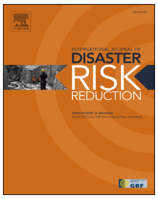
International Journal of Disaster Risk Reduction 100 (2024) 104206

Contents lists available at ScienceDirect

International Journal of Disaster Risk Reduction

journal homepage: www.elsevier.com/locate/ijdrr



Official heat warnings miss situations with a detectable societal heat response in European countries

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ARTICLE INFO

Keywords:
Heat wave
Google trends
Societal attention
Europe
Heat warnings

ABSTRACT

The frequency and intensity of heat waves are increasing globally. In this context it is not clear how the related impacts differ between countries with different vulnerability and exposure characteristics, such as overall climatic conditions and implemented adaptation strategies, e.g. urban planning and planting trees to reduce heat island effect, air conditioning, communication with the public about danger of heat waves. The release of official heat warnings two to six days in advance plays an important role in notifying the population. However, it remains uncertain to which extent they capture days with societal heat responses. Here, we analyze and compare the response of several societal metrics (Google search attention, excess mortality, press attention) to hot temperatures in twelve European countries. We identify country-specific temperature thresholds above which societal responses increase. We find higher thresholds in warmer countries, indicating overall lower heat vulnerability in southern Europe. Meanwhile, we find similar numbers of societally relevant hot days across countries, computed as the sum of days on which more than 50 % of a country's population experiencing temperatures above the detected thresholds. This indicates that the reduced vulnerability and exposure found for warmer countries are counteracted by hotter heat waves. Finally, the determined number of societally relevant hot days generally exceeds the number of days with heat warnings in five investigated countries: Belgium, Germany, Netherlands, Romania, and Sweden. This suggests that lower temperature thresholds would be better aligned with detectable societal responses and should therefore be considered in the context of warning systems.

1. Introduction

Heat waves have severe impacts on the economy, ecosystems, and society [1], and are becoming more frequent and intense [2]. They challenge the healthcare system [3], the economy [4], and infrastructure, one example being the electricity system [5]. Moreover, increased excess mortality is a direct consequence of heat waves. Thereby, the causes of death include hyperthermia, dehydration, respiratory disease, cerebrovascular disease, or heat stroke [6]. The vulnerability of people to heat waves depends on their individual vulnerability and exposure, which are related to a person's socio-economic and health status, such as having pre-existing health problems, living in urban areas, spending time or working outside, or having access to air conditioning. Age is another aspect

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https://doi.org/10.1016/j.ijdrr.2023.104206
Received 11 May 2023; Received in revised form 14 December 2023; Accepted 15 December 2023

in this context, such that elderly people and children are more at health risk. At the same time, people in other age groups might be affected differently, for example through lower labor productivity, especially in outdoor activities [7–9]. This might lead to economic losses; for example, reduced agricultural and food production might affect the entire national economy [10].

In this context, heat warnings issued by national agencies two to six days in advance are an important means to notify the population and allow for sufficient preparation of upcoming heat in order to mitigate foreseeable impacts. Weather services across European countries use different approaches to classify weather conditions for which heat warnings are issued, mostly based on temperature thresholds applied for time periods of one or a few days [11]. The warnings can be issued for the entire country or for its heat-affected regions, but within the same political boundaries. It can happen that for similar weather conditions in neighboring countries, a heat warning is issued in one country or its region but not on the other side of the border [12]. This brings attention to the challenge to identify relevant hot days in the absence of universally valid criteria.

In recent years, many data streams for European countries have become available which allows a comprehensive characterization of the societal response to heat. This includes health-related data from hospitals and mortality as well as attention-related data from web searches and press articles. Weather-related news coverage increases during extreme weather events [13], also in the case of heat waves [14,15], alerting the public to potential hazards, impacts on infrastructure, and reporting on damage. The media direct people's attention to particular issues [16,17] and can potentially drive interest to an issue that might result in increased internet searches [18]. Increased search activity may also be a response to heat effects on health experienced or observed by an individual. For example, Adams et al. [19] demonstrated a correlation between internet search frequency and health-related emergency department visits [20]. showed that internet search frequencies for the term "heat stroke" were a better predictor of heat stroke cases and deaths than maximum temperature data. Further, using Germany as a case study, it has been shown that Google search attention, media attention, heat-related hospitalizations, and excess mortality data can be used to obtain temperature thresholds above which the societal response to heat increases markedly within the study period of 2010–2019 [14]. These thresholds are found to be similar across the studied data streams. In the current study, we extend our study to twelve European countries and further develop the methodology to estimate societally relevant hot days. Similar to the previous study, we use piecewise regression for threshold estimation. In this study, we determine temperature thresholds for a heat-related societal response using health and attention-related metrics from twelve European countries. We define the heat-related societal response as a result of physiological heat effects (e.g. excess mortality) as well as increased internet search behavior (e.g. Google search frequency) of people who notice hot temperatures and increased media attention. Then, the number of days with temperatures above the inferred thresholds are regarded as societally relevant hot days. We then compare the number of societally relevant hot days with the number of days with heat warnings issued in five selected countries where heat warning data are available. At the same time, the comparison of derived temperature thresholds across countries in different climate regimes allows us to assess and compare heat-related vulnerability and exposure across the continent.

2. Data and methods

We focus on European countries with different climates for the study period 2010–2020. We select countries with (i) a population of at least 10 million people to ensure sufficient data, (ii) a size not larger than 500′000 km^2 to ensure mostly similar weather conditions across the country, (iii) where Google has the highest market share among search engines (> 90 % Statcounter [21]; Table S1 in Supplementary information) and (iv) where the number of internet users exceeds 50 % in 2015 and 70 % in 2020 [22] (Fig. S1 in Supplementary information). Based on these criteria, we select twelve countries: United Kingdom (UK), Sweden, Denmark, Netherlands, Belgium, Germany, Poland, Romania, Portugal, Italy, Spain, and Greece (the countries are ordered according to mean temperature, which is the multiannual average temperature of the five warmest months within the study period 2010–2020). For each country, we use the same set of data streams. See Table S2 in for a summary of our data sources. We use a weekly time scale. We consider the five warmest months of each year for each country during the 2010–2020 study period. The warmest months are identified by computing an average for each month-of-year across all considered temperature variables (see next subsection) and years. The weekly temporal resolution of our analysis is governed by data availability, and allows us to exclude short-term weather variability.

