Ekaterina Bogdanovcih[1], Ekaterina Bogdanovich[2], Alexander Brenning[3], Markus Reichstein[2], Kelley De Polt[2], Lars Guenther[4], Dorothea Frank[2], and René Orth[2]

[1]Affiliation not available
[2]Department of Biogeochemical Integration, Max Planck Institute for Biogeochemistry
[3]Department of Geography, Friedrich Schiller University Jena
[4]Institute for Journalism and Communication Studies, University of Hamburg

June 23, 2023

Title:

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

Authors:

Ekaterina Bogdanovich[1*], Alexander Brenning[2], Markus Reichstein[1], Kelley De Polt[1], Lars Guenther[3], Dorothea Frank[1], René Orth[1]

Affiliations:

[1]Department of Biogeochemical Integration, Max Planck Institute for Biogeochemistry, Hans-Knöll Straße 10, 07745 Jena, Germany

[2]Department of Geography, Friedrich Schiller University Jena, Löbdergraben 32, 07743 Jena, Germany

[3]Institute for Journalism and Communication Studies, University of Hamburg, Grindelberg 5, 20144 Hamburg, Germany

*Corresponding author. E-mail: ebogdan@bgc-jena.mpg.de

https://orcid.org/0000-0003-1095-8047

Keywords: heat wave, Google Trends, societal attention, Europe, heat warnings

Abstract

The frequency, duration, and intensity of heat waves are expected to increase in the coming decades across the globe. In this context it is not clear how the related impacts differ between countries as a result of different vulnerability and exposure characteristics, such as overall climatic conditions and implemented adaptation strategies. Such strategies include the release of official heat warnings. It remains, however, to be tested to which extent they capture days with detectable 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 during 2010-2020. Applying a piecewise regression analysis, we identify country-specific temperature thresholds above which societal responses start to increase. We find higher thresholds in countries with a warmer climate consistently across societal response variables, indicating overall lower heat vulnerability in southern Europe. At the same time, we find similar numbers of societally relevant hot days across European countries, computed as the sum of days on which more than 50% of the population in a country is 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 European countries. This suggests that lower temperature thresholds would be better aligned with detectable societal responses and should therefore be considered in the context of (early) warning systems.

1 Introduction

Heat waves have severe impacts on the economy, ecosystems, and society (Hughes et al. 2016), and are expected to continue to become more frequent and intense in the future (IPCC 2021). They challenge the healthcare system (Mason et al. 2022), the economy (García-León et al. 2021), and infrastructure, one example being the electricity system (Ke et al. 2016). 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 (Hajat et al. 2010). The vulnerability of people to heat waves depends on individual vulnerability and exposure, which are related to living in urban areas, time or work spent outside, or pre-existing health problems. Age is another aspect 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, e.g., through lower productivity (Kjellström et al. 2019; Zander et al. 2015), which can lead to economic losses (Orlov et al. 2019).

In this context, heat warnings issued by national agencies 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 (Casanueva et al. 2019). This way, it can happen that for similar weather conditions in neighboring countries, there is a heat warning in one country but not on the other side of the border (Brimicombe et al. 2021). 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. These data have been used to study the societal response to heat waves (Adams et al. 2022; Grasso et al. 2017; Li et al. 2016). Further, using Germany as a case study, it has been shown that these datasets can be used to obtain temperature thresholds above which the societal response to heat increases markedly, and that these thresholds are similar across the different data streams (Bogdanovich et al. 2023, *submitted*).

In this study, we determine temperature thresholds for a heat-related societal response using health- and attention-related metrics from several European countries. Then, the number of days with temperatures above the inferred thresholds are regarded as societally relevant hot days and compared with the issued heat warnings in each country. At the same time, the comparison of the inferred temperature thresholds across different 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 selected 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 GlobalStats (2022); Table S1 in Supplementary information) and (iv) where the number of internet users exceeds 50% in 2015 and 70% in 2020 (Eurostat (n.d.-a); Figure S1 in Supplementary information). Based on these criteria, we selected twelve countries: Sweden, United Kingdom (UK), Denmark, Netherlands, Belgium, Germany, Poland, Portugal, Romania, Spain, Italy, and Greece. For each country, we use the same set of data streams. See Table S2 in Supplementary information for a summary of our data sources. We use a weekly time scale and consider the five warmest months of the year determined for each country. 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

In order to characterize the societal response to heat waves, we consider societal attention, press attention, and excess mortality.

To assess societal attention, we use search interest for the topics *heat wave* and *heat stroke* from Google Trends. 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 (Google News Initiative 2022). The daily data are downloaded using the python package PyTrens (Hogue n.d.) 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. 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 in Supplementary information. 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 in Supplementary information). 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 (Eurostat n.d.-b) is used as a proxy for the impact of heat waves on public health. We calculated excess mortality by subtracting the mean seasonal cycle from the raw mortality rates, after linearly detrending them to reduce the effect of demographic changes. 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 (Obradovich et al. 2017). 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 (National Weather Service 2021).

Daily maximum, minimum, and mean temperatures are obtained from the ERA5 reanalysis (Hersbach et al. 2020) at a spatial resolution of 0.25˚ x 0.25˚. Apparent temperature is calculated from maximum temperature and relative humidity (the equation and full list of coefficients can be found in (Rothfusz 1990). Relative humidity in this context is also derived from ERA5.

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 in Supplementary information. 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 (Center for

International Earth Science Information Network - CIESIN - Columbia University 2018b). 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 Figure 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 (Figure 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 (Figure 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 - CIESIN - Columbia University 2018a). 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 in Supplementary information). Then, we count the number of days on which more than 50% (25%) of the population in a country is experiencing warning conditions.

