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Quantifying impact-relevant heatwave durations

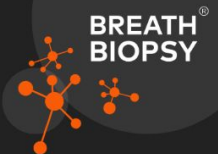
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Kelley De Polt^{1,2,*} , Philip J Ward^{2,3} , Marleen de Ruiter² , Ekaterina Bogdanovich¹ ,
Markus Reichstein¹ , Dorothea Frank¹ and René Orth¹ ¹ Department of Biogeochemical Integration, Max Planck Institute for Biogeochemistry, Jena, Germany² Institute for Environmental Studies, Vrije Universiteit Amsterdam, Amsterdam, The Netherlands³ Department of Climate Adaptation and Disaster Risk Management, Deltares, Delft, The Netherlands

* Author to whom any correspondence should be addressed.

E-mail: kdepolt@bgc-jena.mpg.de**Keywords:** extreme heat, health impacts, societal attention, heatwave durationSupplementary material for this article is available [online](#)**Abstract**

Heatwaves are weather hazards that can influence societal and natural systems. Recently, heatwaves have increased in frequency, duration, and intensity, and this trend is projected to continue as a consequence of climate change. The study of heatwaves is hampered by the lack of a common definition, which limits comparability between studies. This applies in particular to the considered time scale for utilised metrics. Here, we study which durations of heatwaves are most impact-relevant for various types of impacts. For this purpose, we analyse societal metrics related to health (heat-related hospitalisations, mortality) and public attention (Google trends, news articles) in Germany. Country-averaged temperatures are calculated for the period of 2010–2019 and the warmest periods of all time scales between 1 and 90 days are selected. Then, we assess and compare the societal response during those periods to identify the heatwave durations with the most pronounced impacts. Note that these durations are based on average temperatures across the given time frame while individual days may be less warm. The results differ slightly between the considered societal metrics but indicate overall that heatwaves induce the strongest societal response at durations between 2 weeks and 2 months for Germany. Finally, we show that heatwave duration affects the societal response independent of, and additionally to, heatwave temperatures. This finding highlights the relevance of making informed choices on the considered time scale in heatwave analyses. The approach we introduce here can be extended to other societal indices, countries, and hazard types to reveal more meaningful definitions of climate extremes to guide future research on these events.

1. Introduction

Heatwaves are weather and climate hazards, that can strongly influence natural and human systems (Perkins and Alexander 2013). Most evidently, these hazards can lead to adverse impacts on human health (Anderson and Bell 2011, Xu *et al* 2016, 2018), agriculture (Zampieri *et al* 2017), ecosystems (Reyer *et al* 2013, Cremonese *et al* 2017, von Buttlar *et al* 2018, Xu *et al* 2020), and infrastructure (McEvoy *et al* 2012, Hallegatte *et al* 2019). Heatwaves can also have indirect impacts, for instance in relation to economic systems they can lead to a decrease in worker productivity (Dunne *et al* 2013, Orlov *et al* 2019),

especially for those with outdoor occupations (Kjellstrom *et al* 2009).

One of the most exceptional heatwaves was the 2003 heatwave in Central and Western Europe, which caused over 70 000 additional deaths (Robine *et al* 2008, Coumou and Rahmstorf 2012). This led to preventative measures being taken throughout the continent (WMO and WHO 2015, Matzarakis 2017, Casanueva *et al* 2019, Martinez *et al* 2019, UKHSA 2022), such as heat warning systems. The 2018 and 2019 heatwaves in Germany resulted in immense damages and costs as well as 7500 heat-related deaths (Trenczek *et al* 2022, Winklmayr *et al* 2022, BMWK 2023). More recently, the 2022 European heatwave

led to the warmest summer (June–August) on record, surpassing the previous record set only 5 years prior by 0.8 °C (Copernicus 2022a, 2022b). During this heatwave event, at least 15 000 deaths could be attributed to the heatwave, 4500 of which occurred within Germany (Kluge 2022). On both regional and global scales, these hazards have increased in frequency, severity, duration, and spatial extent (Alexander *et al* 2006, Della-Marta *et al* 2007, Ding *et al* 2010), which also exacerbates population exposure to heat stress (Lyon *et al* 2019, Freychet *et al* 2022). These increases are predicted to continue with projected anthropogenic climate change (Dosio *et al* 2018, Naumann *et al* 2021, Seneviratne *et al* 2021).

In the literature, there is no consistent definition of a heatwave, though they are generally described as periods of consecutive days when the air temperature is warmer than normal (Habeeb *et al* 2015, Sutanto *et al* 2020, Murray *et al* 2021, USEPA 2022). Accordingly, there are also a variety of ways in which heatwaves can be researched (Perkins 2015) and classified by indicators (e.g. DWD, UBA, EDO). Indices are often used to quantify heatwaves, which are usually based upon observations of meteorological variables that are above given thresholds for a certain period (Alexander *et al* 2006, Anderson and Bell 2011, Perkins *et al* 2012, Coumou and Robinson 2013, Tong *et al* 2015, Xu *et al* 2017). These thresholds have been defined in many ways in the literature, which means that events that share the same name are classified or measured in different and potentially non-comparable ways (Seneviratne *et al* 2021).

In order to better understand and compare impacts from these hazards, common approaches are needed (Orth *et al* 2022). This is particularly challenging as different research and operational communities have developed approaches to quantify heatwaves in relation to their specific sector. However, it has yet to be tested whether it is possible to develop a universal approach that can characterise impact-relevant heatwave duration across sectors.

Heatwaves can be explicitly explained through intensity and duration. As most definitions emphasise the intensity of these hazards through percentiles, duration is either missing or is a secondary aspect within current definitions. In particular, the duration of heatwaves is an important characteristic to consider as it has been shown to contribute to the extent of resulting impacts. Previous literature has stated that longer heatwaves intensify societal impacts (Vogel *et al* 2020), ecosystem impacts (von Buttlar *et al* 2018, Flach *et al* 2021), and adverse health outcomes (Anderson and Bell 2011). Furthermore, the duration of extreme heat may also factor into the recovery of a system or sector following an event.

In this study, we collect and analyse multiple data sources capturing diverse heatwave impacts and responses across sectors in Germany. In particular we consider public health and societal attention. The

