Title:

Quantifying impact-relevant heatwave durations

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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. Here, we study which temporal scales of heatwaves are most impact-relevant for various types of impacts. For this purpose, we analyse societal metrics related to health (heat-related hospitalizations, mortality) and public attention (Google trends, news articles) in Germany. Country-averaged temperatures are calculated for the period of 2010-2020 and the warmest periods of all durations 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. The results differ slightly between the considered societal metrics but indicate overall that heatwaves induce the strongest societal response at time scales 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. An improved understanding of weather and climate hazards with their impacts on society, economy and environmental systems will support better preparation, response, and future adaptation.

Keywords:
Extreme heat; health impacts; societal attention; heatwave duration

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., 2018, 2016), agriculture (Zampieri et al., 2017), ecosystems (Cremonese et al., 2017; Reyer et al., 2013; von Buttlar et al., 2018; Xu et al., 2020), and infrastructure (Hallegatte et al., 2019; McEvoy et al., 2012). 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 (Coumou and Rahmstorf, 2012; Robine et al., 2008). This led to preventative measures being taken throughout the continent (Casanueva et al., 2019; Martinez et al., 2019; Matzarakis, 2017; UKHSA, 2022; WMO and WHO, 2015), such as heat warning systems. The 2018 and 2019 heatwaves in Germany resulted in immense damages and costs as well as 7,500 heat-related deaths (BMWK, 2023; Trenczek et al., 2022; Winklmayr et al., 2022). 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, 4,500 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 (Freychet et al., 2022; Lyon et al., 2019). 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; Murray et al., 2021; Sutanto et al., 2020; 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; Coumou and Robinson, 2013; Perkins et al., 2012; 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 (Flach et al., 2021; von Buttlar et al., 2018), 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. Using these indicators, we calculate and compare the impacts of hot temperatures determined across different time scales, 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 to 2020, 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) identifying extreme heat events from the underlying daily mean temperature data; (2) examining the daily impact and attention anomalies within each event; (3) aggregating the daily anomalies for each event; and (4) repeating above steps for all events of all lengths.

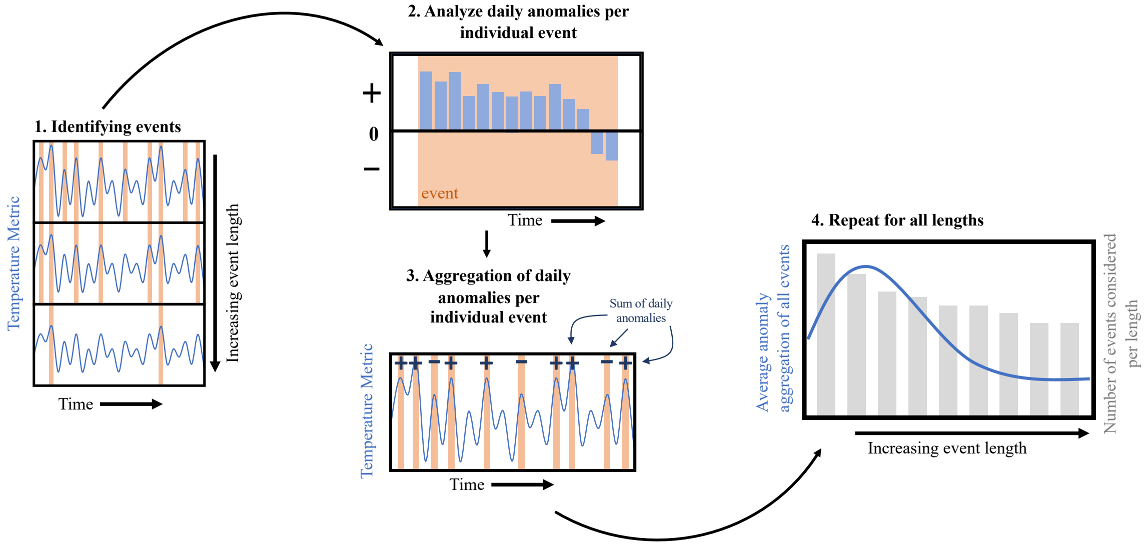

Figure 1. Schematic summary of the workflow. For each time scale, we find the hottest periods (between 1-day and 90-days; incrementing in daily intervals) and aggregate the related heatwave impacts or response for each considered data stream in order to identify the most impact-relevant time scales.