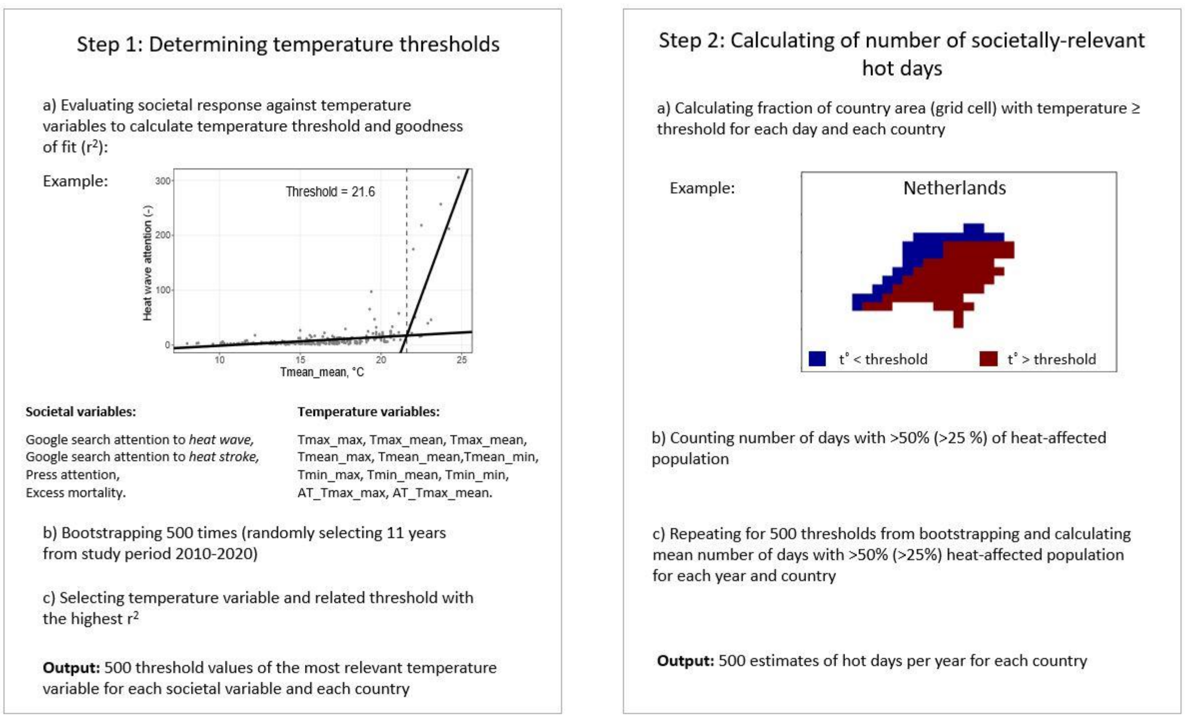

Figure 1. Workflow of the statistical analyses performed in this study.

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 in Supplementary information). We compare the typical temporal evolution of the considered variables during heat waves in all considered countries (Figure 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. We do not detect relevant time lags between hot temperatures and the societal response at the considered weekly time scale. Overall, these results suggest that hot temperatures are affecting the considered attention and mortality data streams such that they can be used to infer temperature thresholds for a societal response to hot temperatures.

The evolution of Google and press attention during heat waves is similar (see also Figure S2 in Supplementary information); this indicates that no metric is clearly driving the other but they are interrelated such that e.g. Google search attention might affect press attention and vice versa. Google search attention to *heat stroke* is overall increased 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 (Adams et al. 2022; Li et al. 2016).

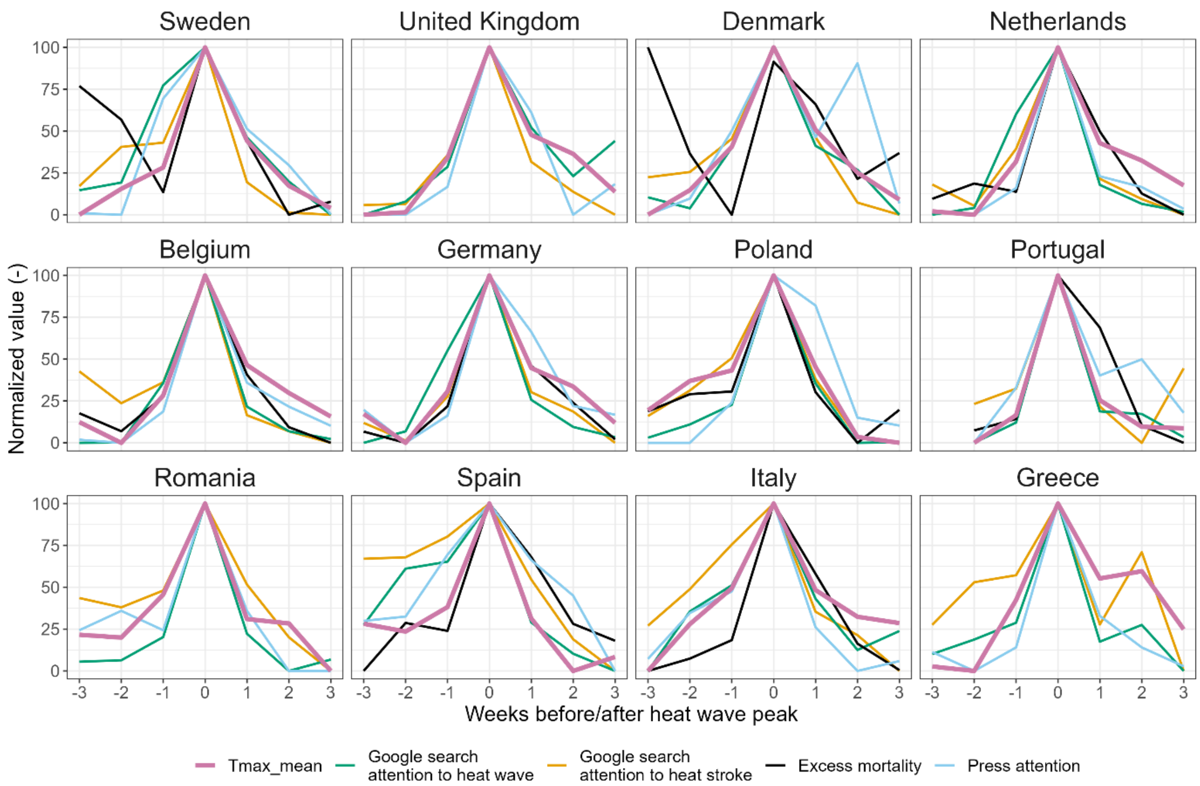

Figure 2. Evolution of temperature (Tmax_mean) and societal metrics during heat waves across considered countries. Countries are ordered from cold to warm climates (top to bottom, left to right). Time series are composites averaged across each year's 11 hottest heat waves. Values are normalized for comparability.