2.1. Societal variables

As for the societal response, we consider (i) increased press attention and changes in internet search behavior of people noticing hot temperatures, as well as (ii) the physiological reaction to heat stress. In order to analyze and quantify the societal response to heat waves, we consider societal attention, press attention, and excess mortality data.

We use search interest for the topics *heat wave* and *heat stroke* from Google Trends to characterize search behavior (time series can be found in Figs. S2 and S3). Thereby, we chose to consider "topics" rather than simple "search terms", because this way we can capture searches in different languages, search for synonyms, acronyms, as well as misspelt search terms [23]. The daily data are downloaded using the python package PyTrens [24] and then aggregated to a weekly timescale by calculating the average weekly values.

To assess press attention, we consider the number of articles with heat wave mentions from the leading newspapers in each country (time series can be found in Fig. S4). We ensure to consider multiple newspapers in each country, and with different political leanings. A full list of selected newspapers is provided in Table S3. Press data are collected from the databases Nexis Uni (https://www.lexisnexis.com), WiSo (https://www.wiso-net.de), Factiva (https://www.dowjones.com/professional/factiva), as well as from newspaper websites directly using keywords in each country's main language (Table S4). Individual newspaper articles were manually screened to select only articles reporting about heat waves happening in the respective country while excluding articles about heat waves elsewhere. Because of the overall low number of articles on individual days, the counts of heat wave articles are aggregated to weekly intervals. In order to ensure that no single newspaper is dominating the heat wave mentions in a particular country, we standardize the weekly time series for each newspaper by multiplying each value with the ratio between the total number of heat wave articles in the corresponding newspaper and the total number of heat wave articles in the newspaper with most heat wave articles in the particular country (Equation (1)).

$$y = x * \left(\frac{A}{B}\right) \tag{1}$$

where y is the standardized number of articles, x is the weekly number of articles in a corresponding newspaper, A is the total number of heat wave articles in the corresponding newspaper, B is the total number of heat wave articles in the newspaper with most heat wave articles.

Country-level mortality data from Eurostat [25] is used as a proxy for the impact of heat waves on public health. The data do not include information on deaths, so to assess the impact of heat waves, we calculate excess mortality (time series can be found in Fig. S5). We linearly detrend the raw mortality rates to reduce the effect of demographic changes and then subtract the mean seasonal cycle, calculated for the study period 2010–2020. Weekly mortality data for the United Kingdom, Greece, and Romania was not available for the entire study period and therefore we do not perform the mortality-related analyses for these countries.

2.2. *Temperature variables*

In this study, we consider several different temperature variables in order to be able to determine the most relevant one for relationships between temperature and societal response. In particular, we consider minimum, maximum, mean and apparent temperature. Maximum and minimum temperatures are commonly used in the criteria underlying heat warnings. The minimum temperature also represents the night-time temperature, which may affect the quality of sleep and consequently the readiness for heat stress during the day [26]. The mean temperature integrates the effect of both daytime and nighttime temperatures on people. Apparent temperature, in turn, is more closely related to people's perception of temperature extremes because it includes the effects of high temperature in combination with humidity [27].

Daily maximum, minimum, and mean temperatures are obtained from the ERA5-Land [28] at a spatial resolution of 9 km. Apparent temperature is calculated from maximum temperature and relative humidity (the equation and full list of coefficients can be found in Ref. [29]. Relative humidity in this context is also derived from ERA5-Land.

Since some of the employed societal datasets are available only with weekly temporal resolution, all daily temperature variables are aggregated to the weekly time scale by computing the average, maximum, and minimum values of each variable. Then, the name of a temperature variable consists of two parts indicating (i) the daily temperature variable (Tmean, Tmax, or Tmin) and (ii) the weekly aggregation approach (mean, max, or min). For example, Tmean_max is the weekly maximum of daily average temperature. A summary of the abbreviations can be found in Table S5. We obtain country-level averages of these variables by averaging them across all respective grid cells, while using a weighting reflecting their population in 2015, which is derived from the United Nations estimated grid-level population density [30]. Finally, in order to characterize the climate in each considered country, we calculated the multiannual average temperature of the five warmest months.