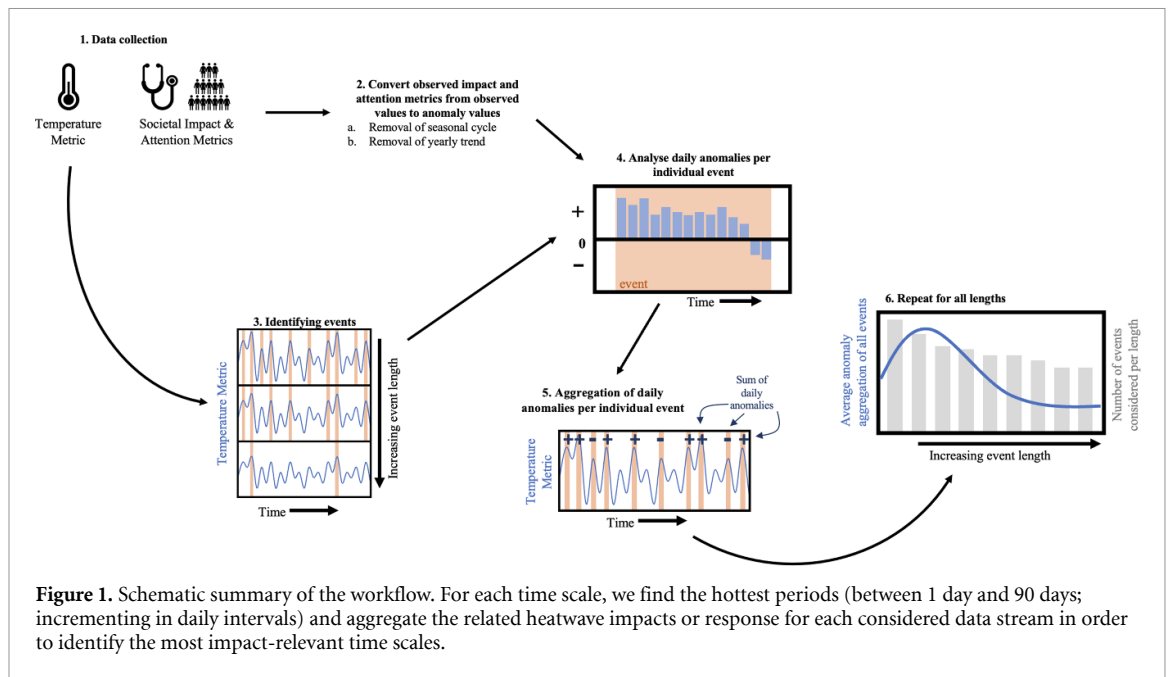
methodology we implement identifies heatwaves on the basis of particularly warm average temperatures over a time frame, not on the basis of the number of consecutive days above a temperature threshold. Using these indicators, we calculate and compare the impacts of hot temperatures, determined across time scales of differing lengths, and thereby establish an approach to determine a range of durations of heatwaves at which impacts in Germany are most notable. Benefitting from the diversity of employed data streams we can further compare the impact-relevant heatwave durations across health and societal attention sectors in order to assess the possibility of establishing a more universal heatwave duration classification scheme.

2. Data and methods

This study uses Germany as a case study to establish and implement a methodology for relating heatwave duration to resulting impacts and responses. Germany has similar weather and temperature conditions throughout the country and is relatively densely populated, so that heatwave impacts can be easily distinguished from noise in societal data streams. The study period is chosen as 2010–2019, limited by the simultaneous availability of all considered data. The main methodological steps of the approach are shown in figure 1, and in brief, the approach consists of: (1) collecting data representing extreme heat events, impact and attention metrics; (2) identifying extreme heat events from the underlying daily mean temperature data; (3) conversion of observed impact and attention metric to anomalies; (4) examining the daily impact and attention anomalies within each event; (5) aggregating the daily anomalies for each event; and (6) repeating above steps for all events of all lengths.

2.1. Data collection and pre-processing

To identify heatwave events over different time scales, we used data from the ERA5 reanalysis dataset (Hersbach *et al* 2020) at a spatial resolution of $0.25^\circ \times 0.25^\circ$ for the time period of 01-01-2010–31-12-2019. ERA5 is a reanalysis dataset describing global climate and weather, combining model data and observation from across the world into a globally consistent dataset. Gridded data is aggregated to a country scale by first weighting each grid cell according to population density and then averaging the values from all grid cells in the country. The population weighted average gives more importance to values in more densely populated areas. Population density was sourced from the Gridded Population of the World, Version 4 which consists of estimates of human population density based on national census and population registers (CIESIN 2018). As the impact and response metrics we consider are societal in nature, population weighting is used to ensure comparability between climate and societal metrics.



We consider four societal variables from independent data streams that represent the impact of heatwaves on public health and societal attention (table 1). For the societal attention variables, we consider Google search frequency and the number of heat-related news articles. For the societal variables related to public health, we consider human mortality and heat-related hospital admissions.

We obtain information on search frequencies for *heatwave* and *heat stroke* from Google trends. Thereby, instead of using these exact search terms we select the respective topics where *heatwave* is labelled ‘disaster type’ and *heat stroke* is labelled as ‘illness’. The topic feature allows us to capture searches for multiple similar heat-related search terms across different languages, making the retrieved time series more informative compared to singular search terms (Rogers 2016, Google 2023). The most relevant search terms related to the topic are then aggregated into the topic. However, Google does not disclose the algorithms used to create the topics and they may change over time. Daily values are retrieved using the PyTrends Python package (Hogue and DeWilde (<https://pypi.org/project/pytrends/>)). If people search for *heatwave* or related searches, which Google then aggregates into the topic *heatwave*, this indicates that they are looking for information about the event. However, when people search for *heat stroke* or related searches, which Google then groups into the topic *heat stroke*, it is indicative of them having a health complaint or searching on behalf of someone else (Green *et al* 2018). Previous analyses found strong correlations between search frequency for the Google topic *heat stroke* and heat stroke-related deaths and hospitalisations (Li *et al* 2016,

Bogdanovich *et al* 2023). Similar results were also found in the United States when analysing internet searches and emergency department visits (Adams *et al* 2022).

Another metric that represents a form of societal attention is news articles. Newspaper articles provide written evidence of diverse and often difficult to quantify negative and positive impacts related to hot weather (Undorf *et al* 2020). We analyse the number of print and online news articles that mention ‘heatwave’ from the popular newspapers. We use the German search term ‘(Deutschland) AND ((Hitzewelle) OR (extreme Hitze))’ to retrieve the articles from the databases Factiva (www.dowjones.com/professional/factiva/) and WiSo (www.wiso-net.de/dosearch) which collect the articles mentioning heatwaves in three leading German newspapers (Die Welt, Die Zeit and Süddeutsche Zeitung). Note that, the most popular German newspaper, Bild, was not included because data are not available for the entire study period. To ensure that no single newspaper dominates the heatwave mentions, we standardise the weekly time series for each newspaper. This is done by multiplying each value by the ratio between the total number of heatwave articles in the corresponding newspaper and the total number of heatwave articles in the newspaper with the most heatwave articles. Although the number of articles is available on a daily basis, it is aggregated to weekly values, there are many days with low numbers of articles published and some news organisations publish on certain days of the week (i.e. Sunday release schedules). Then we map this back to a daily time scale by using the weekly value over all the individual days of each week. For example, if the data are associated with a Sunday, the

Table 1. List of datasets to determine impact or response from detected extreme events.

Variable	Sector	Spatial resolution(s)	Temporal resolution	Source
Google trends	Public attention	Country	Daily	Google
News articles	Public attention	Country	Daily	WiSo Factiva
Mortality	Health impact	Country	Weekly	Eurostat
Heat-related hospitalisations	Health impact	Country	Weekly	German Federal Statistical Office

value for that Sunday is also attributed to the preceding Monday through Saturday.

As for health impacts, all-cause mortality counts obtained from Eurostat are used as a proxy. An additional proxy for the health impact of extreme heat events is the number of heat-related hospital admissions. Data on hospitalisations are provided by the Federal Statistical Office. Both health impact measures are weekly counts. Following the procedure used for the press attention metric, weekly counts are brought to a daily scale by associating the weekly count with each day of the previous week.

2.2. Extreme heat event identification

Various metrics and indices have been developed and introduced to measure heatwaves. In the present study, we implement our methodology with 2 m daily mean temperature (T_{mean}), as well as four additional heat stress metrics. These include the 2 m daily maximum temperature (T_{max}), apparent temperature (AT), heat index (HI; Rothfus 1990) and wet bulb globe temperature (WBGT)—simplified (CoABoM 2010, Blazejczyk *et al* 2012, Lemke and Kjellstrom 2012) which are calculated using functions from the Python package MetPy (<https://unidata.github.io/MetPy/latest/index.html>) and Thermofeel (<https://thermofeel.readthedocs.io/>). HI and AT, common metrics used as indicators of the heat-related stress on the human body, take into account both temperature and humidity aspects. The disadvantage of using these is that it assumes that the population that is exposed to the temperature will be in the shade. WBGT, a similar indicator of heat stress, but representative of exposure to direct sunlight, can overcome this. WBGTs is utilised compared to the un-simplified version, WBGT, due to its wide use and applicability given the availability of input parameters (Buzan *et al* 2015). Further information about equations and sources of these indices are described in table S1.