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. Figure 3 shows the temperature thresholds for Tmax_mean. The determined thresholds increase from cold countries to warm countries (Figure 3a). For example, the threshold for Google attention to *heat waves* in the coldest country Sweden is 22.3 ˚C, whereas in Greece, the hottest country, the threshold is 29.5 ˚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 (Figure S3 in Supplementary information).

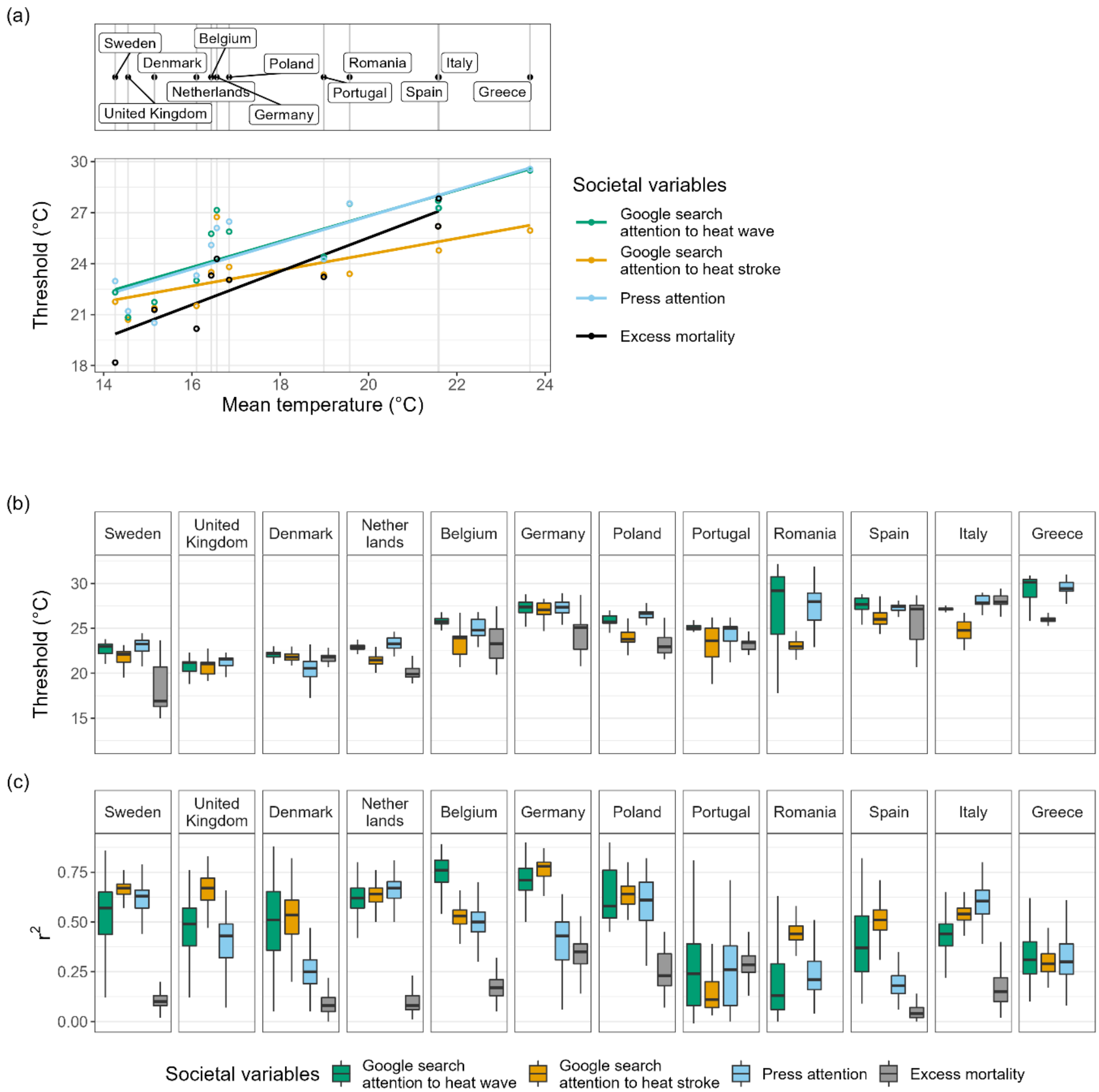

Figure 3. (a) Temperature thresholds for the societal response to hot temperatures across countries and variables. Piecewise linear regressions are fitted to estimate the thresholds for each societal variable. Results computed for thresholds in terms of daily maximum temperature (Tmax_mean), which is 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. (b) Uncertainty of temperature threshold estimates as determined through bootstrapping. (c) Explanatory power of the piecewise regressions for all bootstrap samples.

Higher temperature thresholds reflect reduced vulnerability and/or exposure 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. While we consider countries here, previous studies have shown that temperature thresholds for the societal response to heat can vary across different regions within the same country (An der Heiden et al. 2020; Singh et al. 2018) or even within the same city (Manoli et al. 2019).

As shown by the regressions in Figure 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-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 (Heudorf and Schade 2014). 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 (McCombs and Shaw 1972). 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 (Figure S4 in Supplementary information).

The fraction of explained variance in the piecewise regression analysis displayed in Figure 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, the lowest r^2 values are found for excess mortality, which reflects the fact that mortality is also affected by factors other than heat. Though, this cannot be investigated further as this data source does not include information about the individual causes of mortality.