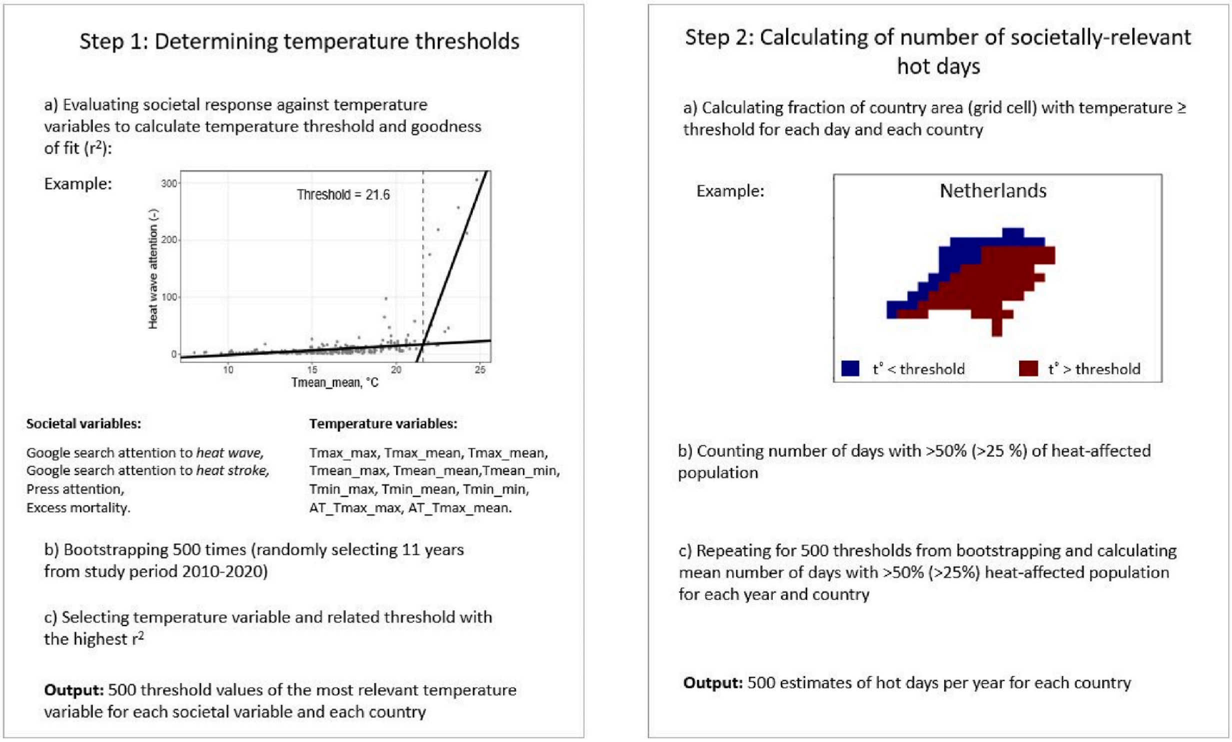
2.3. *Statistical analysis*

An overview of our statistical analysis workflow is given in Fig. 1. We first determine temperature thresholds above which a societal response to heat can be detected. This is done by assessing each individual societal response variable's time series against the corresponding weekly temperatures, and then we apply piecewise linear regression. The threshold is then defined as a breaking point between the two linear models fitted to the data (Fig. 1 Step 1). The calculation is applied to each temperature and societal variable separately. To infer the uncertainty of the detected threshold, we generate 500 bootstrapping replicates. For each replicate, we resample years randomly (with replacement) and estimate a threshold for each bootstrap sample. For the further analyses, we choose the temperature variable with the highest average adjusted r^2 of piecewise relationships of the bootstrapping replicates for each country.

Next, we calculate the number of societally relevant hot days (Fig. 1 Step 2). First, we estimate a fraction of the country area with temperature above the determined threshold for each day of the study period using the optimal temperature variable from the previous step. Second, based on these areas we calculate the fraction of a country's population experiencing temperatures above the threshold. We apply the temperature thresholds detected from weekly data to daily time series here, and assume that they are valid across these two scales. Then, a day is counted as a societally relevant hot day if more than 50 % of the population in a country is experiencing temperatures above the detected threshold.

To test the sensitivity of the results to the considered fraction of affected population, we also repeat the calculations for the case, where more than 25 % of the population are experiencing temperatures above the detected threshold. Population counts data in this context are obtained from Center for International Earth Science Information Network [31]. We perform a bootstrapping analysis to assess the uncertainty of our estimates.

To evaluate the agreement of the observed societal response with the issued heat warnings, we determine the days with issued heat warnings using either (i) heat warnings provided by the German Weather Service (DWD) in the case of Germany, as well as the Royal Netherlands Meteorological Institute (KNMI) and the National Institute for Public Health and the Environment (RIVM) in the case of the Netherlands, or (ii) published definitions of heat warning conditions by the country's weather services for Sweden, Belgium, Netherlands, and Romania (Table S6). Then, we count the number of days on which more than 50 % (25 %) of the population in a country is experiencing warning conditions.



Step 1: Determining temperature thresholds

a) Evaluating societal response against temperature variables to calculate temperature threshold and goodness of fit (r^2):

Example:

Societal variables:

Google search attention to *heat wave*,
Google search attention to *heat stroke*,
Press attention,
Excess mortality.

Temperature variables:

Tmax_max, Tmax_mean, Tmax_mean,
Tmean_max, Tmean_mean,Tmean_min,
Tmin_max, Tmin_mean, Tmin_min,
AT_Tmax_max, AT_Tmax_mean.

b) Bootstrapping 500 times (randomly selecting 11 years from study period 2010-2020)

c) Selecting temperature variable and related threshold with the highest r^2

Output: 500 threshold values of the most relevant temperature variable for each societal variable and each country

Step 2: Calculating of number of societally-relevant hot days

a) Calculating fraction of country area (grid cell) with temperature ≥ threshold for each day and each country

Example:

b) Counting number of days with >50% (>25 %) of heat-affected population

c) Repeating for 500 thresholds from bootstrapping and calculating mean number of days with >50% (>25%) heat-affected population for each year and country

Output: 500 estimates of hot days per year for each country

Fig. 1. Workflow of the statistical analyses performed in this study.

3. Results and discussion

3.1. Evolution of temperature and societal metrics during heat waves

We study the temporal evolution of the societal response variables before, during, and after the hottest week in each year and for each country. The temporal evolution is averaged across years to obtain a composite for each societal variable and country. While this analysis can not establish causality, it does indicate whether or not the societal response variables are systematically affected by changes in (extreme) temperatures. In this analysis the temperature variable we use is Tmax_mean for all countries, as this is found to be the metric most related with the societal response variables (see Table S7). We compare the typical temporal evolution of the considered variables during heat waves in all considered countries (Fig. 2). The most attention to heat waves (both Google search and press attention) and highest excess mortality were observed in the week of the temperature peak in most countries. We observe strong increases towards the temperature peak, and strong decreases thereafter, largely synchronously across the considered societal variables. The temperature at which societal response begins to increase is higher in warm countries. This analysis is moving beyond previous studies; to our knowledge there is no relevant research on the evolution of online search frequency behavior during heat waves. However, confirming our results, it has been shown that social media activity increases toward the temperature peak and decreases afterward as well [32,33]. Previous research has shown that increases in excess mortality during heat waves are often lagged by three to four days [34]. We do not detect relevant time lags between hot temperatures and the societal response. This discrepancy could be related to the relatively coarse considered weekly time scale. Overall, these results suggest that hot temperatures are influencing attention and mortality data indicating hot temperatures can indeed be used to infer temperature thresholds for a societal response to hot temperatures.