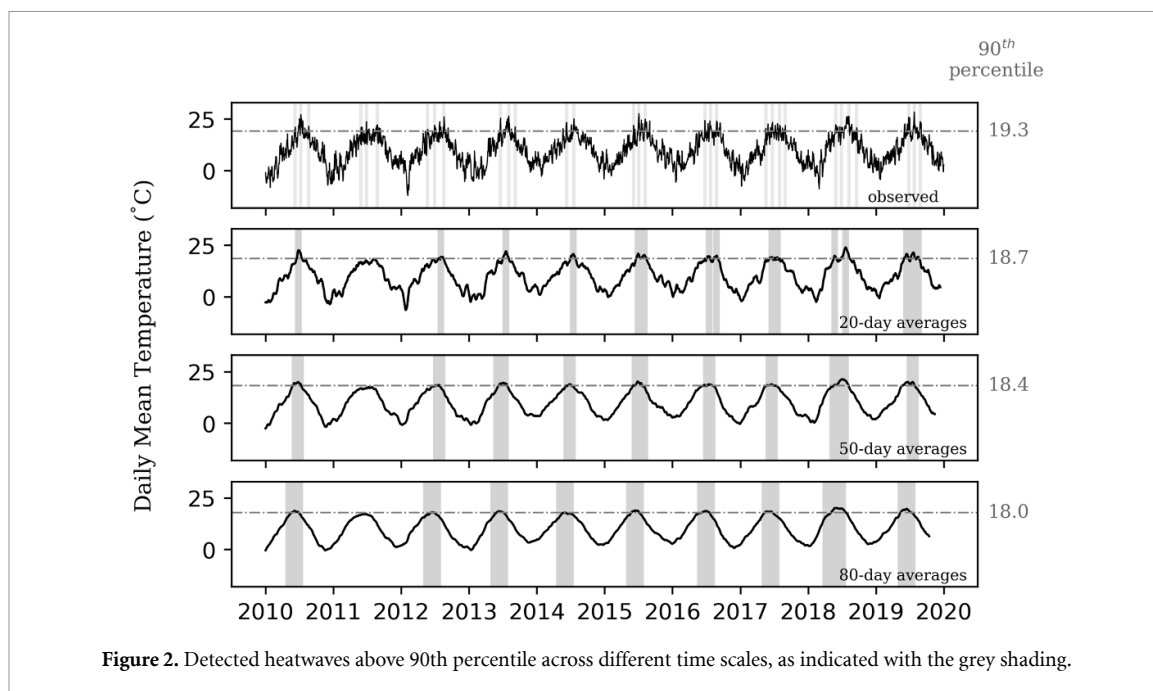
As the definition of heatwaves varies between researchers, we use the term *extreme heat events* to cover heatwaves of both short and long duration. The first step in this process is to derive moving average time series for each time scale of interest considered (1 day to 90 days). This is done by taking the mean of 1–90 days from each individual day of the time series and assigning it to that particular day as the day of onset of the event. (see time series; figure 2). Second,

from the moving averages of all time scales, we find the 90th percentile of all individual values separately for each time scale (see grey dashed lines; figure 2). Finally, events are identified for each time scale by repeatedly: (i) finding the hottest day of each time series (e.g. the day with the peak temperature of that event); (ii) excluding the 30 days around it to ensure independence between detected heatwave events; and (iii) finding the hottest value of the remaining time series. Steps (i)–(iii) are repeated to detect further heatwave events until the detected hottest temperature value of the observed time series does not exceed the 90th percentile of the initial time series after the moving average procedure (see grey vertical bars; figure 2). Disregarding the 30 days around the peak in the temperature metric for each event allows more events to be considered within our sample size. We also test an overlap allowance of 20 days and 40 days, which shows similar end results (figures S1 and S2). This is particularly evident for events of longer duration. To account for events of higher intensity, the entire procedure is repeated to identify events above the 93rd (figure S3) and 96th percentiles (figure S4).

We use this methodology to classify extreme heat events of any length, which to our knowledge is the first use of this approach. Thereby, our approach is more flexible than existing definitions. In previous literature, heatwaves generally defined as a number of days above a threshold (e.g. Anderson and Bell 2011, Tong *et al* 2015, Xu *et al* 2017), exclude extreme heat events of longer duration and already impose a minimum duration, which then excludes these durations from being potentially impact relevant (figure S5).

2.3. Analysis and aggregation of daily anomalies

The method used to assess the relationship between duration and impact is the aggregation of daily anomalies (step 2–3 in figure 1). Each day's impact or response metric value is converted from the observed value to a seasonal anomaly by removing the seasonal cycle. It is particularly important to remove the mean seasonal cycle from this time series in order to derive excess mortality, as it is better suited to studying the impact of heatwaves by filtering out the effects of other causes of death operating on seasonal to annual timescales. To relate societal attention and health impacts to heatwave duration, we aggregate daily anomalies from the societal data sources over



a time window equal to the length of the heatwave under consideration. Anomalies are used instead of raw values because they represent a deviation from baseline or expected values. We assume that people, and human and environmental systems, are largely adapted to baseline conditions, as expressed by the mean seasonal cycle, and are therefore less prepared for deviations from this baseline. Positive anomalies imply a more pronounced response than normal and vice versa. Ultimately, we are interested in the length of heatwaves that produce a more pronounced response, indicated by a larger positive anomaly over the entire event. This methodology is achieved by adding all observed anomaly values for the length of the event (i.e. events with length of 1 day consider one anomaly value; events with length of 2 days add the anomaly values of day 1 and day 2), which allows positive anomalies to accumulate and negative anomalies to subtract from the overall values. This is repeated for all societal metrics and heatwave lengths. Having completed the previous step, we then compare between event lengths (step 4 in figure 1). The mean of all aggregated daily anomalies of all events of the same length is then calculated, producing a single value, which is then related to the length of the heatwave.