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. 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 Figure 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 5 (7) days (median and interquartile range) for Denmark to 105 (18) days for Spain in case of Google attention to *heat wave*, from 5 (8) days for Belgium to 124 (19) days for Romania in case of Google attention to *heat stroke*, and 9 (11) days for Denmark to 141 (67) 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 (Eurostat 2017), who are particularly vulnerable during heat waves (Bethel and Harger 2014; Orlov et al. 2019). Romania is also a country with lower average income compared to the other countries analyzed (Eurostat 2022), which could limit the use of air conditioning (Thomson et al. 2019). 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 (Abrahamson et al. 2008; van Loenhout and Guha-Sapir 2016). In a comparative study, van Loenhout and Guha-Sapir (2016) showed that the population in Belgium is more concerned and informed about the danger of heat waves than the

Dutch population. This might explain the low number of societally relevant hot days in Belgium compared to the Netherlands. Moreover, we also analyze the agreement between the numbers of hot days detected through the three societal variables and find moderate agreement (Figure S5 in Supplementary information).

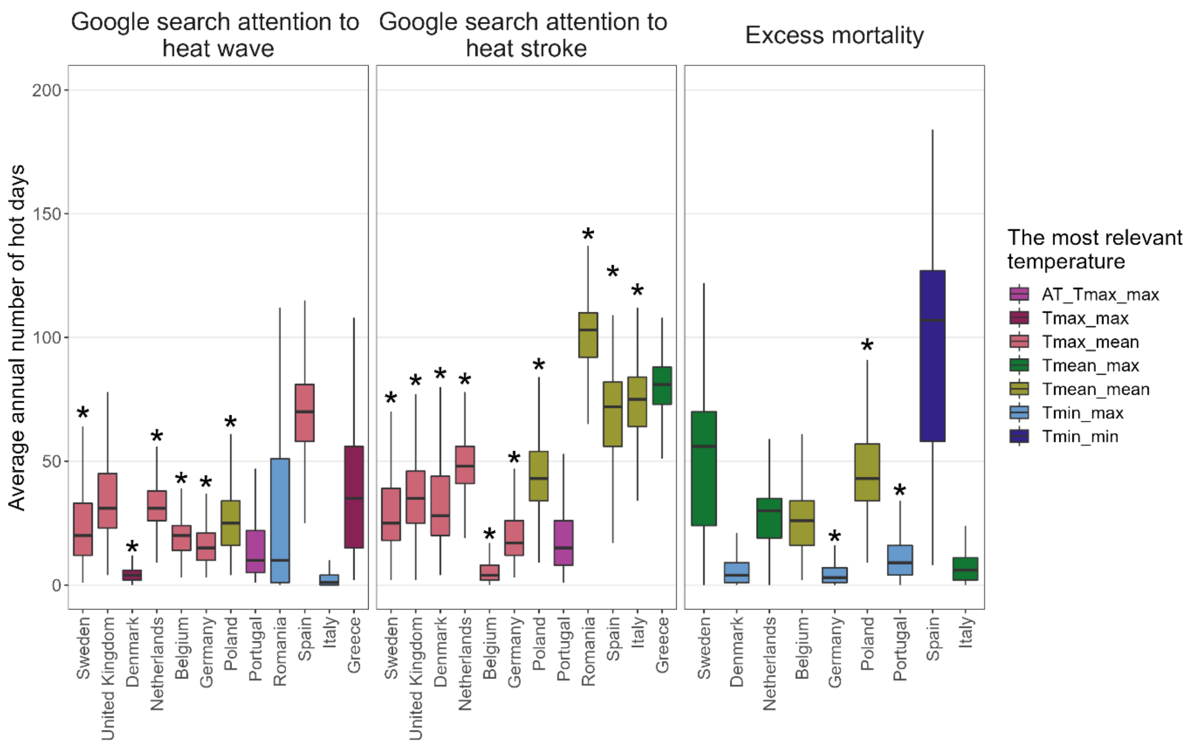

Figure 4. Average annual number of hot days during 2010-2020 affecting 50 % of the population of each country. Countries are ordered from cold (left) to warm (right) climate. Colors indicate the most influential temperature variable for each country and societal response metric. * indicates $r^2 \geq 0.5$ for Google attention to *heat wave* or *heat stroke*, and $r^2 \geq 0.2$ for excess mortality

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 Figure 4). This estimation of uncertainty can be seen from the bootstrap results shown in Figures S6-S8. 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 nighttime temperatures reflected in Tmean and Tmin are relevant for health but not so much for attention. This can be explained as nighttime temperatures influence sleep quality and therefore preparedness for heat stress during daytime hours (Obradovich et al. 2017), moreover, poor sleep quality can increase the risk of heat stroke (Otani et al. 2021). 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 (Adams et al. 2022; Li et al. 2016).

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 (Figure S9 in Supplementary information). Finally, investigating long-term trends in the number of societally-relevant hot days, we find increases during the last two decades (Figure S10 in Supplementary information).

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

The number of societally relevant hot days from Figure 4 are shown alongside the number of days with official heat warnings within the selected countries in Figure 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. Comparison between 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, suggesting that the sensitivity of the country's population to hot temperatures might be underestimated by the warning criteria. Similar results are found when considering a 25%

population threshold in the determination of days with heat warnings or a societal response to heat (Figure S11 in Supplementary information).

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 (Figure S12 in Supplementary information). The results show that days with heat warnings are in most cases also detected as days 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.

