Borderless heat hazards with bordered impacts

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

Correspondence to:

C. Brimicombe,
c.r.brimicombe@pgr.reading.ac.uk

Citation:

Brimicombe, C., Di Napoli, C., Cornforth, R., Pappenberger, F., Petty, C., & Cloke, H. L. (2021). Borderless heat hazards with bordered impacts. *Earth's Future*, *9*, e2021EF002064. https://doi.org/10.1029/2021EF002064

Received 4 MAR 2021
Accepted 26 AUG 2021

Author Contributions:

Conceptualization: Chloe Brimicombe, Claudia Di Napoli, Hannah L. Cloke
Formal analysis: Chloe Brimicombe
Investigation: Chloe Brimicombe
Methodology: Chloe Brimicombe
Resources: Chloe Brimicombe, Claudia Di Napoli
Supervision: Claudia Di Napoli, Rosalind Cornforth, Florian Pappenberger, Celia Petty, Hannah L. Cloke
Validation: Chloe Brimicombe
Visualization: Chloe Brimicombe

Borderless Heat Hazards With Bordered Impacts

Chloe Brimicombe[1], Claudia Di Napoli[2], Rosalind Cornforth[3], Florian Pappenberger[4], Celia Petty[3,5], and Hannah L. Cloke[1,6,7,8]

[1]Department of Geography and Environmental Science, University of Reading, Reading, UK, [2]School of Agriculture, Policy, and Development, University of Reading, Reading, UK, [3]University of Reading, Walker Institute, Reading, UK, [4]European Centre for Medium-Range Weather Forecasts (ECMWF), Reading, UK, [5]Evidence for Development, University of Reading, Reading, UK, [6]Department of Meteorology, University of Reading, Reading, UK, [7]Department of Earth Sciences, Uppsala University, Uppsala, Sweden, [8]Centre of Natural Hazards and Disaster Science, CNDS, Uppsala, Sweden

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).

Writing – original draft: Chloe Brimicombe
Writing – review & editing: Chloe Brimicombe, Claudia Di Napoli, Rosalind Cornforth, Florian Pappenberger, Celia Petty, Hannah L. Cloke

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.

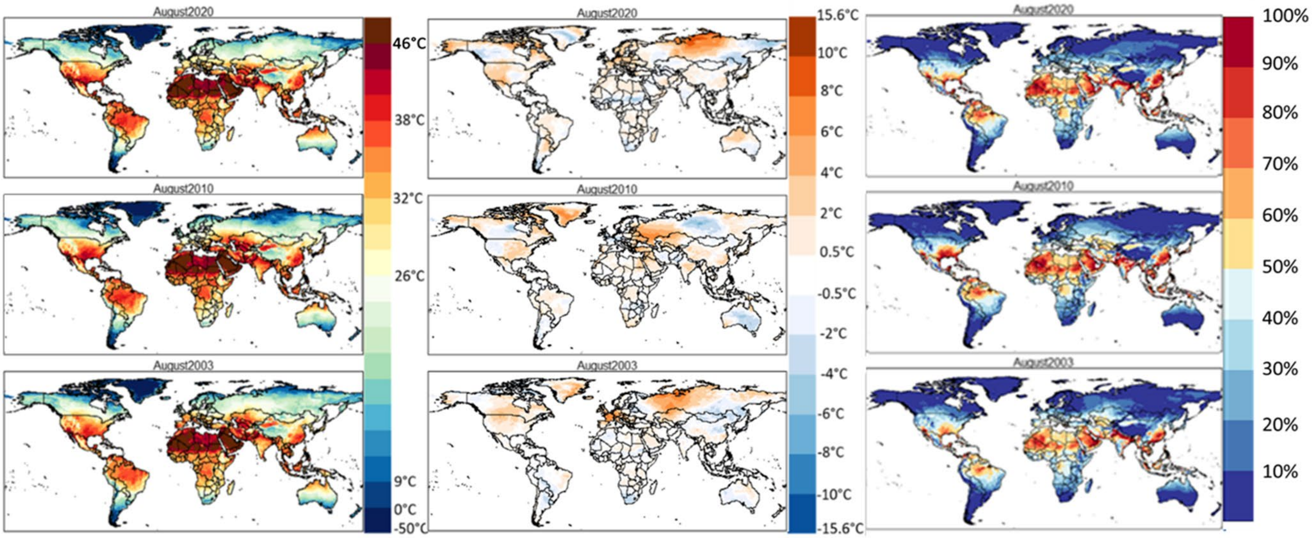

Figure 1. Universal Thermal Comfort Index (UTCI) monthly mean of the daily maxima (left), corresponding anomalies with respect to climatology (center), percentage time that hourly UTCI is over heat stress threshold (26°C) (right) from August 2020, 2010, and 2003 heatwaves.