3. Results and discussion

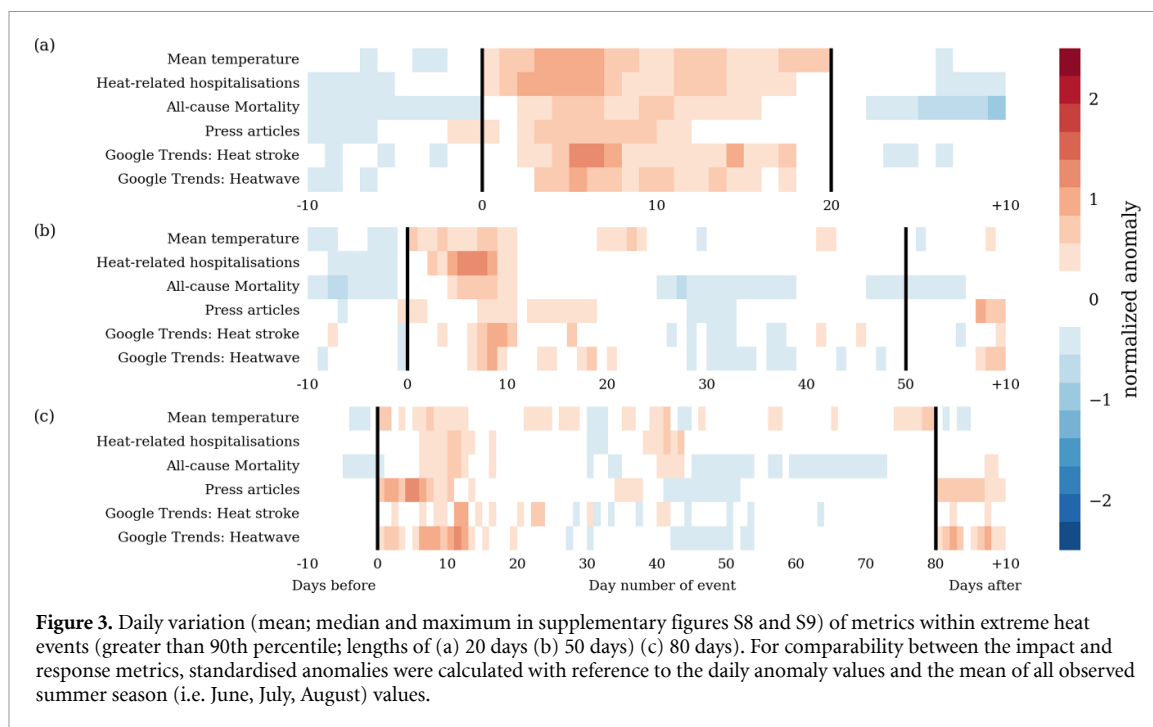
3.1. Evolution of heatwave temperatures and societal response

The first set of analyses examines the distribution of health impacts and public attention before, during and after our detected extreme heat events. To do this, we calculate the mean anomalies for each event day across detected events of the same duration;

this is done for three example durations in figure 3. The metrics have been normalised with respect to the mean of all observed summer season values (i.e. June, July, August).

Comparing the three durations, it can be seen that for 20 day duration events (see figure 3(a)), the response metrics show positive anomalies, i.e. they exceed the summer season mean for the entire event. This means that societal attention, as well as the number of hospitalisations and excess mortality, are higher than usual. The response is generally similar across societal metrics and sectors, as well as with the evolution of the temperature anomaly itself, both in terms of magnitude and timing. For 50 day duration events (see figure 3(b)), the response metrics show positive anomalies in the first half of the events, but not in the second half. Finally, similar to the results for 50 day heatwaves, the results for 80 day duration events (see figure 3(c)) show slightly scattered positive anomalies alongside normal conditions during the course of the events. Except for the longest heatwaves, there are no noticeable delayed positive anomalies in the days following the events.

The mean temperature does not have a clear 'peak' in any event length. This can be interpreted as the temperature peak occurring at any time within the event, or that temperatures during these events are consistently above the summer mean. When comparing health impact metrics, hospitalisations tend to be at their highest at the same time and with a greater deviation from the mean than mortality. Societal metrics relevant to public attention may show an increase ahead of an increase in mean temperature anomalies due to heat health warning systems (Kovats and Ebi 2006, Matzarakis 2017, 2022), heat health action plans (Lowe *et al* 2016), weather forecasts, or



similar examples of discussion within one's social network (Wolf *et al* 2010). Warnings and information dissemination may differ between locations and governmental structures, among other factors, but are typically through the means of media announcements, bulletins or webpages, leaflets, telephone help-lines, or home visits (Kovats and Ebi 2006). When comparing societal attention to health impacts, a peak in Google attention for *heat stroke* occurs after an increase in hospitalisations, which could be caused by people searching for diagnoses or symptoms of themselves, their family members, friends or neighbours. When only higher intensity events are examined (figures S6 and S7), the pattern between all lengths generally remains the same, although the anomalies become more positive, indicating a higher intensity response. The scatter observed in longer duration events also becomes more pronounced.

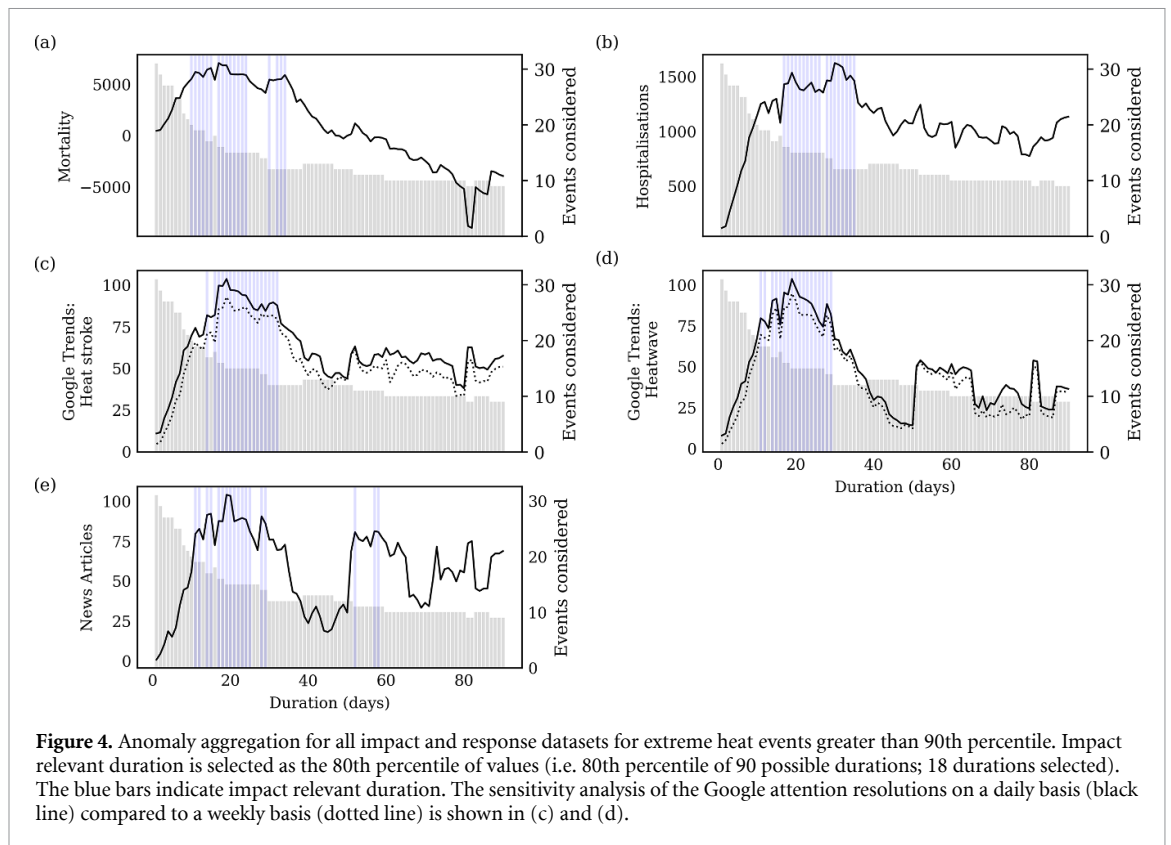
Although all the metrics come from different data streams, they all follow similar patterns depending on the length of the extreme event. This has previously been shown in the literature where societal attention metrics can indicate the public health response to heat (Bogdanovich *et al* 2023). Together, these results provide important insights into how the metrics under consideration evolve during extreme heat events of different durations.