The evolution of Google and press attention during heat waves shows a similar timing (see also Fig. S6); this indicates that no metric is clearly driving the other, and this reconciles previous research which provided evidence that they are interrelated such that e.g. press attention might affect Google search attention, i.e. what people perceive as important topic to search [16,18], and vice versa, search attention to a particular issue might affect media coverage [35]. Google search attention to *heat stroke* is greater in southern Europe and responds earlier to rising temperatures compared to the other metrics. Therefore, we assume that Google search in warm countries might be driven by actual health impacts. Previous research has reported a strong relationship between online search frequencies and the number of hospitalizations [20,19].

We also observe stronger increases in societal response during the late heat waves, which occur mostly in late July and August in most countries (Fig. S7). These heat waves are also more severe in terms of temperature.

3.2. Temperature thresholds shaping societal responses to hot temperatures

Next, we study the spatial variation of temperature thresholds for societally relevant hot days across countries. Fig. 3 shows the temperature thresholds for Tmax_mean. The determined thresholds increase from cold countries to warm countries (Fig. 3a). For ex-

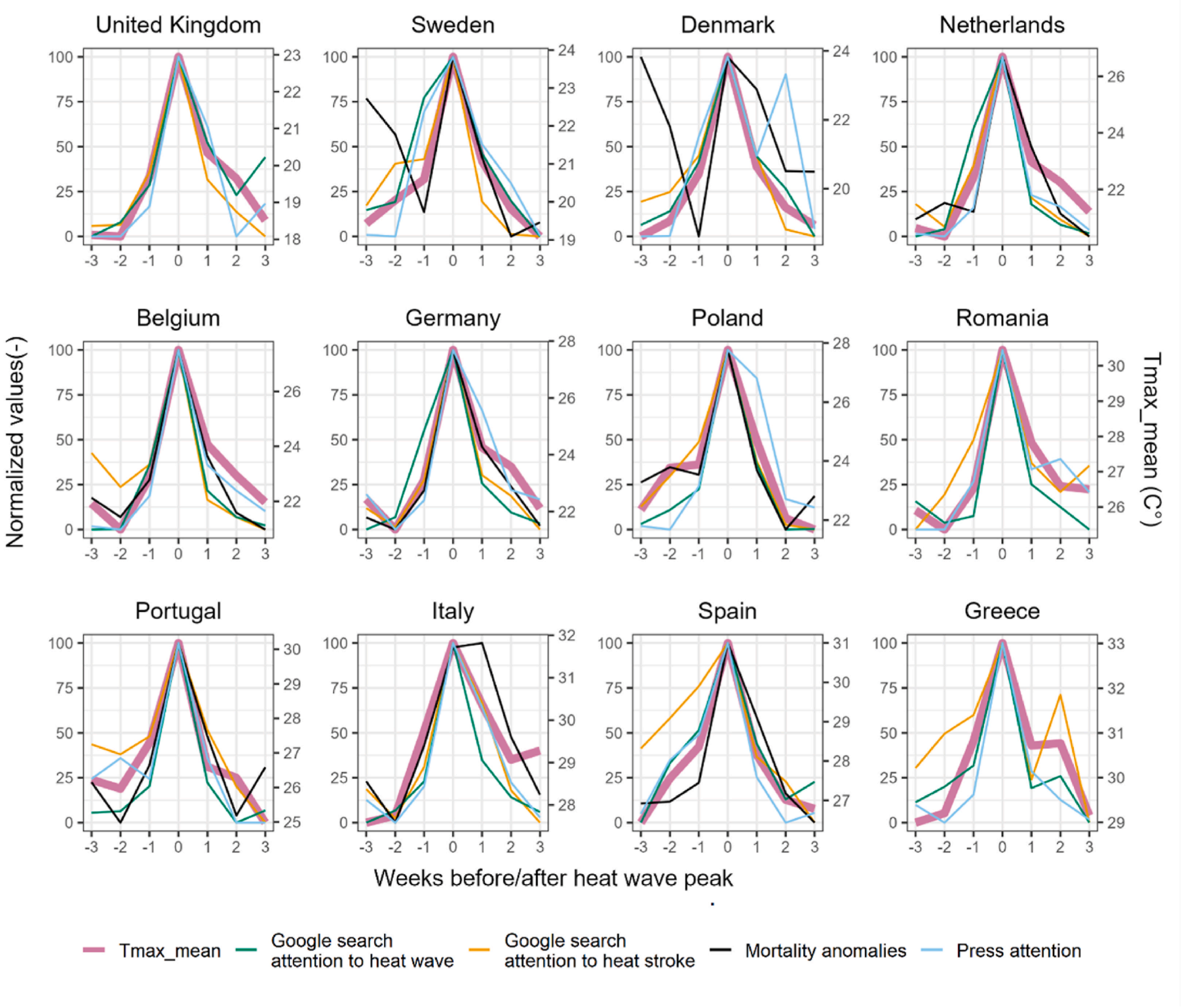


Fig. 2. Evolution of temperature (Tmax_mean) and societal metrics during heat waves across considered countries. Countries are ordered from cold to warm climates (top to bottom, left to right). Time series are composites averaged across each year's 11 hottest heat waves. Values are normalized for comparability.

ample, the mean threshold for Google attention to *heat waves* in the coldest country the UK is 21.1 °C, whereas in Greece, the hottest country, the mean threshold is 31.0 °C. ANOVA (Analysis of Variance) test showed the slopes are not significantly different from 1 for Google attention to *heat wave*, press attention, and excess mortality. The increase in temperature is relatively rapid from cold to temperate countries and weaker towards even warmer countries. These patterns are consistent across the considered attention and health variables. Similar results are found for temperature thresholds for other temperature variables (Fig. S8). This finding is consistent with the results presented by Ref. [36]; they showed that increase in minimum mortality occurred by higher temperatures in warm European countries, than in cold countries [37]. showed a higher mortality threshold in maximum apparent temperature for southern European cities. While we consider countries here, previous studies have shown.