2.1 Extreme heat event identification

To identify heatwave events over different time scales, we used 2-metre daily mean temperature (Tmean). Tmean was retrieved from the ERA5 reanalysis dataset (Hersbach et al., 2020) at a spatial resolution of 0.25° × 0.25°. Tmean 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. As the impact and response metrics we consider are societal in nature, population weighting is used to ensure comparability between climate and societal metrics.

Various metrics and indices have been developed and introduced to measure heat waves. In the present study, we test our methodology on three additional metrics. The first is the 2-metre daily maximum temperature (Tmax) which was also retrieved from the ERA5 reanalysis dataset. From Tmax, apparent temperature (AT) and wet bulb temperature (WBT) are calculated using functions from the Python package MetPy. AT, which is also referred to as heat index (HI) when the ambient temperature is above a certain threshold, is a common metric used as an indicator of the heat-related stress on the human body, taking into account both temperature and humidity aspects. The disadvantage of using the AT is that it assumes that the population that is exposed to the temperature will be in the shade. WBT, a similar indicator of heat stress, but representative of exposure to direct sunlight, can overcome this.

As the definition of heat waves varies between researchers, we use the term *extreme heat events* to cover heat waves 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 heat wave events; and (iii) finding the hottest value of the remaining time series. Steps (i)-(iii) are repeated to detect further heat wave 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 (Figure S1, Figure 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).

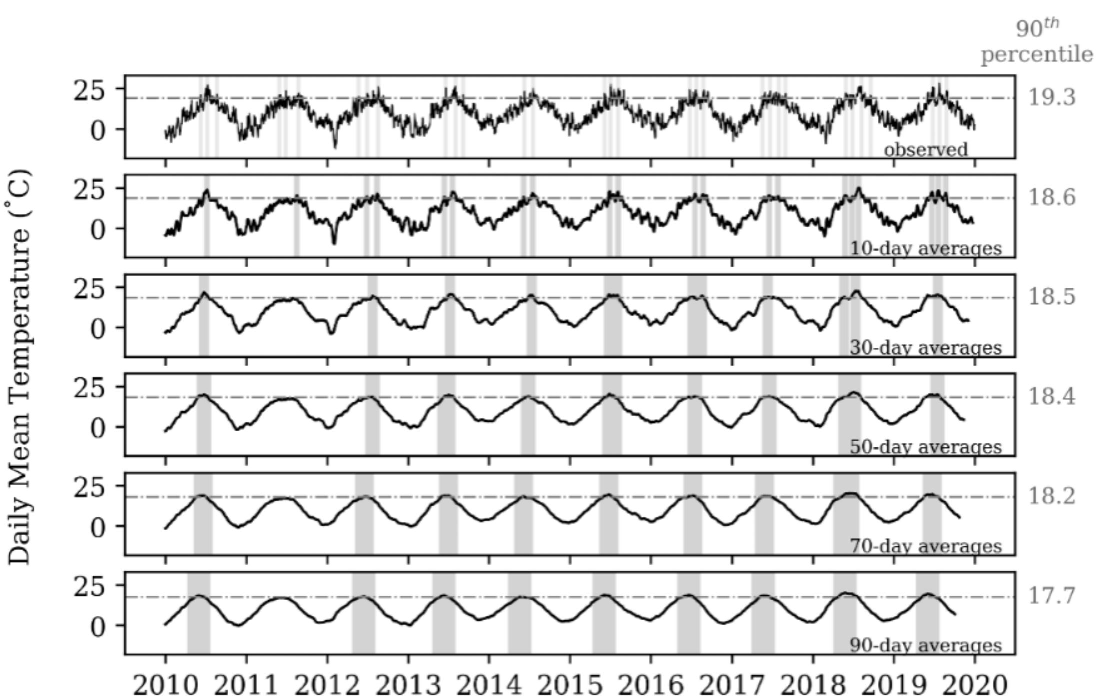

Figure 2. Detected heatwaves above 90th percentile across different time scales, as indicated with the grey shading.