3.2. Societal response across heatwave durations

To assess impact-relevant durations, we first examine each metric and how anomaly summations differ across durations. Figure 4 shows the mean anomalies of the health impact and societal attention metrics across extreme heat events of different durations (solid black lines in figure 4). The durations with

the most pronounced attention or impact are marked with blue background shading in figure 4. The grey bars show the number of events considered for each length. When considering extreme heat events of all intensities considered (i.e. >90th percentile), the impact-relevant durations (indicated by blue bars in figure 4) are similar and peak in the time scales of 2 weeks to 1 month. If only very high intensity events are considered (i.e. events above the 93rd percentile and events above the 96th percentile), the peak and magnitude of the metrics differ (figures S10 and S11).

The societal attention metrics (figures 4(c)–(e)) increase from time scales of 1 day to about 20 days, as larger anomaly sums of the societal attention metrics can accumulate. At longer time scales, aggregated societal attention decreases for most metrics (but remains positive), as societal attention anomalies tend to be less pronounced at longer heatwave lengths, and this is not much counteracted by a longer duration of these anomalies (see figure 3). The evolution of aggregated societal attention beyond time scales of 20–30 days is different for the different metrics considered. A number of factors play a role in this development, in particular the fact that events of longer duration do not change in terms of ‘notability’ or ‘importance’ to the population affected. This finding may be explained by the fact that the amount of media coverage can have an agenda-setting effect, with readers (Liu *et al* 2011) and other news organisations (Sweetser *et al* 2008) attributing greater importance to things that receive more coverage. In an analysis of the 2019 European heatwave, journalists producing news articles focused on discussing the record-breaking temperatures as the most important aspect (Strauss *et al* 2022); suggesting that the



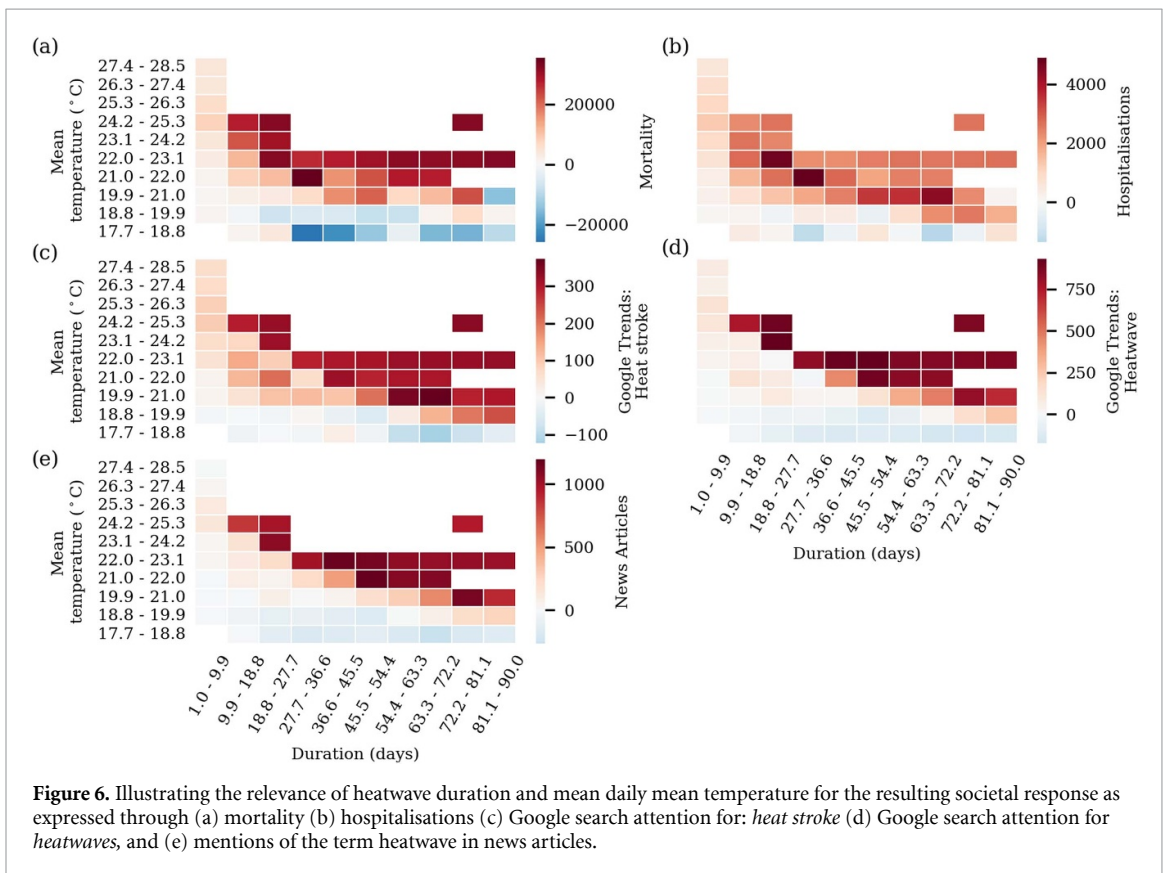
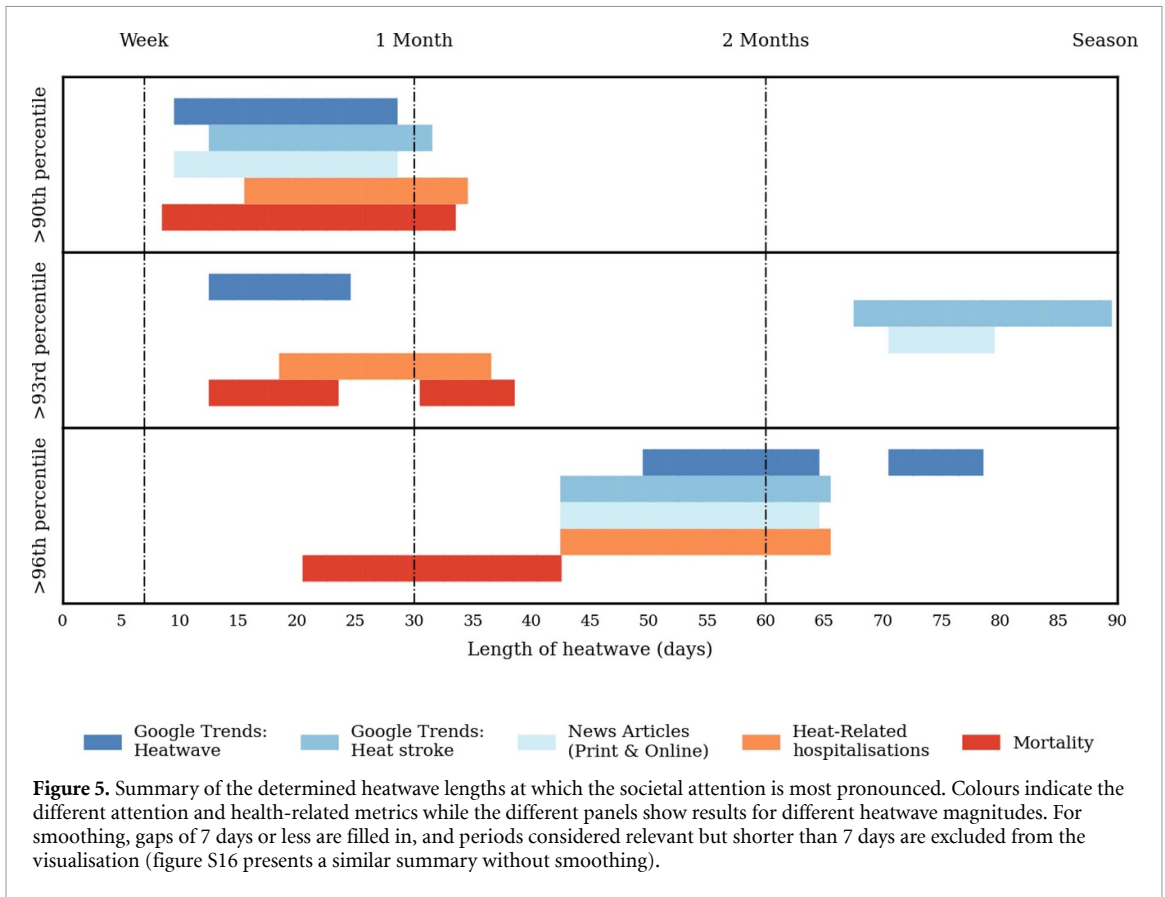
recording of record-breaking temperatures or the duration of record-breaking temperatures are reasons for which more articles may be published.