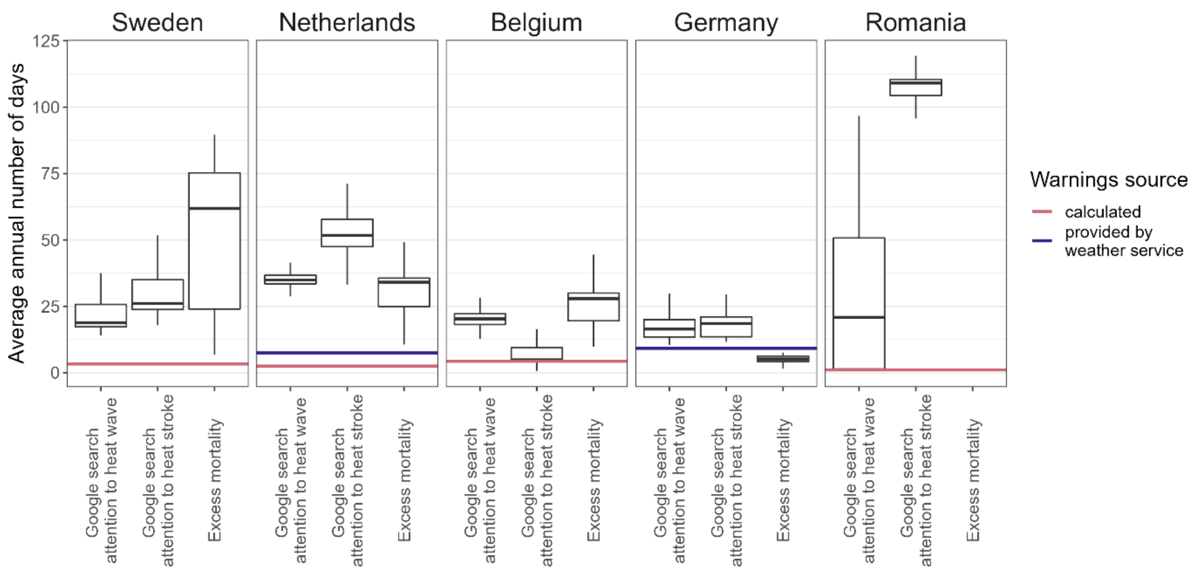

Figure 5. Average annual number of societally relevant hot days (boxes) and heat warnings (horizontal lines) affecting 50% of the country's population. Computed for the time period 2010-2020. The number of days with warnings is calculated using official heat warnings definitions (red lines) or/and heat warnings provided by the national weather service or a public health institution (blue lines).

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 motivation of users underlying the Google searches is probably differs 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 (Lazer et al. 2014; Nuti et al. 2014). 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 (Kam et al. 2019; Singh et al. 2018), 2019). 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. Finally, internet use in countries is different and varies from 78% (Italy, Portugal, Romania, and Spain) to 99 % (Denmark) in 2020 (Figure S1 in Supplementary information). 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 and countries. Our results show that warmer countries have a generally lower vulnerability and/or exposure to heat, as reflected in higher threshold temperatures at which a societal response to heat can be detected. 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.

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).

References

Abrahamson, V., J. Wolf, I. Lorenzoni, B. Fenn, S. Kovats, P. Wilkinson, W. N. Adger, and R. Raine, 2008: Perceptions of heatwave risks to health: interview-based study of older people in London and Norwich, UK. *J. Public Health*, **31,** 119-126.

Adams, Q. H., Y. Sun, S. Sun, and G. A. Wellenius, 2022: Internet searches and heat-related emergency department visits in the United States. *Sci. Rep.*, **12,** 9031.

An der Heiden, M., S. Muthers, H. Niemann, U. Buchholz, L. Grabenhenrich, and A. Matzarakis, 2020: Heat-Related Mortality: An Analysis of the Impact of Heatwaves in Germany Between 1992 and 2017. *Deutsches Ärzteblatt International*, **117,** 603.

Bethel, J. W., and R. Harger, 2014: Heat-Related Illness among Oregon Farmworkers. *Int. J. Env. Res. Public Health*, **11,** 9273-9285.

Bogdanovich, E., L. Guenther, M. Reichstein, D. Frank, G. Ruhrmann, A. Brenning, J. M. C. Denissen, and R. Orth, 2023: Societal attention to heat waves can indicate public health impacts. *Wea. Climate Soc.***,** submitted.

Brimicombe, C., C. Di Napoli, R. Cornforth, F. Pappenberger, C. Petty, and H. L. Cloke, 2021: Borderless heat hazards with bordered impacts. *Earth's Future*, **9,** e2021EF002064.

Casanueva, A., A. Burgstall, S. Kotlarski, A. Messeri, M. Morabito, A. D. Flouris, L. Nybo, C. Spirig, and C. Schwierz, 2019: Overview of existing heat-health warning systems in Europe. *Int. J. Env. Res. Public Health*, **16,** 2657.

Center for International Earth Science Information Network - CIESIN - Columbia University, 2018a: Gridded Population of the World, Version 4 (GPWv4): Population Count, Revision 11. https://doi.org/10.7927/H4JW8BX5.

Center for International Earth Science Information Network - CIESIN - Columbia University, 2018b: Gridded Population of the World, Version 4 (GPWv4): Population Density, Revision 11. https://doi.org/10.7927/H49C6VHW.

Eurostat, 2017: Farmers in the EU - statistics. Accessed 30.03.2023. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Archive:Farmers_in_the_EU_-_statistics#Further_Eurostat_information.

Eurostat, 2022: New indicator on annual average salaries in the EU. Accessed 04.04.2023. https://ec.europa.eu/eurostat/web/products-eurostat-news/w/ddn-20221219-3.

Eurostat, n.d.-a: Individuals - internet use. https://ec.europa.eu/eurostat/databrowser/view/ISOC_CI_IFP_IU__custom_3636561/default/table?lang=en.

Eurostat, n.d.-b: Deaths by week and sex. https://ec.europa.eu/eurostat/databrowser/view/DEMO_R_MWK_TS/default/table?lang=en&category=demo.demomwk.

García-León, D., A. Casanueva, G. Standardi, A. Burgstall, A. D. Flouris, and L. Nybo, 2021: Current and projected regional economic impacts of heatwaves in Europe. *Nat. Commun.*, **12,** 1-10.