2.2 Daily impact and response anomalies

We consider 4 societal variables from separate data streams that represent the impact of heatwaves on public health and societal attention. 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.

Google trends topics *heatwave - type of disaster* and *heatstroke - illness* are considered in this analysis as a representation of societal attention. The topic feature allows us to capture searches for multiple similar heat-related search terms across languages, making the retrieved time series more informative compared to singular terms (Google, 2023; Rogers, 2016). 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, n.d.). 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 analysis in Shanghai found strong correlations between search frequency for the Google topic *heatstroke* and heat stroke-related deaths and hospitalisations (Li et al., 2016). 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 (https://www.dowjones.com/professional/factiva/) and WiSo (https://www.wiso-net.de/dosearch) to collect the articles mentioning heatwaves in three leading German newspapers (Die Welt, Die Zeit and Süddeutsche Zeitung). The most popular German newspaper, Bild, was not included because data are not available for the entire study period. Although the number of articles is available on a daily basis, it is aggregated to weekly values. To ensure that no single newspaper dominates the heatwave mentions, we standardise the weekly time series for each newspaper 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. 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). We use the weekly value over all the individual days of each week. For example, if the data are associated with a Sunday, the value for that Sunday is also attributed to the preceding Monday through Saturday.

All-cause mortality counts obtained from Eurostat are used as a proxy for health impacts. Another proxy for the health impact of extreme heat events is 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.

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

2.3 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., 1 day has 1 anomaly value; 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 heatwaves (see Figure 3a), 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 heatwaves (see Figure 3b), 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 heatwaves (see Figure 3c) 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 peak at the same time and with a greater deviation from the mean than mortality. When comparing societal attention to health impacts, a peak in Google attention for *heat stroke* occurs after peaks 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 (Figure S5, Figure S6), 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., minor revisions pending). Together, these results provide important insights into how the metrics under consideration evolve during extreme heat events of different durations.