Google attention data are used to form the only response or impact metric in this analysis that is available at daily resolution. To investigate whether there is an influence caused by differences in the daily vs. weekly resolutions of the metrics, we conduct a sensitivity analysis using both Google attention datasets. This is done by creating weekly averages from the daily data and then comparing the results from both time scales (figures 4(c) and (d); dotted line is weekly). A Kolmogorov–Smirnov test was performed to determine the similarity of the results, and we found that there is no significant difference between the impact-relevant duration results between the daily and weekly scales (table S2).

The anomaly aggregation results for heat-related hospitalisations and Google attention for *heat stroke* follow similar distributions. However, after the peak, the anomaly aggregation of all event subsets (i.e. above the 90th percentile) becomes stable. The anomaly aggregation of heat-related hospitalisations remains stable for longer periods, which could be explained by the fact that higher than normal temperatures in the warm season increase the risk of death and healthcare utilisation (Sarofim *et al* 2016). Alternatively, the relationship between all-cause mortality anomaly aggregation and event length declines after its peak at around two to three weeks, and even

shows negative anomaly summations for events of longer lengths (figure 4(a)). However, this pattern disappears when only higher intensity events are considered. These results are consistent with those of other studies showing evidence of a negative anomaly following extreme events. Mortality displacement, also referred to as harvesting, is the process by which deaths within a frail or extremely vulnerable population are brought forward in time (Arbuthnott and Hajat 2017); prominent during the European heatwave of 2003 (Toulemon and Barbieri 2008). This effect is typically identified by the occurrence of fewer deaths than expected following a mortality crisis; after the heatwave, the number of deaths is lower than expected.

Having analysed the metrics separately, we now summarise them together and between different intensities. In general, the most impact-relevant durations of heatwaves are in the range of 2 weeks to 2 months (figure 5). When analysing all identified events above the 90th percentile, the impact-relevant duration is between 1 week and 1 month. If only higher intensity events are analysed, the impact-relevant duration increases. Health metrics (i.e. all-cause mortality and heat-related hospitalisations) exhibit a shorter impact duration than social attention metrics particularly in the case of higher intensity events. Similar end results are observed between the current metric Tmean, with the additional metrics Tmax (figure S12), AT (figure S13), HI (figure S14), and WBGTs (figure S15). Overall, across all



considered heatwave magnitudes the heatwave durations that trigger the strongest societal response in Germany are between 2 weeks and 2 months.

3.3. Relevance of heatwave duration vs. temperature

In addition to heatwave duration, other characteristics describing the heatwave magnitude may also be relevant for impact or attention outcomes. In order to test the relevance of heatwave duration versus heatwave temperature we study the variation of the societal response in relation to those two characteristics (mean event daily T_{mean} in figure 6; mean event daily T_{max} in figure S17). We find that the heatwave response varies according to both, i.e. colours change in horizontal and vertical directions. This indicates that heatwave duration affects the societal response to heatwaves independently from, and additionally to, heatwave temperatures. This underlines the significance of identifying impact-relevant time scales to be employed in future heatwave analyses, as done here.

4. Summary and conclusions

In this study we establish and implement a methodology to determine the most impact-relevant duration of climate extremes. This is done for Germany as a case study region. With our approach, we find that heatwaves are most impact-relevant at time scales between 2 weeks and 2 months, i.e. if the temperature averaged at such a time scale is particularly high, a societal response is to be expected. Moreover, while heatwave magnitudes can be characterised in multiple ways, we demonstrate that duration is an essential feature to consider next to other variables such as temperature.

Our analyses are carried out with multiple societal data streams related to attention and health impacts that are concurrently available for Germany. This is particularly relevant as each individual data stream has particular shortcomings and can only capture a particular aspect of the societal heatwave response. We find that the most relevant heatwave durations detected with the individual and independent response variables are similar when investigating events across different levels of intensities. This suggests that the societal heatwave response may be more similar across sectors than previously thought, at least in the case of relevant heatwave durations.

We note that future studies in other regions and sectors are needed to complement our analysis in order to assess potential spatial differences in impact-relevant heatwave durations. The methodology introduced here can serve as a starting point for this. Expanding to other regions is important as there are geographic and regional differences in heat risk behaviours, perceptions, and outcomes, particularly in terms of demographics and differences in beliefs

such as risk perceptions, experience of health impacts, and demographic factors such as age, gender, and ethnicity (Sheridan and Allen 2018, Esplin *et al* 2019). These differences may translate into different impact-relevant durations. Differences in geographic characteristics, such as urban versus rural, may also have an influence (Fischer *et al* 2012, Zhao *et al* 2018, Shreevastava *et al* 2021).

Heatwave impacts are not exclusively governed by duration or temperature, but also by exposure and vulnerability. These characteristics can vary between regions such that it is desirable to repeat our analysis for even smaller and more coherent regions than Germany, even though this requires informative societal data at sufficient temporal resolution and length. At present, this is hard to obtain as most statistics are either exclusively available at national scale, or the data at sub-national scale sample too small populations such that the noise level becomes problematic for our workflow.

Despite these limitations, our study can inform future research on heatwaves by suggesting useful time scales at which temperatures can be aggregated. In this way, we find that analyses focusing on e.g. monthly time scales can be considered to be more strongly related to a societal response to hot temperatures than analyses considering for example daily or seasonal time scales. This way, the knowledge of impact-relevant heatwave timescales will help to identify major events in the historical record as well as in future climate projections, particularly as future trends in heatwave frequency and intensity may be different for different timescales.

Data availability statements

The data and methods that support the findings of this study are available upon reasonable request from the corresponding author.