That temperature thresholds for mortality to heat can vary across different regions within the same country [38] or even within the same city [39]. Temperature thresholds for Google search frequency have also been shown to increase from southern to northern regions within the same country [40]. To our knowledge, our study is the first to examine changes in internet search frequency during heat waves with cross-national comparisons. Higher temperature thresholds may reflect reduced vulnerability and/or exposure, or better adaptation to hot temperatures. For example, people in warm countries may be better adapted to hot temperatures, related to, e.g. air conditioning, white-colored houses, and fewer outside activities during the hottest times of the day. They might also have a tendency to consider heat as normal and not recognize its associated health risks [33]. However, much of the more vulnerable population (the elderly, children, the underserved) remains highly exposed to heat [41].

As shown by the regressions in Fig. 3a, temperature thresholds are generally lower in the case of health-related metrics (i.e., Google search attention to *heat stroke* and mortality), compared with awareness-related metrics such as Google search attention to *heat wave* and press mentions. Lower temperature thresholds indicate higher sensitivity to heat, and people represented with health-

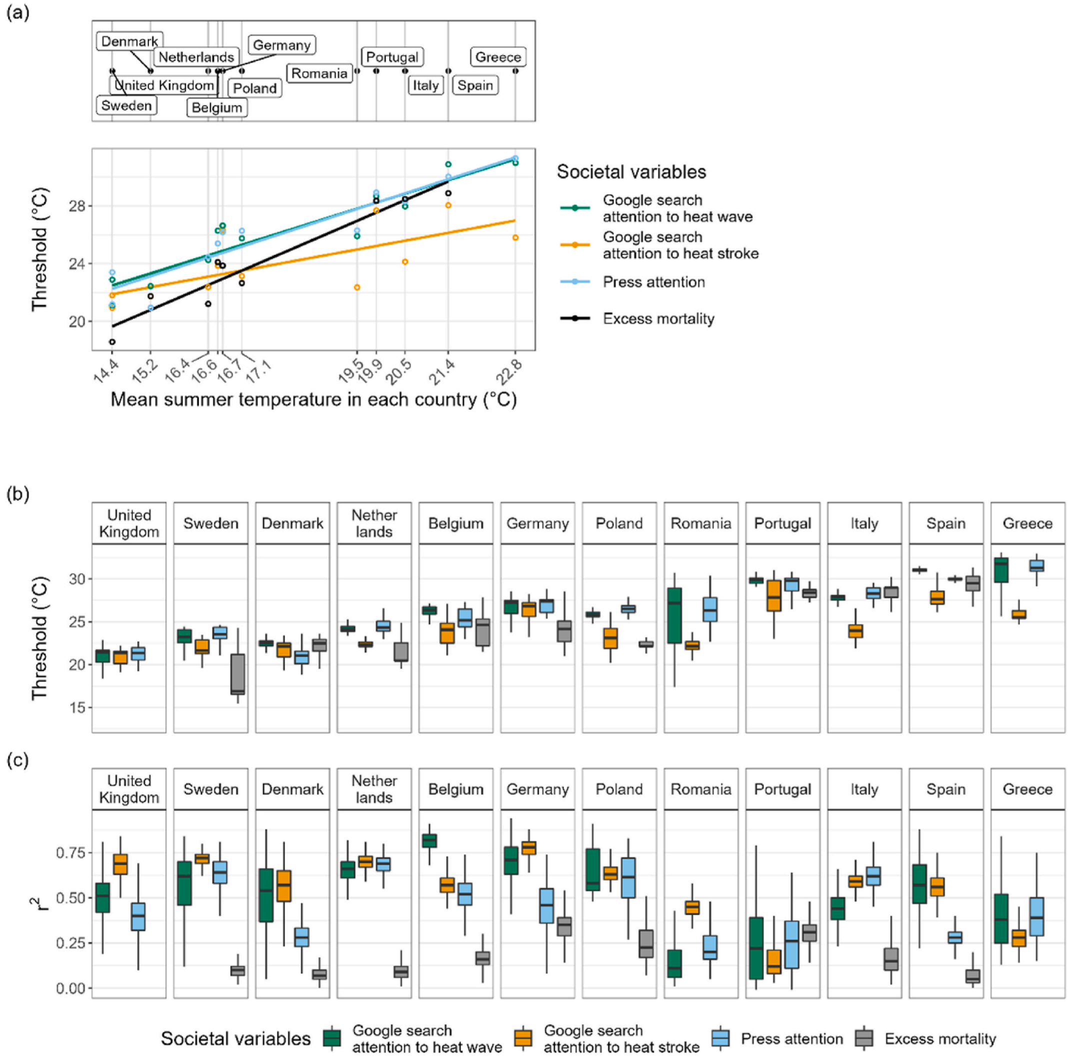


Fig. 3. (a) Mean temperature thresholds for the societal response to hot temperatures across countries and variables. Piecewise linear regressions are fitted to estimate the thresholds for each societal variable. Results are computed for thresholds in terms of daily maximum temperature (Tmax_mean), which is the temperature variable that is most consistently related to the societal responses across all countries. Mean temperature is the multiannual average temperature of the five warmest months within the study period 2010–2020. The mean temperature in each country is shown with vertical lines. (b) Uncertainty of temperature threshold estimates as determined through bootstrapping. (c) Explanatory power of the piecewise regressions for all bootstrap samples.

related societal metrics might therefore be older or more vulnerable to heat compared to the people sampled with attention-related metrics. This is in line with recent findings for Germany where it was shown that most of the overall mortality resulted from the oldest age groups [42]. However, we only have general information about the composition of the population contributing to the Google search interest.

