forecasting across multiple sectors (Heo et al., 2019). It is important to forecast WBGT to inform decisions about heat stress warnings and adaptations. There are many benefits when forecasts are made openly accessible and many factors to consider (Budd, 2008; Buzan et al., 2015; Lemke & Kjellstrom, 2012). These include: the accuracy of a WBGT approximation in comparison to the ISO observed values used in Equation 1; the robustness of thresholds in indicating heat hazards and heat stress risk levels; the appropriateness of WBGT for different climates and acclimatization levels (Ahn et al., 2022; Budd, 2008; D'Ambrosio Alfano et al., 2014). These factors also hold true for other heat indices and should be carefully considered (Ahn et al., 2022; Zare et al., 2019).

5. Conclusion

$WBGT_{Brimicombe}$ has been demonstrated to be an accurate approximation of WBGT. $WBGT_{Brimicombe}$ is within 1 heat stress category of $WBGT_{Liljegren}$ across the land surface and in general has anomalies of no more than ±2°C for the 3 heatwave case studies here chosen. In addition, it has a strong positive correlation with $WBGT_{Liljegren}$ and low MAE. In addition, the T_g method for $WBGT_{Brimicombe}$ can be suggested to be equivalent to that of $WBGT_{Liljegren}$ enhancing understanding of the relationship of different forms of radiation. Further, $WBGT_{Brimicombe}$ has a strong linear relationship between it's observed and reanalysis data and at most an MAE of 5°C.

$WBGT_{ACSM87}$ is not an accurate approximation of WBGT and should not be continued to be used. $WBGT_{ACSM87}$ often has a three heat stress category difference to $WBGT_{Liljegren}$ and it widely has anomalies of ±4°C for the three heatwave case studies chosen. Although $WBGT_{ACSM87}$ has a strong positive correlation with $WBGT_{Liljegren}$, it shows high MAE values.

It is hoped that by integrating $WBGT_{Brimicombe}$ into reanalysis, climate models and forecasts, that this information would be made openly accessibly and incorporated into sectors heat warning and adaptations, providing improvements to early warning systems and adaptation policy. Finally, $WBGT_{Brimicombe}$ is a worthy heat stress index candidate for a global forecasting early warning system and would not only be beneficial to a range of sectors but also has the real potential to save lives.

Nomenclature

$\cos\theta$	Cosine of the solar zenith angle (°)
h_{cg}	mean convection coefficient (W/m^2K)
A_h	the convective heat transfer coefficient (W/m^2K)
T_a	2 m Temperature/Dry Bulb Temperature in K or °C as described
T_g	Globe Temperature in K or °C as described
T_w	Wet Bulb Temperature in K or °C as described
e_a	Saturation vapor pressure of the air (kpa)
e_w	Saturation vapor pressure of the wick (kpa)
α_g	albedo of the globe (0.05)
α_{sfc}	albedo of the surface (0.45)
ε_a	the emissivity of the air (W/m^2)
ε_g	the emissivity of the globe (0.95)
ΔF_{net}	the net radiant heat flux (W/m^2K)
D	Globe Diameter 0.15 m
dsrp	downward solar radiation proportion (W/m^2)
h	mean convection coefficient (W/m^2K)
ssrd	Solar Surface Radiation downwards (W/m^2)
T_{MRT}	Mean Radiant Temperature in K or °C as described
v_a	10 m wind speed m/s
ε	Emissivity 0.98 that of a clothed body (Bedford & Warner, 1934; De Dear, 1987)
Nu	Nusselt Number is the ratio of convective to conductive heat transfer (dimensionless)
P	Surface Pressure (kpa)
Pr	Prandtl Number is the ratio of momentum diffusivity to thermal diffusivity (dimensionless)
R	Relative Humidity (%)
Sh	Sherwood Number a mass transfer operation (dimensionless)
Sc	Schmidt Number is the ratio of the kinematic viscosity to the molecular diffusion coefficient (dimensionless)
a	is a constant of the value 0.56
e	Saturation Water Vapor Pressure Hpa (hPa)
σ	the Stefan-Boltzmann constant (dimensionless)

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

ERA5 is freely accessible from Hersbach et al. (2020). $WBGT_{Brimicombe}$ and $WBGT_{ACSM87}$ can be calculated using *thermofeel* (Brimicombe et al., 2021, 2022) and $WBGT_{Liljegren}$ is available on request from Kong and Huber (2021).

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