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.

10.1029/2021EF002064

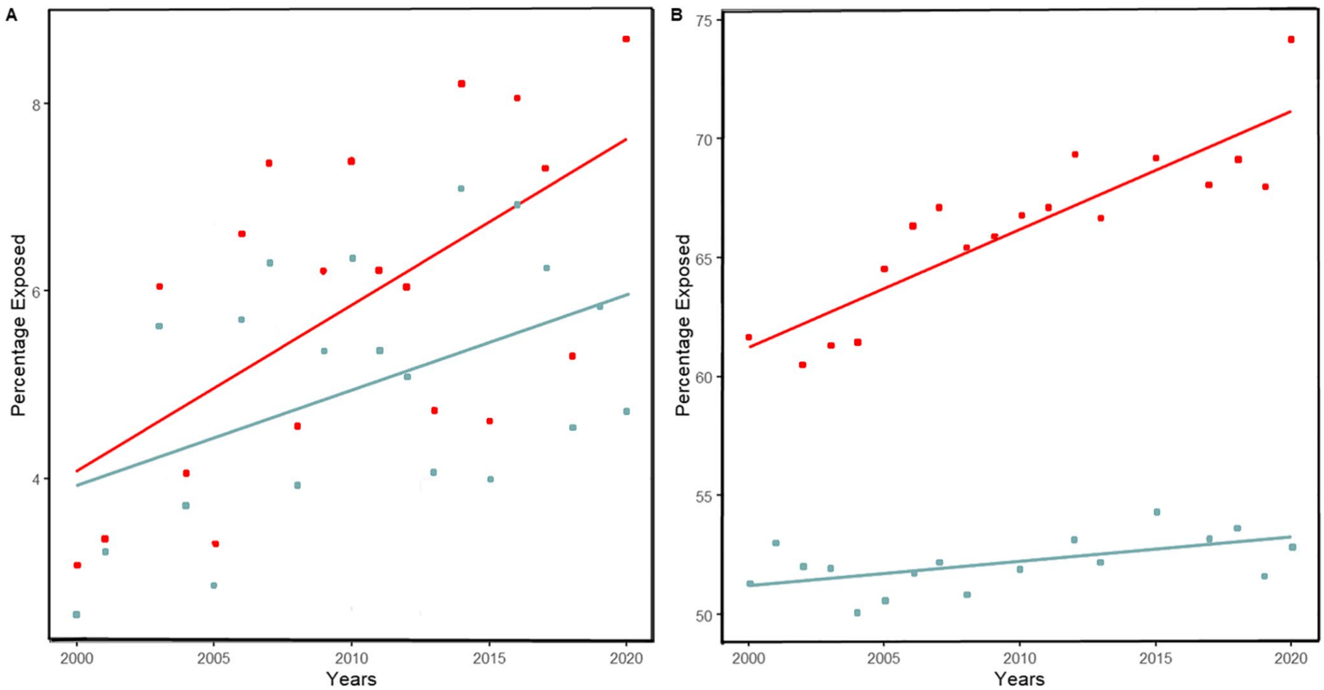

Figure 2. Percentage of land area exposed to heat stress values from 2000 to 2020, Red/Top: Proportion of populated land area as defined by LandScanTM (2000–2019) (Dobson et al., 2000; Vijayaraj et al., 2007), Blue/Bottom: Proportion of total land mass. Panel (a) uses values over a 5°C anomaly compared 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).

Acknowledgments
All the authors would like to acknowledge the invaluable comments of the reviewers. C. Brimicombe would like to thank the University of Reading, SCENARIO DTP, and ECMWF for their continued support.