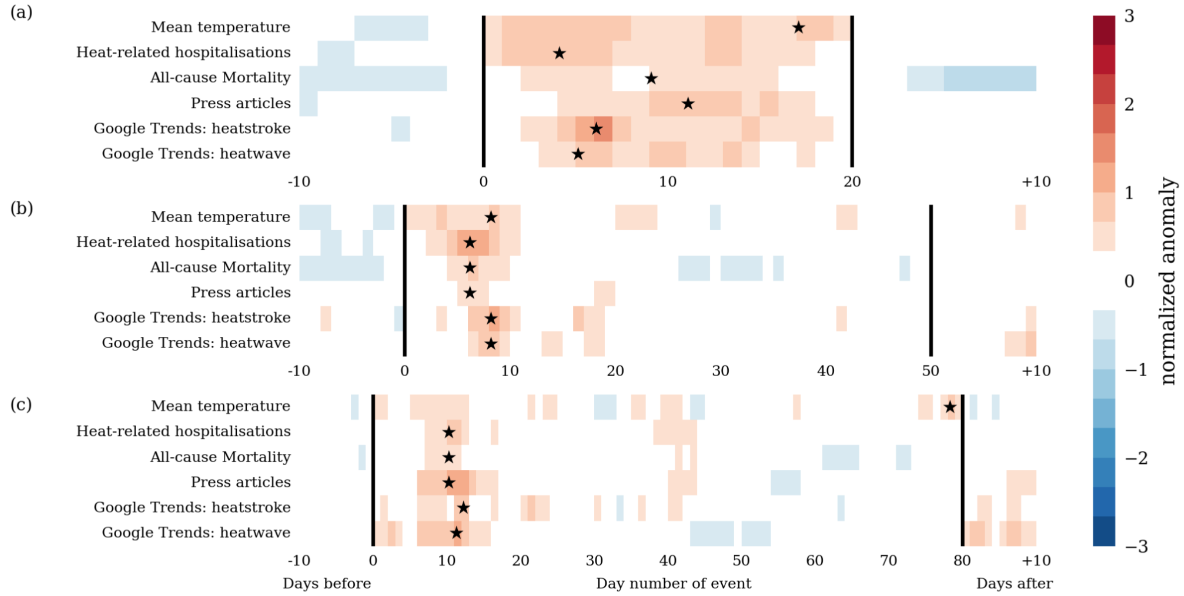

Figure 3. Daily variation (mean; median and maximum in supplementary Figure S7 and Figure S8) of metrics within extreme heat events (greater than 90th percentile; lengths of (a) 20-days (b) 50-days) (c) 80-days). For comparability between the impact and response metrics, standardised anomalies were calculated with reference to the daily anomaly values and the mean of all observed summer season (i.e., June, July, August) values. The maximum daily mean value for each metric is denoted by a star.

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 two weeks to one 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 (Figure S9, Figure S10).

The societal attention metrics (Figure 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 (Figure 4. c-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 S1).

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 90^{th} 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 4a). 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.

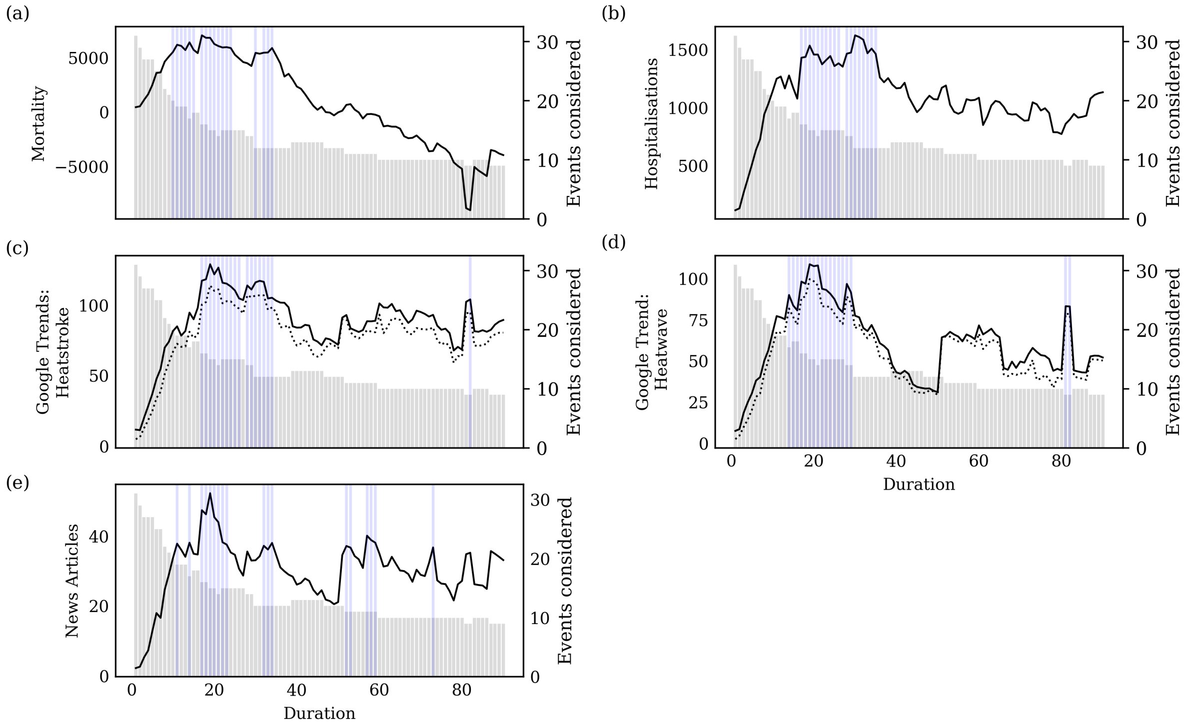

Figure 4. Anomaly aggregation for all impact and response datasets for extreme heat events greater than 90th percentile. Impact relevant duration is selected as the 80th percentile of values (i.e., 80th percentile of 90-days; 18-days selected). The blue bars indicate impact relevant duration. The sensitivity analysis of the Google attention resolutions on a daily basis (black line) compared to a weekly basis (dotted line) is shown in (c) and (d).