Google search attention *to heat waves* is in better agreement with press attention than other societal metrics. The presence of a strong relationship between media and public attention is well-known [16,17]. In the case of the press data we find that the inferred temperature thresholds do not depend strongly on the selection of newspapers; similar thresholds are found for different types of newspapers highlighting the robustness of the press-inferred temperature thresholds (Fig. S9).

The fraction of explained variance in the piecewise regression analysis displayed in Fig. 3c can serve as an indication of the validity of the inferred temperature threshold. We find that the r^2 exceeds 0.5 in many cases, but tends to be lower in the warmer countries, potentially related to less temperature variability during summers while the change between cold and hot periods in temperate countries makes it easier to detect the corresponding societal response. Among the societal variables, excess mortality has the lowest r^2 values, which reflects the fact that mortality is also affected by factors other than heat. However, this cannot be investigated further as this data source does not include information on the individual causes of mortality. Future research can benefit the incorporation of mortality causes into the Eurostat weekly mortality dataset. Nevertheless, it is essential to acknowledge the security and privacy considerations associated with this addition that some countries and regions may have.

3.3. Analysis of societally relevant numbers of hot days

As shown in the previous subsection, the vulnerability and/or exposure to heat is decreased in countries with warmer climates; however, they face more and hotter heat extremes [2]. This raises the question if they systematically experience more or fewer days with a societal response to hot temperatures, i.e. temperatures above the detected temperature threshold, compared with countries in colder climates. The average number of hot days by country and variable is shown in Fig. 4. We find an increase in the number of hot days towards warmer countries in the case of Google attention to *heat stroke*, but not for Google attention to *heat wave* and excess mortality.

Overall, there is a lot of variation between the results for different societal metrics and between countries, ranging from 1 (3) days (median and interquartile range) for Denmark and Portugal to 31 (26) days for Italy in case of Google attention to *heat wave*, from 2 (6) days for Portugal to 107 (21) days for Romania in case of Google attention to *heat stroke*, and 5 (11) days for Denmark to 70 (47) for Spain in case of mortality. This indicates that the combination of vulnerability, exposure, and climate (affecting typical heat wave magnitude) yields very country-specific counts of societally relevant hot days. For example, even for countries with similar climates, different vulnerability and/or exposure could induce differences in our results. Ways in which vulnerability and exposure can be affected include population age, level of urbanization, socio-economic status and access to health care. For example, high number of societally relevant hot days for Romania might be related to the highest proportion of agricultural workers in this country [43], who are particularly vulnerable during heat waves [10,44]. Romania is also a country with lower average income compared to the other countries analyzed [45], which could limit the use of air conditioning [46]. In addition to other factors affecting the vulnerability to heat waves, the perception of heat wave risk also plays a role, and might be low even among the vulnerable groups [33,47,48]. In a comparative study [48], showed that the population in Belgium is more concerned and informed about the danger of heat waves than the Dutch population. Moreover, we also analyze the agreement between the numbers of hot days detected through the three societal variables and find moderate agreement (Fig. S10). At least once during the study period societally-relevant hot days co-occur in all twelve countries challenging European businesses, power infrastructure, and health-care (Fig. S11).

Note, that a part of the variability is also related to uncertainties in the estimation of thresholds with the piecewise regressions, especially in the case of low r^2 values (no asterisk in Fig. 4). This estimation of uncertainty can be seen from the bootstrap results shown in Figs. S15–S16. In terms of the most influential temperature variables we find that Tmax is relevant for Google attention to *heat waves* in many countries, while in the case of Google attention to *heat stroke* we find that Tmax is most relevant in cold countries while Tmean is most relevant in warm countries, and for mortality, Tmean and Tmin are generally more important. This suggests that night-time temperatures reflected in Tmean and Tmin are relevant for health but not so much for attention. This can be explained as night-time temperatures influence sleep quality and therefore preparedness for heat stress during daytime hours [26], moreover, poor sleep quality can increase the risk of heat stroke [49]. Previous research has also shown that Google attention to *heat stroke* can be an informative proxy for health impacts of heat waves, as expressed, e.g., by the number of hospitalizations [20,19].