Google News Initiative, 2022: Basics of Google Trends. Accessed 10.07.2022. https://newsinitiative.withgoogle.com/resources/lessons/basics-of-google-trends/.

Grasso, V., A. Crisci, M. Morabito, P. Nesi, and G. Pantaleo, 2017: Public crowdsensing of heat waves by social media data. *Adv. Sci. Res.*, **14,** 217.

Hajat, S., M. O'Connor, and T. Kosatsky, 2010: Health effects of hot weather: from awareness of risk factors to effective health protection. *The Lancet*, **375,** 856-863.

Hersbach, H.et al., 2020: The ERA5 global reanalysis. *Q. J. Roy. Meteorol. Soc.*, **146,** 1999-2049.

Heudorf, U., and M. Schade, 2014: Heat waves and mortality in Frankfurt am Main, Germany, 2003–2013. *Zeitschrift für Gerontologie und Geriatrie*, **47,** 475-482.

Hogue, J., DeWilde, B., n.d.: pytrends: Pseudo API for Google Trends. Accessed 04.04.2022. https://github.com/GeneralMills/pytrends.

Hughes, L., E. Hanna, and J. Fenwick, 2016: The silent killer: Climate change and the health impacts of extreme heat0994492642.

IPCC, 2021: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.

Kam, J., K. Stowers, and S. Kim, 2019: Monitoring of drought awareness from google trends: a case study of the 2011–17 California drought. *Wea. Climate Soc.*, **11,** 419-429.

Ke, X., D. Wu, J. Rice, M. Kintner-Meyer, and N. Lu, 2016: Quantifying impacts of heat waves on power grid operation. *Appl. Energy*, **183,** 504-512.

Kjellström, T., N. Maître, C. Saget, M. Otto, and T. Karimova, 2019: *Working on a warmer planet: The effect of heat stress on productivity and decent work.* International Labour Organization.

Koninklijk Nederlands Meteorologisch Instituut, 2015: Herijking Waarschuwingssytematiek. Accessed 31.05.2022. https://cdn.knmi.nl/system/downloads/files/000/000/025/original/Herijking_waarschuwingssystematiek_final_220615.pdf?1443525081.

Lazer, D., R. Kennedy, G. King, and A. Vespignani, 2014: The parable of Google Flu: traps in big data analysis. *Science*, **343,** 1203-1205.

Li, T., F. Ding, Q. Sun, Y. Zhang, and P. L. Kinney, 2016: Heat stroke internet searches can be a new heatwave health warning surveillance indicator. *Sci. Rep.*, **6,** 37294.

Manoli, G., S. Fatichi, M. Schläpfer, K. Yu, T. W. Crowther, N. Meili, P. Burlando, G. G. Katul, and E. Bou-Zeid, 2019: Magnitude of urban heat islands largely explained by climate and population. *Nature*, **573,** 55-60.

Mason, H., J. C King, A. E Peden, and R. C Franklin, 2022: Systematic review of the impact of heatwaves on health service demand in Australia. *BMC Health Serv. Res.*, **22,** 1-13.

McCombs, M. E., and D. L. Shaw, 1972: The Agenda-Settings Function of Mass Media. *Public Opin. Q.*, **36,** 176-187.

National Weather Service, 2021: What is the heat index? Accessed 24.09.2021. https://www.weather.gov/ama/heatindex.

Nuti, S. V., B. Wayda, I. Ranasinghe, S. Wang, R. P. Dreyer, S. I. Chen, and K. Murugiah, 2014: The use of google trends in health care research: a systematic review. *PloS one*, **9,** e109583.

Obradovich, N., R. Migliorini, S. C. Mednick, and J. H. Fowler, 2017: Nighttime temperature and human sleep loss in a changing climate. *Sci. Adv.*, **3,** e1601555.

Orlov, A., J. Sillmann, A. Aaheim, K. Aunan, and K. De Bruin, 2019: Economic losses of heat-induced reductions in outdoor worker productivity: a case study of Europe. *Econ. Disaster Clim. Chang.*, **3,** 191-211.

Otani, S., S. Funaki Ishizu, T. Masumoto, H. Amano, and Y. Kurozawa, 2021: The effect of minimum and maximum air temperatures in the summer on heat stroke in Japan: a time-stratified case-crossover study. *Int. J. Env. Res. Public Health*, **18,** 1632.

Public Health Agency of Sweden, 2022: Guidance in the event of a heatwave. Accessed 20.10.2022.

https://www.folkhalsomyndigheten.se/contentassets/80aa0a196f54477f983fc44908963deb/guidance-event-heatwave-friends-family.pdf.

Rothfusz, L. P., 1990: The heat index equation (or, more than you ever wanted to know about heat index). Scientific Services Division NWS Southern Region Headquarters, Fort Worth, TX, Fort Worth, Texas: National Oceanic and Atmospheric Administration, National Weather Service, Office of Meteorology.

Royal Meteorological Institute of Belgium, 2022: Legend Heat. Accessed 31.05.2022. https://www.meteo.be/en/weather/warnings/legend-heat.

Singh, T., C. Siderius, and Y. Van der Velde, 2018: When do Indians feel hot? Internet searches indicate seasonality suppresses adaptation to heat. *Environ. Res. Lett.*, **13,** 054009.

Statcounter GlobalStats, 2022: Search Engine Market Share Worldwide. Accessed https://gs.statcounter.com/search-engine-market-share/.

Thomson, H., N. Simcock, S. Bouzarovski, and S. Petrova, 2019: Energy poverty and indoor cooling: An overlooked issue in Europe. *Energy and Buildings*, **196,** 21-29.

van Loenhout, J. A. F., and D. Guha-Sapir, 2016: How resilient is the general population to heatwaves? A knowledge survey from the ENHANCE project in Brussels and Amsterdam. *BMC Res. Notes*, **9,** 1-5.

Zander, K. K., W. J. Botzen, E. Oppermann, T. Kjellstrom, and S. T. Garnett, 2015: Heat stress causes substantial labour productivity loss in Australia. *Nat. Clim. Change*, **5,** 647-651.