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ORCID iDs

Kelley De Polt  <https://orcid.org/0000-0003-3087-799X>

Philip J Ward  <https://orcid.org/0000-0001-7702-7859>

Marleen de Ruiter  <https://orcid.org/0000-0001-5991-8842>

Ekaterina Bogdanovich  <https://orcid.org/0000-0003-1095-8047>

Markus Reichstein  <https://orcid.org/0000-0001-5736-1112>

René Orth  <https://orcid.org/0000-0002-9853-921X>

References

- Adams Q H, Sun Y, Sun S and Wellenius G A 2022 Internet searches and heat-related emergency department visits in the United States *Sci. Rep.* **12** 9031
- Alexander L V et al 2006 Global observed changes in daily climate extremes of temperature and precipitation *J. Geophys. Res.* **111** D05109
- Anderson G B and Bell M L 2011 Heat waves in the United States: mortality risk during heat waves and effect modification by heat wave characteristics in 43 U.S. communities *Environ. Health Perspect.* **119** 210–8
- Arbuthnott K G and Hajat S 2017 The health effects of hotter summers and heat waves in the population of the United Kingdom: a review of the evidence *Environ. Health* **16** 119
- Blazejczyk K, Epstein Y, Jendritzky G, Staiger H and Tinz B 2012 Comparison of UTCI to selected thermal indices *Int. J. Biometeorol.* **56** 515–35
- BMWK 2023 Was uns die Folgen des Klimawandels kosten Merkblatt #04: die "stillen" Extremwetter: hitze und Dürre (Bundesministerium für Wirtschaft und Klimaschutz)
- Bogdanovich E, Guenther L, Reichstein M, Frank D, Ruhrmann G, Brenning A, Denissen J M C and Orth R 2023 Societal attention to heat waves can indicate public health impacts *Weather Clim. Soc.* **15** 557–69
- Buzan J R, Oleson K and Huber M 2015 Implementation and comparison of a suite of heat stress metrics within the Community land model version 4.5 *Geosci. Model Dev.* **8** 151–70
- Casanueva A, Burgstall A, Kotlarski S, Messeri A, Morabito M, Flouris A D, Nybo L, Spirig C and Schwierz C 2019 Overview of existing heat-health warning systems in Europe *Int. J. Environ. Res. Public Health* **16** 2657
- CIESIN 2018 *Gridded Population of the World, Version 4 (GPWv4): Population Density, Revision 11* (NASA Socioeconomic Data and Applications Center (SEDAC)) (<https://doi.org/10.7927/H45Q4T5F>)
- CoABoM 2010 Thermal comfort observations (available at: www.bom.gov.au/info/thermal_stress/) (Accessed 28 July 2023)
- Copernicus 2022a OBSERVER: a wrap-up of Europe's summer 2022 heatwave | Copernicus (available at: www.copernicus.eu/en/news/news/observer-wrap-europes-summer-2022-heatwave) (Accessed 11 August 2022)
- Copernicus 2022b Copernicus: summer 2022 Europe's hottest on record | Copernicus (available at: <https://climate.copernicus.eu/copernicus-summer-2022-europes-hottest-record>) (Accessed 11 August 2022)
- Coumou D and Rahmstorf S 2012 A decade of weather extremes *Nat. Clim. Change* **2** 491–6
- Coumou D and Robinson A 2013 Historic and future increase in the global land area affected by monthly heat extremes *Environ. Res. Lett.* **8** 034018
- Cremonese E, Filippa G, Galvagno M, Siniscalco C, Oddi L, Morra Di Cella U and Migliavacca M 2017 Heat wave hinders green wave: the impact of climate extreme on the phenology of a mountain grassland *Agric. For. Meteorol.* **247** 320–30
- Della-Marta P M, Haylock M R, Luterbacher J and Wanner H 2007 Doubled length of western European summer heat waves since 1880 *J. Geophys. Res.* **112**
- Ding T, Qian W and Yan Z 2010 Changes in hot days and heat waves in China during 1961–2007 *Int. J. Climatol.* **30** 1452–62
- Dosio A, Mentaschi L, Fischer E M and Wyser K 2018 Extreme heat waves under 1.5 °C and 2 °C global warming *Environ. Res. Lett.* **13** 054006
- Dunne J P, Stouffer R J and John J G 2013 Reductions in labour capacity from heat stress under climate warming *Nat. Clim. Change* **3** 563–6
- Esplin E D, Marlon J R, Leiserowitz A and Howe P D 2019 "Can you take the heat?" Heat-induced health symptoms are associated with protective behaviors *Weather Clim. Soc.* **11** 401–17
- Fischer E M, Oleson K W and Lawrence D M 2012 Contrasting urban and rural heat stress responses to climate change *Geophys. Res. Lett.* **39** L03705
- Flach M, Brenning A, Gans F, Reichstein M, Sippel S and Mahecha M D 2021 Vegetation modulates the impact of climate extremes on gross primary production *Biogeosciences* **18** 39–53
- Freychet N, Hegerl G C, Lord N S, Lo Y T E, Mitchell D and Collins M 2022 Robust increase in population exposure to heat stress with increasing global warming *Environ. Res. Lett.* **17** 064049
- Google 2023 FAQ about Google trends data—trends help (available at: https://support.google.com/trends/answer/4365533?hl=en&ref_topic=6248052&sjid=14736594622505588750-EU) (Accessed 18 April 2023)
- Green H K, Edeghere O, Elliot A J, Cox I J, Morbey R, Pebody R, Bone A, McKendry R A and Smith G E 2018 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? *Environ. Res.* **166** 707–12
- Habeeb D, Vargo J and Stone B 2015 Rising heat wave trends in large US cities *Nat. Hazards* **76** 1651–65
- Hallegatte S, Rentschler J and Rozenberg J 2019 Natural shocks are a leading cause of infrastructure disruptions and damages *Lifelines: The Resilient Infrastructure Opportunity (Sustainable Infrastructure Series)* (The World Bank) pp 57–83
- Hersbach H et al 2020 The ERA5 global reanalysis *Q. J. R. Meteorol. Soc.* **146** 1999–2049
- Hogue J and DeWilde B pytrends: pseudo API for google trends (available at: <https://pypi.org/project/pytrends/>)
- Kjellstrom T, Kovats R S, Lloyd S J, Holt T and Tol R S J 2009 The direct impact of climate change on regional labor productivity *Arch. Environ. Occup. Health* **64** 217–27
- Kluge H 2022 Statement—climate change is already killing us, but strong action now can prevent more deaths