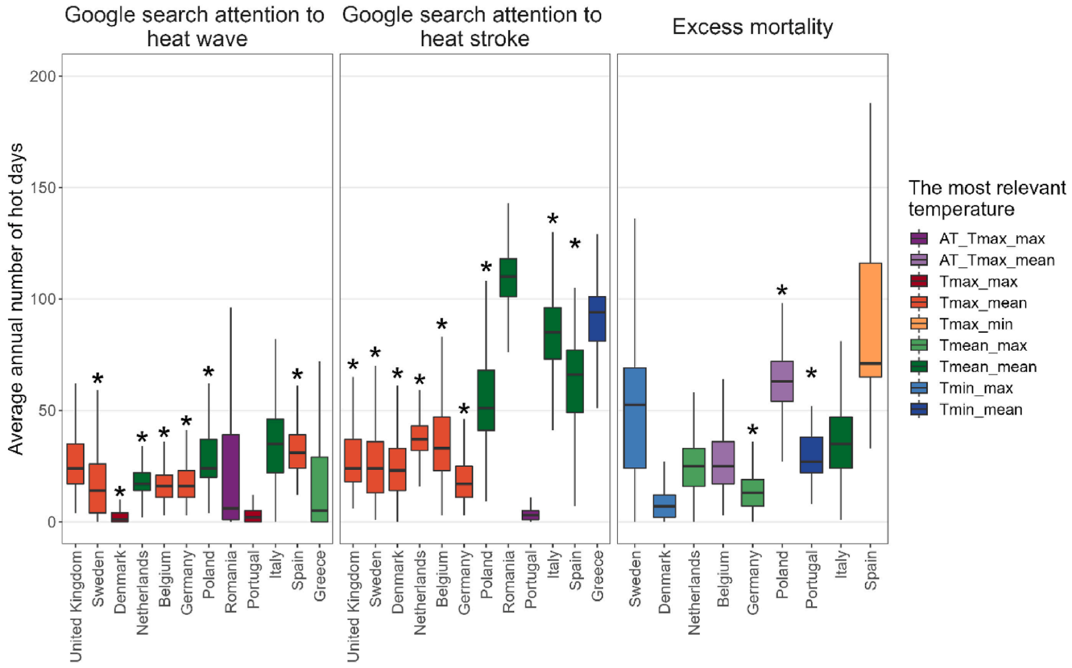


Fig. 4. Average annual number of hot days during 2010–2020 affecting 50 % of the population of each country. Countries are ordered from cold (left) to warm (right) climate. Colors indicate the most influential temperature variable for each country and societal response metric. * indicates $r^2 \geq 0.5$ for Google attention to *heat wave* or *heat stroke*, and $r^2 \geq 0.2$ for excess mortality. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

When changing the 50 % threshold for the affected population in the definition of hot days for a country to 25 %, we find similar results, though a higher number of hot days (Fig. S12). Finally, investigating long-term trends in the number of societally-relevant hot days, we find increases during the last two decades (Fig. S13).

3.4. Comparing the days with heat warnings with societally relevant hot days

The number of societally relevant hot days from Fig. 4 are shown alongside the number of days with official heat warnings within the selected countries in Fig. 5. For the Netherlands and Germany, we use heat warnings which were actually issued by the national weather services (National Institute for Public Health and the Environment, The Royal Netherlands Meteorological Institute, and German Weather Service), while for the other countries we inferred the warnings by applying published definitions of heat wave warning conditions from weather services. This way, the warnings provided by weather services are based on forecasted temperature values, whereas the inferred warnings are based on actual temperatures. The use of both actual and inferred warnings is possible in the case of the Netherlands and shows similar results.

In general, we find a higher number of societally relevant hot days than days with warning conditions or published warnings. Similar results are found when considering a 25 % population threshold in the determination of days with heat warnings or a societal response to heat (Fig. S17). This suggests that the sensitivity of the country's population to hot temperatures might be underestimated by the warning criteria. Some studies have also shown that the health risks of heat are often underestimated [50] and will increase in the future [51]. Therefore, warning criteria should be adapted in order to yield heat warnings also in situations where they are currently not issued while societal responses to heat can be detected. In addition to the number of heat warnings, also their effectiveness is an important parameter which may furthermore be related to their number. Note, however, that evaluating the effectiveness of heat warnings is complex and beyond the scope of this study. The effectiveness of heat warnings depends on many factors, including the accuracy of temperature forecasts, the economic costs of development and implementation, and communication of heat warnings to the public [6]. Moreover, heat warnings may be ineffective because people, even vulnerable ones, do not perceive themselves as being at risk [33,47,48]. In addition, the criteria for heat warnings vary across countries, and heat warnings are adapted to local characteristics, which is certainly important. However, there is a lack of standardization [41]. It may happen that despite similar weather conditions in neighboring countries, one country may issue a heat warning while the other side of the border does not [12].

Excess mortality is often used to evaluate the effectiveness of heat warnings [6]. To our knowledge, there are no studies comparing the number of heat warnings with the frequency of internet searches in many countries. Previous studies instead showed the correlation between Google search frequency and heat-related hospital admissions [14,20,19].

Interestingly, the difference between the number of heat warning days and the number of socially relevant hot days is smaller for Germany than for other countries. This may be related to the slightly higher temperature threshold for a societal response to heat in Germany (Fig. 3b) which indicates lower vulnerability in this country, in which in turn may be an expression of efficient heat warning communication and/or infrastructure.

We additionally calculate the fraction of societally relevant hot days with no heat warnings issued and number of days with heat warnings and no societal response (Fig. S18). The results show that days with heat warnings are in most cases also detected as days