References

Abass, R., Mensah, A., & Fosu-Mensah, B. (2018). The role of formal and informal institutions in smallholder agricultural adaptation: The case of Lawra and Nandom districts, Ghana. *West African Journal of Applied Ecology*, *26*, 56–72.

Achberger, C., Ackerman, S. A., Ahlstrøm, A., Alfaro, E. J., Allan, R. J., Alves, L., et al. (2011). State of the climate in 2010. *Bulletin of the American Meteorological Society*, *92*, S1–S236.

Alfieri, L., Burek, P., Dutra, E., Krzeminski, B., Muraro, D., Thielen, J., & Pappenberger, F. (2013). GloFAS—Global ensemble streamflow forecasting and flood early warning. *Hydrology and Earth System Sciences*, *17*, 1161–1175.

American Meteorological Society. (2004). State of the climate in 2003. *Bulletin of the American Meteorological Society*, *85*, S1–S72. https://doi.org/10.1175/1520-0477-85.6s.S1

Arbuthnott, K. G., & Hajat, S. (2017). The health effects of hotter summers and heat waves in the population of the United Kingdom: A review of the evidence. *Environmental Health*, *16*, 119.

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.

Bröde, P., Fiala, D., Błażejczyk, K., Holmér, I., Jendritzky, G., Kampmann, B., et al. (2012). Deriving the operational procedure for the Universal Thermal Climate Index (UTCI). *International Journal of Biometeorology*, *56*, 481–494.

Campbell, S., Remenyi, T. A., White, C. J., & Johnston, F. H. (2018). Heatwave and health impact research: A global review. *The Healing Place*, *53*, 210–218.

Ceola, S., Laio, F., & Montanari, A. (2014). Satellite nighttime lights reveal increasing human exposure to floods worldwide. *Geophysical Research Letters*, *41*, 7184–7190. https://doi.org/10.1002/2014GL061859

Chambers, J. (2020). Global and cross-country analysis of exposure of vulnerable populations to heatwaves from 1980 to 2018. *Climate Change*, *163*, 539–558. https://doi.org/10.1007/s10584-020-02884-2

Copernicus Climate Change Service. (2021). *European State of the climate 2020*.

CRED. (2020a). *EM-DAT | The international disasters database EM-DAT*. Retrieved from https://www.emdat.be/

CRED. (2020b). *EM-DAT glossary EM-DAT gloss*. Retrieved from https://www.emdat.be/Glossary

CRED. (2020c). *Email correspondence with CRED about EM-DAT recording of heatwaves*.

Cullmann, J., Dilley, M., Egerton, P., Fowler, J., Grasso, V. F., Honoré, C., et al. (2020). 2020 State of climate services, risk information and early warning systems. In EGU General Assembly Conference Abstracts.

Di Napoli, C., Barnard, C., Prudhomme, C., Cloke, H. L., & Pappenberger, F. (2020). ERA5-HEAT: A global gridded historical dataset of human thermal comfort indices from climate reanalysis. *Geoscience Data Journal*, *8*(1), 2–10. https://doi.org/10.1002/gdj3.102

Di Napoli, C., Pappenberger, F., & Cloke, H. L. (2018). Assessing heat-related health risk in Europe via the Universal Thermal Climate Index (UTCI). *International Journal of Biometeorology*, *62*, 1155–1165.

Di Napoli, C., Pappenberger, F., & Cloke, H. L. (2019). Verification of heat stress thresholds for a health-based heat-wave definition. *Journal of Applied Meteorology and Climatology*, *58*, 1177–1194. https://doi.org/10.1175/JAMC-D-18-0246.1

Dobson, J. E., Bright, E. A., Coleman, P. R., Durfee, R. C., & Worley, B. A. (2000). A global population database for estimating populations at risk. *Photogrammetric Engineering & Remote Sensing*, *66*, 849–857.

Emerton, R. E., Stephens, E. M., Pappenberger, F., Pagano, T. C., Weerts, A. H., Wood, A. W., et al. (2016). Continental and global scale flood forecasting systems. *Wiley Interdisciplinary Reviews: Water*, *3*, 391–418.

Fankhauser, S., & McDermott, T. K. J. (2014). Understanding the adaptation deficit: Why are poor countries more vulnerable to climate events than rich countries? *Global Environmental Change*, *27*, 9–18.