- (available at: www.who.int/europe/news/item/07-11-2022-statement—climate-change-is-already-killing-us—but-strong-action-now-can-prevent-more-deaths) (Accessed 11 August 2022)
- Kovats S R and Ebi K L 2006 Heatwaves and public health in Europe *Eur. J. Public Health* **16** 592–9
- Lemke B and Kjellstrom T 2012 Calculating workplace WBGT from meteorological data: a tool for climate change assessment *Ind. Health* **50** 267–78
- Li T, Ding F, Sun Q, Zhang Y and Kinney P L 2016 Heat stroke internet searches can be a new heatwave health warning surveillance indicator *Sci. Rep.* **6** 37294
- Liu X, Lindquist E and Vedlitz A 2011 Explaining media and congressional attention to global climate change, 1969–2005: an empirical test of agenda-setting theory *Polit. Res. Q.* **64** 405–19
- Lowe R, García-Díez M, Ballester J, Creswick J, Robine J-M, Herrmann F R and Rodó X 2016 Evaluation of an early-warning system for heat wave-related mortality in Europe: implications for sub-seasonal to seasonal forecasting and climate services *Int. J. Environ. Res. Public Health* **13** 206
- Lyon B, Barnston A G, Coffel E and Horton R M 2019 Projected increase in the spatial extent of contiguous US summer heat waves and associated attributes *Environ. Res. Lett.* **14** 114029
- Martinez G S, Linares C, Ayuso A, Kendrovski V, Boeckmann M and Diaz J 2019 Heat-health action plans in Europe: challenges ahead and how to tackle them *Environ. Res.* **176** 108548
- Matzarakis A 2022 Communication aspects about heat in an era of global warming—the lessons learnt by Germany and beyond *Atmosphere* **13** 226
- Matzarakis A 2017 The heat health warning system of DWD—concept and lessons learned *Perspectives on Atmospheric Sciences (Springer Atmospheric Sciences)* ed T Karacostas, A Bais and P T Nastos (Springer) pp 191–6
- McEvoy D, Ahmed I and Mullett J 2012 The impact of the 2009 heat wave on Melbourne’s critical infrastructure *Local Environ.* **17** 783–96
- Murray V et al 2021 Hazard information profiles: supplement to UNDRR-ISC hazard definition & classification review *Technical Report* (United Nations Office for Disaster Risk Reduction (UNDRR))
- Naumann G, Cammalleri C, Mentaschi L and Feyen L 2021 Increased economic drought impacts in Europe with anthropogenic warming *Nat. Clim. Change* **11** 485–91
- Orlov A, Sillmann J, Aaheim A, Aunan K and de Bruin K 2019 Economic losses of heat-induced reductions in outdoor worker productivity: a case study of Europe *EconDisCliCha* **3** 191–211
- Orth R, O S, Zscheischler J, Mahecha M D and Reichstein M 2022 Contrasting biophysical and societal impacts of hydro-meteorological extremes *Environ. Res. Lett.* **17** 014044
- Perkins S E 2015 A review on the scientific understanding of heatwaves—their measurement, driving mechanisms, and changes at the global scale *Atmos. Res.* **164–165** 242–67
- Perkins S E and Alexander L V 2013 On the measurement of heat waves *J. Clim.* **26** 4500–17
- Perkins S E, Alexander L V and Nairn J R 2012 Increasing frequency, intensity and duration of observed global heatwaves and warm spells *Geophys. Res. Lett.* **39** L20714
- Reyer C P O et al 2013 A plant’s perspective of extremes: terrestrial plant responses to changing climatic variability *Glob. Change Biol.* **19** 75–89
- Robine J-M, Cheung S L K, Le Roy S, Van Oyen H, Griffiths C, Michel J-P and Herrmann F R 2008 Death toll exceeded 70,000 in Europe during the summer of 2003 *Comptes Rendus Biologies, Dossier : Nouveautés En cancérogénèse/New Developments in Carcinogenesis* **331** 171–8
- Rogers S 2016 What is Google trends data—and what does it mean? *Google News Lab* (available at: <https://medium.com/google-news-lab/what-is-google-trends-data-and-what-does-it-mean-b48f07342ee8>) (Accessed 18 April 2023)
- Rothfus L P 1990 Technical Attachment The Heat Index “Equation” (or, More Than You Ever Wanted to Know About Heat Index) SR 90-23 (NWS Scientific Services Division)
- Sarofim M C, Saha S, Hawkins M D, Mills D M, Hess J, Horton R, Kinney P, Schwartz J and St. Juliana A 2016 Temperature-related death and illness *The Impacts of Climate Change on Human Health in the United States: A Scientific Assessment* (U.S. Global Change Research Program) ch 2 (<https://doi.org/10.7930/J0MG7MDX>)
- Seneviratne S I, Zhang X, Adnan M, Badi W, Dereczynski C, Di Luca A, Vicente-Serrano S M, Wehner M and Zhou B 2021 Weather and climate extreme events in a changing climate *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* ed V Masson-Delmotte et al (Cambridge University Press) pp 1513–766
- Sheridan S C and Allen M J 2018 Temporal trends in human vulnerability to excessive heat *Environ. Res. Lett.* **13** 043001
- Shreevastava A, Prasanth S, Ramamurthy P and Rao P S C 2021 Scale-dependent response of the urban heat island to the European heatwave of 2018 *Environ. Res. Lett.* **16** 104021
- Strauss N, Painter J, Ettinger J, Doutreix M-N, Wonneberger A and Walton P 2022 Reporting on the 2019 European heatwaves and climate change: journalists’ attitudes, motivations and role perceptions *Journal. Pract.* **16** 462–85
- Sutanto S J, Vitolo C, Di Napoli C, D’Andrea M and van Lanen H A J 2020 Heatwaves, droughts, and fires: exploring compound and cascading dry hazards at the pan-European scale *Environ. Int.* **134** 105276
- Sweetser K D, Golan G J and Wanta W 2008 Intermedia Agenda setting in television, advertising, and blogs during the 2004 election *Mass Commun. Soc.* **11** 197–216
- Tong S, FitzGerald G, Wang X-Y, Aitken P, Tippett V, Chen D, Wang X and Guo Y 2015 Exploration of the health risk-based definition for heatwave: a multi-city study *Environ. Res.* **142** 696–702
- Toulemon L and Barbieri M 2008 The mortality impact of the August 2003 heat wave in France: investigating the ‘harvesting’ effect and other long-term consequences *Popul. Stud.* **62** 39–53
- Trenczek J, Lühr O, Eiserbeck L, Sandhövel M and Ibens D 2022 *Projektbericht “Kosten durch Klimawandelfolgen” Schäden der Dürre- und Hitzeextreme 2018 und 2019 Eine ex-post-Analyse* (Prognos AG)
- UKHSA 2022 Heatwave plan for England: protecting health and reducing harm from severe heat and heatwaves
- Undorf S, Allen K, Hagg J, Li S, Lott F C, Metzger M J, Sparrow S N and Tett S F B 2020 Learning from the 2018 heatwave in the context of climate change: are high-temperature extremes important for adaptation in Scotland? *Environ. Res. Lett.* **15** 034051
- USEPA 2022 *Technical Documentation: Heat Waves* (US EPA)
- Vogel M M, Zscheischler J, Fischer E M and Seneviratne S I 2020 Development of future heatwaves for different hazard thresholds *J. Geophys. Res.* **125** e2019JD032070
- von Buttler J et al 2018 Impacts of droughts and extreme-temperature events on gross primary production and ecosystem respiration: a systematic assessment across ecosystems and climate zones *Biogeosciences* **15** 1293–318
- Winklmayr C, Muthers S, Niemann H, Mücke H-G and Heiden M A D 2022 Heat-related mortality in Germany from 1992 to 2021 *Dtsch. Arztebl. Int.* **119** 451–7
- WMO and WHO 2015 *Heatwaves and Health: Guidance on Warning-System Development* WMO-No. 1142 (World Meteorological Organization and World Health Organization)
- Wolf J, Adger W N, Lorenzoni I, Abrahamson V and Raine R 2010 Social capital, individual responses to heat waves and climate change adaptation: an empirical study of two UK

- cities *Glob. Environ. Change, Adaptive Capacity to Global Change in Latin America* **20** 44–52
- Xu H, Xiao J and Zhang Z 2020 Heatwave effects on gross primary production of northern mid-latitude ecosystems *Environ. Res. Lett.* **15** 074027
- Xu Z, Cheng J, Hu W and Tong S 2018 Heatwave and health events: a systematic evaluation of different temperature indicators, heatwave intensities and durations *Sci. Total Environ.* **630** 679–89
- Xu Z, Crooks J L, Black D, Hu W and Tong S 2017 Heatwave and infants' hospital admissions under different heatwave definitions *Environ. Pollut.* **229** 525–30
- Xu Z, FitzGerald G, Guo Y, Jalaludin B and Tong S 2016 Impact of heatwave on mortality under different heatwave definitions: a systematic review and meta-analysis *Environ. Int.* **89–90** 193–203
- Zampieri M, Ceglár A, Dentener F and Toreti A 2017 Wheat yield loss attributable to heat waves, drought and water excess at the global, national and subnational scales *Environ. Res. Lett.* **12** 064008
- Zhao L, Oppenheimer M, Zhu Q, Baldwin J W, Ebi K L, Bou-Zeid E, Guan K and Liu X 2018 Interactions between urban heat islands and heat waves *Environ. Res. Lett.* **13** 034003