Having analysed the metrics separately, we now summarize them together and between different intensities. In general, the most impact-relevant durations of heatwaves are in the range of two weeks to two months (Figure 5). When analysing all identified events above the 90th percentile, the impact-relevant duration is between one week and one 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 S11), AT (Figure S12), and WBT (Figure S13). Overall, across all considered heatwave magnitudes the heatwave durations that trigger the strongest societal response in Germany are between two weeks and two months.

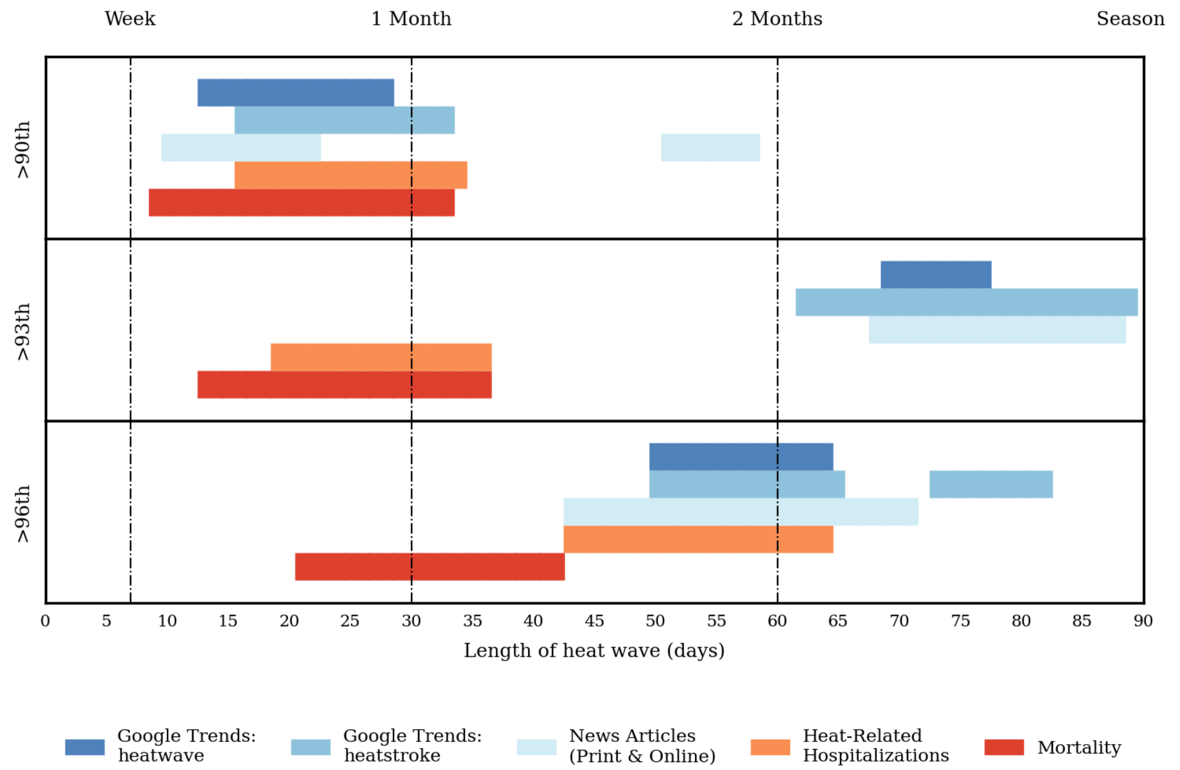

Figure 5. Summary of the determined heatwave lengths at which the societal attention is most pronounced. Colours indicate the different attention and health-related metrics while the different panels show results for different heatwave magnitudes. For smoothing, gaps of 7 days or less are filled in, and periods considered relevant but shorter than 7 days are excluded from the visualisation (Figure S14 presents a similar summary without smoothing).

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 Tmean in Figure 6; mean event daily Tmax in Figure S15; mean event daily Tmin in Figure S16). 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.