Gall, M., Borden, K. A., & Cutter, S. L. (2009). When do losses count? *Bulletin of the American Meteorological Society*, *90*, 799–809.

Guigma, K. H., Todd, M., & Wang, Y. (2020). Characteristics and thermodynamics of Sahelian heatwaves analysed using various thermal indices. *Climate Dynamics*, *1*, 3. https://doi.org/10.1007/s00382-020-05438-5

Harrington, L. J., & Otto, F. E. L. (2020). Reconciling theory with the reality of African heatwaves. *Nature Climate Change*, *10*, 796–798.

Howarth, C., Kantenbacher, J., Guida, K., Roberts, T., & Rohse, M. (2019). Improving resilience to hot weather in the UK: The role of communication, behaviour and social insights in policy interventions. *Environmental Science & Policy*, *94*, 258–261.

Jendritzky, G., de Dear, R., & Havenith, G. (2012). UTCI-Why another thermal index? *International Journal of Biometeorology*, *56*, 421–428.

Khare, S., Hajat, S., Kovats, S., Lefevre, C. E., de Bruin, W. B., Dessai, S., & Bone, A. (2015). Heat protection behaviour in the UK: Results of an online survey after the 2013 heatwave. *BMC Public Health*, *15*, 878.

Kitzinger, J. (1999). Researching risk and the media. *Health, Risk & Society*, *1*, 55–69.

Kotz, M., Wenz, L., Stechemesser, A., Kalkuhl, M., & Levermann, A. (2021). Day-to-day temperature variability reduces economic growth. *Nature Climate Change*, *11*, 1–7.

Kovats, R. S., & Hajat, S. (2008). Heat stress and public health: A critical review. *Annual Review of Public Health*, *29*, 41–55.

Larcom, S., She, P. W., & van Gevelt, T. (2019). The UK summer heatwave of 2018 and public concern over energy security. *Nature Climate Change*, *9*, 370–373.

McGregor, G. R., & Vanos, J. K. (2018). Heat: A primer for public health researchers. *Public Health*, *161*, 138–146.

National Centers for Environmental Information. (2020). *NOAA National Centers for Environmental Information, State of the Climate: Global Climate Report for August 2020*. Retrieved from https://www.ncdc.noaa.gov/sotc/global/202008

Nazarian, N., Acero, J. A., & Norford, L. (2019). Outdoor thermal comfort autonomy: Performance metrics for climate-conscious urban design. *Building and Environment*, *155*, 145–160.

Nazarian, N., & Lee, J. K. W. (2020). Personal assessment of urban heat exposure: A systematic review. *Environmental Research Letters*, *16*, 033005. https://doi.org/10.1088/1748-9326/abd350

Nazarian, N., & Lee, J. K. W. (2021). Personal assessment of urban heat exposure: A systematic review. *Environmental Research Letters*, *16*, 33005. https://doi.org/10.1088/1748-9326/abd350

Neumayer, E., Plümper, T., & Barthel, F. (2014). The political economy of natural disaster damage. *Global Environmental Change*, *24*, 8–19.

Oppermann, E., Brearley, M., Law, L., Smith, J. A., Clough, A., & Zander, K. (2017). Heat, health, and humidity in Australia's monsoon tropics: A critical review of the problematization of "heat" in a changing climate. *Wiley Interdisciplinary Reviews Climate Change*, *8*(4), e468.

Pappenberger, F., Jendritzky, G., Staiger, H., Dutra, E., Di Giuseppe, F., Richardson, D. S., & Cloke, H. L. (2015). Global forecasting of thermal health hazards: The skill of probabilistic predictions of the Universal Thermal Climate Index (UTCI). *International Journal of Biometeorology*, *59*, 311–323.

Perkins-Kirkpatrick, S. E., & Gibson, P. B. (2017). Changes in regional heatwave characteristics as a function of increasing global temperature. *Scientific Reports*, *7*, 1–12.

Robine, J. M., Cheung, S. L. K., Le Roy, S., Van Oyen, H., Griffiths, C., Michel, J. P., & Herrmann, F. R. (2008). Death toll exceeded 70,000 in Europe during the summer of 2003. *Comptes Rendus Biologies*, *331*, 171–178.