Supplementary information

Title:

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

Authors:

Ekaterina Bogdanovich[1*], Alexander Brenning[2], Markus Reichstein[1], Kelley De Polt[1], Lars Guenther[3], Dorothea Frank[1], René Orth[1]

Affiliations:

[1]Department of Biogeochemical Integration, Max Planck Institute for Biogeochemistry, Hans-Knöll Straße 10, 07745 Jena, Germany

[2]Department of Geography, Friedrich Schiller University Jena, Löbdergraben 32, 07743 Jena, Germany

[3]Institute for Journalism and Communication Studies, University of Hamburg, Grindelberg 5, 20144 Hamburg, Germany

*Corresponding author. E-mail: ebogdan@bgc-jena.mpg.de

https://orcid.org/0000-0003-1095-8047

Figures

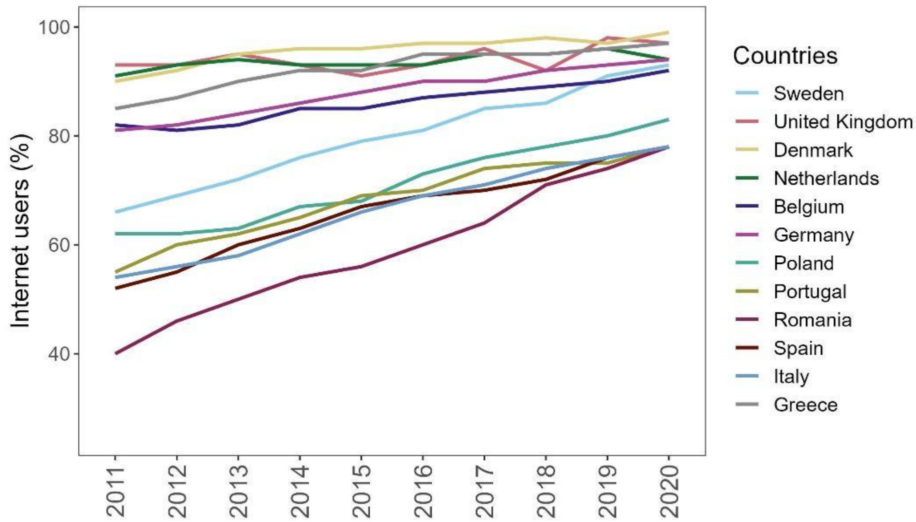

Figure S1. Internet users by country (Eurostat n.d.-a)

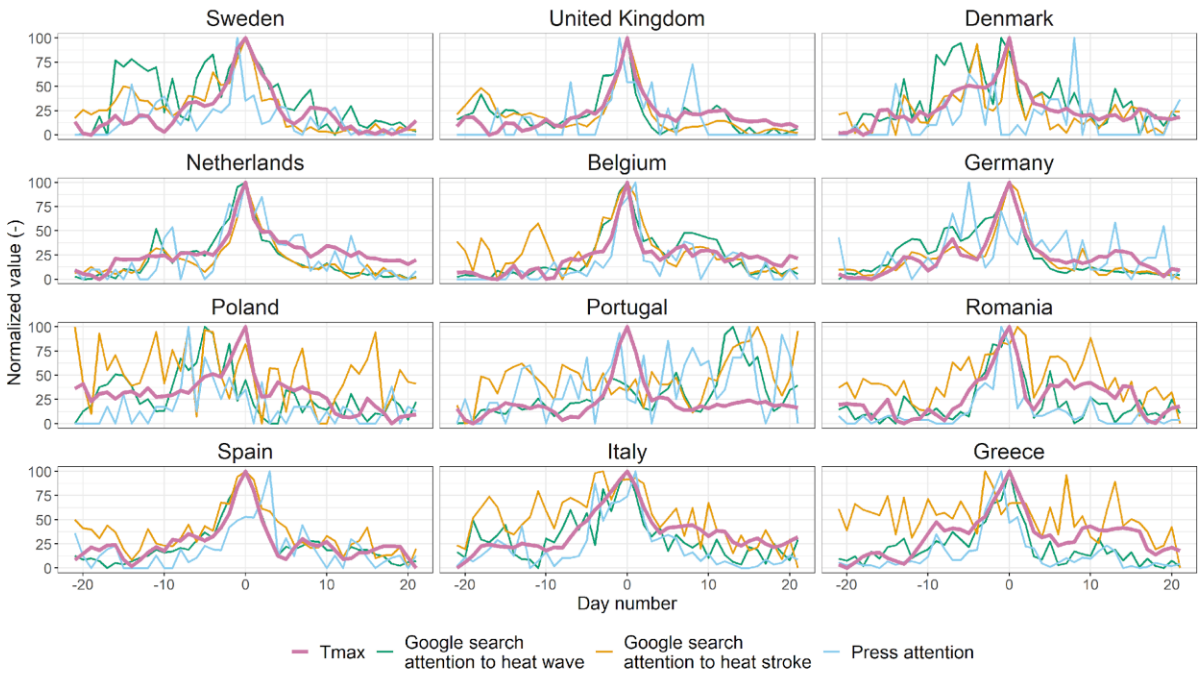

Figure S2. Evolution of temperature and considered societal metrics during heat waves. Values are normalized for comparability, and averaged across 11 events which are the hottest events in each year, respectively.