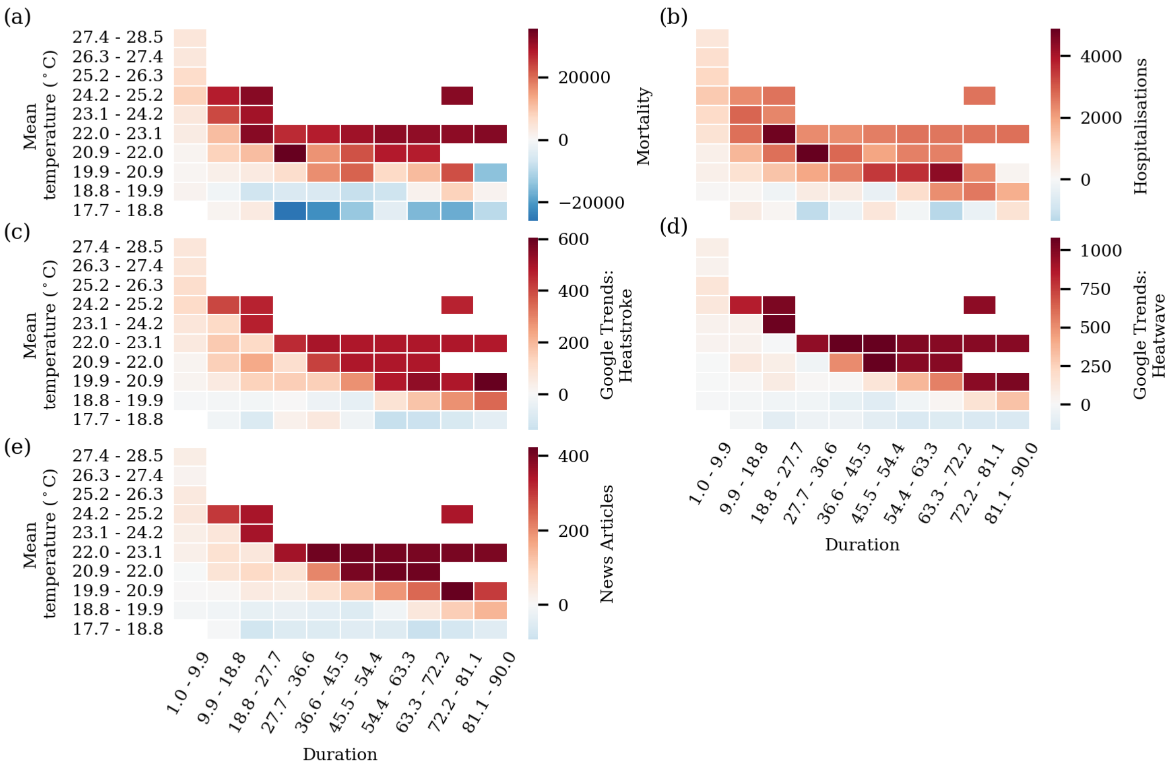

Figure 6. Illustrating the relevance of heatwave duration and mean daily mean temperature for the resulting societal response as expressed through (a) Mortality (b) Hospitalisations (c) Google search attention for: *heat stroke* (d) Google search attention for *heatwaves,* and (e) mentions of the term heatwave in news articles.

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 and data, we find that heatwaves are most impact-relevant at time scales between two weeks and two 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 mean 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 (Esplin et al., 2019; Sheridan and Allen, 2018). 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; Shreevastava et al., 2021; Zhao et al., 2018).

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.

Acknowledgements

The authors thank Ulrich Weber for retrieving and processing ERA5 data, and the Hydrology–Biosphere–Climate Interactions group at the Max Planck Institute for Biogeochemistry for fruitful discussions. Kelley De Polt and Ekaterina Bogdanovich acknowledge support from the International Max Planck Research School on global biogeochemical cycles.

Funding

Kelley De Polt, Marleen de Ruiter and Philip J. Ward are supported by funding from the MYRIAD-EU project from the European Union's Horizon 2020 research and innovation programme (grant no. 101003276), and Rene Orth is supported by funding from the German Research Foundation (Emmy Noether grant no. 391059971).

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