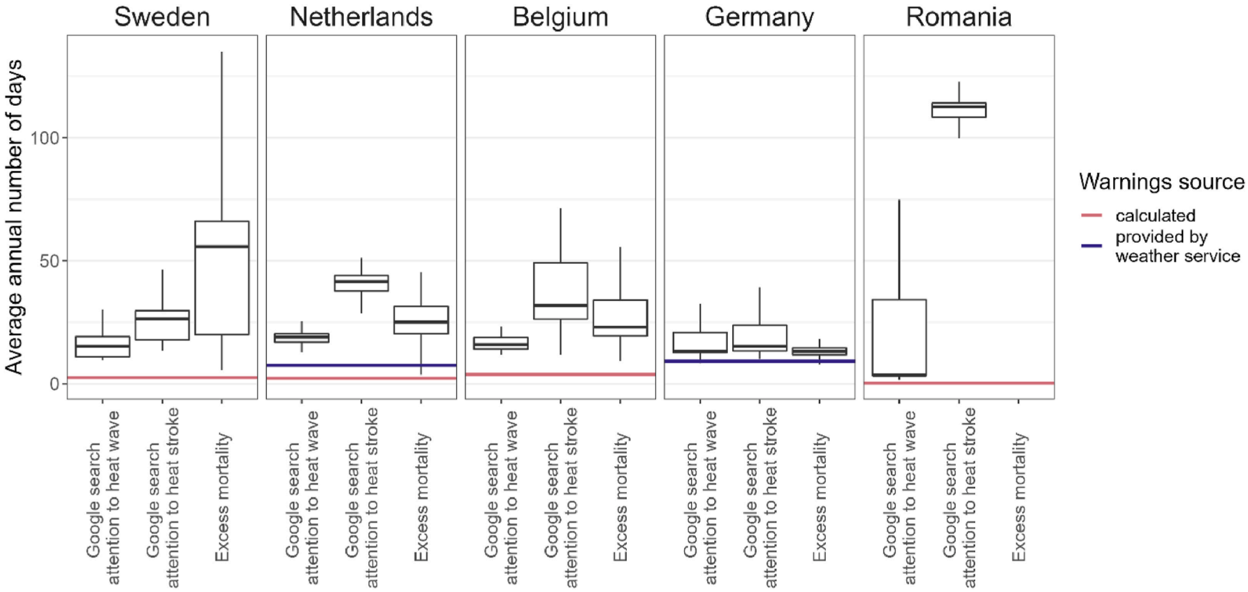


Fig. 5. Average annual number of societally relevant hot days (boxes) and heat warnings (horizontal lines) affecting 50 % of the country's population. Computed for the time period 2010–2020. The number of days with warnings is calculated using official heat warnings definitions (red lines) or/and heat warnings provided by the national weather service or a public health institution (blue lines). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

with a societal response to heat, confirming our detection approach. Conversely, many days for which we do detect a societal response to heat often had no heat warning. For example, in the Netherlands, Sweden, Belgium, and Romania, there are no days with warnings but no Google attention *to heat wave* (50 % of the population is affected by heat). In contrast, the number of days with Google attention to *heat wave* but no warning is over 82 % in these countries. In the Netherlands, the results between calculated warnings and those provided by weather/health institutions are similar. In Germany, 7.9 % of days with warnings have no search attention, but about 50 % of days with Google search attention have warnings. Similar results were found for Google attention to *heat stroke* and excess mortality.

We recognize that also heat warnings can influence the societal response to heat waves. However, the results in Fig. S18 illustrate that most of the days with a societal response to heat are not covered by heat warnings such that they probably do not interfere much with our diagnosed societal response to heat.

3.5. Limitations

The results of this study need to be considered in light of several potential limitations. First, Google algorithms are not transparent and change through time. Second, the motivations of users performing Google searches probably differ between searches; people can search for information about an event in other regions, i.e. not actually affecting them or follow Google autocomplete search suggestions [52,53]. However, Google trends data have been employed previously and have been shown to be a useful tool for understanding societal attention to health-related hazards [40,54]. Third, the age composition of Google users is not exactly known. Thus, elderly people, the most vulnerable group, might be underrepresented in Google data, and this underrepresentation may vary from country to country. However, younger relatives can google heat-related topics and warn about health risks. Fourth, internet use in countries is different and varies from 78 % (Italy, Portugal, Romania, and Spain) to 99 % (Denmark) in 2020 (Fig. S1). Finally, we are not able to capture short-term weather variability in our analysis, as social data streams do not have sufficient temporal resolution to do so. In general, the similarity of our results between different employed societal metrics illustrates the robustness of our conclusions, and suggests that they are not severely affected by limitations in an individual societal data stream.

4. Conclusions

In this study we introduce an approach to derive the societally relevant number of hot days, and illustrate that this works across societal data streams (i.e. Google search attention, excessed mortality) and countries. There are no systematic differences between the results of small and large countries across all figures, suggesting that regional differences and characteristics do not have a major impact on our findings. Our results provide an indication that warmer countries may generally have a lower vulnerability, exposure, or better adaptation to heat, as reflected in higher threshold temperatures at which a societal response to heat can be detected. However, despite the lower vulnerability as indicated by the higher temperature thresholds, the warm countries overall show more days with a societal heat response, because the heat wave temperatures are so much higher in these countries such that somewhat higher temperature thresholds can not compensate this. More research needs to be done to further evaluate this finding. At the same time, they are facing more frequent and intense heat waves such that the number of days with a detected societal response to heat varies and does not show systematic differences between countries of different climate regimes. Instead, this number varies strongly between countries, possibly reflecting differences in vulnerability (e.g. infrastructure, daily routines, exposure, climate), but also possible biases and confounding factors. Future research should investigate these differences further, as a better understanding can provide guidance towards lowering the number of days with heat effects on the population.

Comparing our detected number of days with a societal response to heat with officially issued heat warnings reveals surprising differences as heat warnings are apparently underestimating the number of days where the population is affected by heat. This is found consistently across several European countries. Therefore, criteria for heat warnings should be revised to ensure that heat warnings are aligned with the expected societal responses to the hot temperatures. This may render heat warnings also more effective as they are in better agreement with the weather experience of the population.

CRediT authorship contribution statement

Ekaterina Bogdanovich: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing - original draft, Writing - review & editing. **Alexander Brenning:** Conceptualization, Supervision, Writing - review & editing. **Markus Reichstein:** Conceptualization, Funding acquisition, Project administration, Supervision, Writing - review & editing. **Kelley De Polt:** Data curation, Methodology, Writing - review & editing. **Lars Guenther:** Conceptualization, Writing - review & editing. **Dorothea Frank:** Conceptualization, Writing - review & editing. **René Orth:** Conceptualization, Formal analysis, Funding acquisition, Methodology, Project administration, Supervision, Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

We thank Ulrich Weber for obtaining and processing ERA5 data, Anne Hoek van Dijke for helpful advice on Dutch weather warning data, and Jasper M.C. Denissen for help with R coding. We thank Georg Ruhrmann and Mike S. Schäfer for fruitful discussions on the analysis. We acknowledge data on heat warnings for Germany which was obtained from pttps://opendata.dwd.de/climate_environment/health/historical_alerts/heat_warnings/with kind advice from Stefan Muthers from the German Weather Service. E. Bogdanovich acknowledges support from the International Max Planck Research School for Global Biogeochemical Cycles. Rene Orth is supported by funding from the German Research Foundation (Emmy Noether grant number 391059971), and Kelley De Polt is supported by funding from the MYRIAD-EU project from the European Union's Horizon 2020 research and innovation programme (grant number 101003276).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijdrr.2023.104206.

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