Russo, S., Marchese, A. F., Sillmann, J., & Immé, G. (2016). When will unusual heat waves become normal in a warming Africa? *Environmental Research Letters*, *11*(5), 054016.

Russo, S., Sillmann, J., & Sterl, A. (2017). Humid heat waves at different warming levels. *Scientific Reports*, *7*, 1–7.

Schubert, S., Wang, H., & Suarez, M. (2011). Warm season subseasonal variability and climate extremes in the northern hemisphere: The role of stationary Rossby waves. *Journal of Climate*, *24*, 4773–4792.

Sutanto, S. J., Vitolo, C., Di Napoli, C., D'Andrea, M., & Van Lanen, H. A. J. (2020). Heatwaves, droughts, and fires: Exploring compound and cascading dry hazards at the pan-European scale. *Environment International*, *134*, 105276.

Urban, A., Di Napoli, C., Cloke, H. L., Kyselý, J., Pappenberger, F., Sera, F., et al. (2021). Evaluation of the ERA5 reanalysis-based Universal Thermal Climate Index on mortality data in Europe. *Environmental Research*, *198*, 111227.

Vanos, J. K., Baldwin, J. W., Jay, O., & Ebi, K. L. (2020). Simplicity lacks robustness when projecting heat-health outcomes in a changing climate. *Nature Communications*, *11*, 1–5. https://doi.org/10.1038/s41467-020-19994-1

Vercillo, S., Weis, T., & Luginaah, I. (2020). A bitter pill: Smallholder responses to the new green revolution prescriptions in northern Ghana. *The International Journal of Sustainable Development and World Ecology*, *27*, 565–575. https://doi.org/10.1080/13504509.2020.1733702

Vijayaraj, V., Bright, E. A., & Bhaduri, B. L. (2007). *High resolution urban feature extraction for global population mapping using high performance computing*. Paper presented at International Geoscience and Remote Sensing Symposium (IGARSS) (pp. 278–281). IEEE.

Vitolo, C., Di Napoli, C., Di Giuseppe, F., Cloke, H. L., & Pappenberger, F. (2019). Mapping combined wildfire and heat stress hazards to improve evidence-based decision making. *Environment International*, *127*, 21–34.

Vogel, M. M., Zscheischler, J., Wartenburger, R., Dee, D., & Seneviratne, S. I. (2019). Concurrent 2018 hot extremes across Northern hemisphere due to human-induced climate change. *Earth's Future*, *7*, 692–703.

Watts, N., Adger, W. N., Ayeb-Karlsson, S., Bai, Y., Byass, P., Campbell-Lendrum, D., et al. (2017). The Lancet Countdown: Tracking progress on health and climate change. *Lancet*, *389*, 1151–1164.

Watts, N., Amann, M., Arnell, N., Ayeb-Karlsson, S., Belesova, K., Berry, H., et al. (2018). The 2018 report of the Lancet Countdown on health and climate change: Shaping the health of nations for centuries to come. *Lancet*, *392*, 2479–2514.

Watts, N., Amann, M., Arnell, N., Ayeb-Karlsson, S., Belesova, K., Boykoff, M., et al. (2019). The 2019 report of The Lancet Countdown on health and climate change: Ensuring that the health of a child born today is not defined by a changing climate. *Lancet*, *394*, 1836–1878.

WMO and WHO. (2015). *Heatwaves and health: Guidance on warning-system development*. Retrieved from http://www.who.int/globalchange/publications/WMO_WHO_Heat_Health_Guidance_2015.pdf

Wolf, J., Adger, W. N., Lorenzoni, I., Abrahamson, V., & Raine, R. (2010). Social capital, individual responses to heat waves and climate change adaptation: An empirical study of two UK cities. *Global Environmental Change*, *20*, 44–52.

World Meteorological Organization. (2004). *WMO Statement on the status of the global climate in 2003*. World Meteorological Organization.

World Meteorological Organization. (2011). *WMO Statement on the status of the global climate in 2010*. World Meteorological Organization.

World Meteorological Organization. (2019). *The global climate in 2015–2019* (Vol. 32). World Meteorological Organization.

World Meteorological Organization. (2020). *State of the climate in Africa 2019*. World Meteorological Organization.

World Meteorological Organization. (2021). *State of the global climate 2020*. World Meteorological Organization.