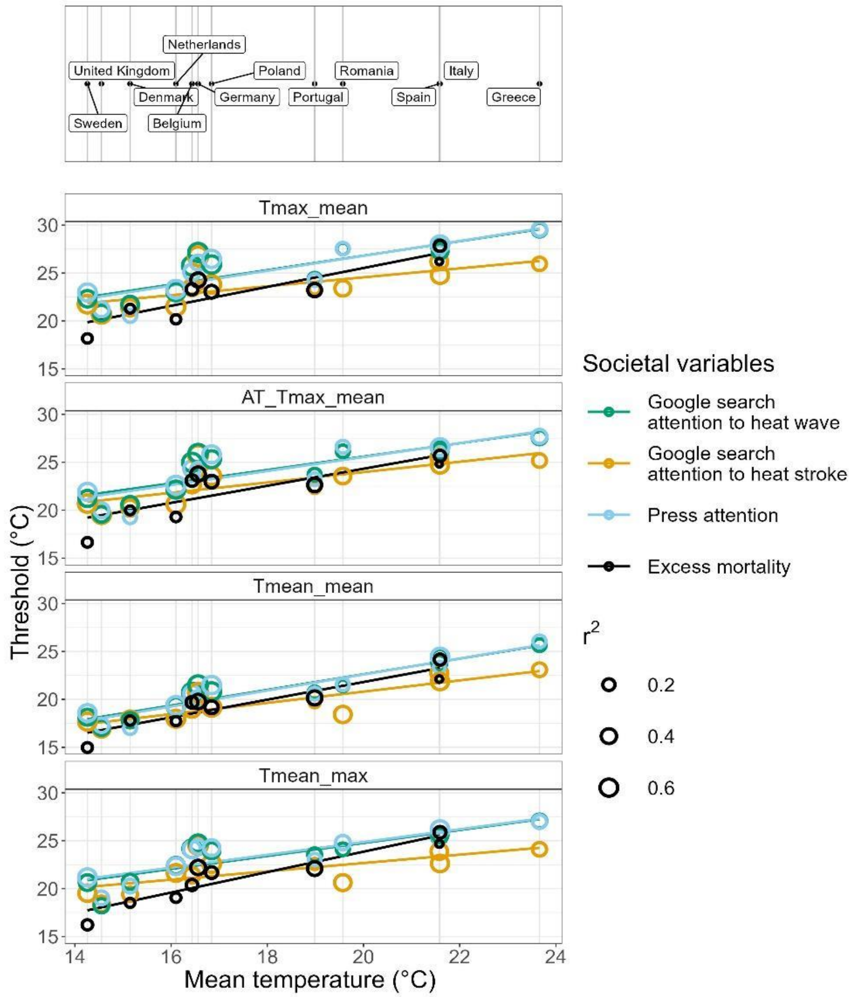

Figure S3. Temperature thresholds (average) in societal variables for four temperature variables with the highest r^2 of temperature-societal variable relationships. Mean temperature is the multiannual average temperature of the five warmest months.

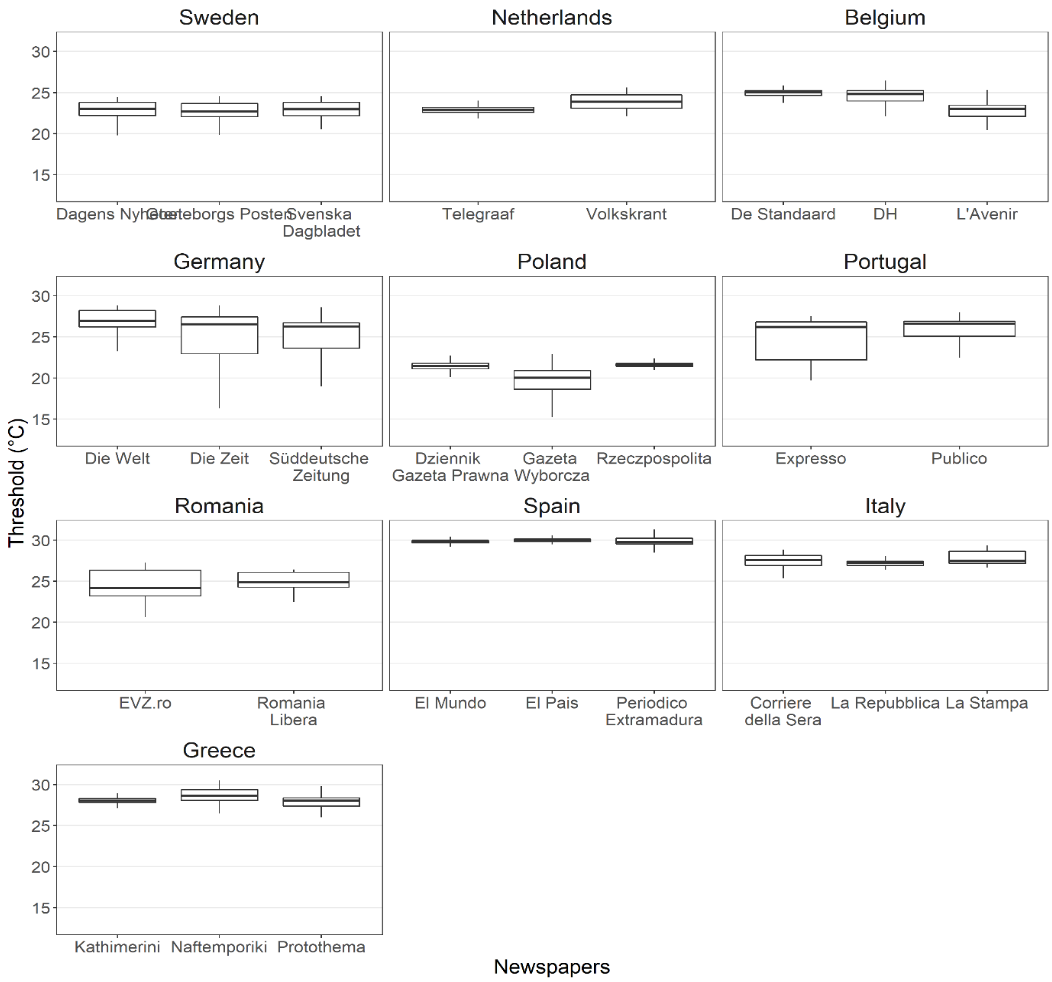

Figure S4. Temperature thresholds in newspapers for each country. Denmark and Great Britain are excluded because of low number of articles. The temperature with the highest r^2 is taken for threshold calculating.

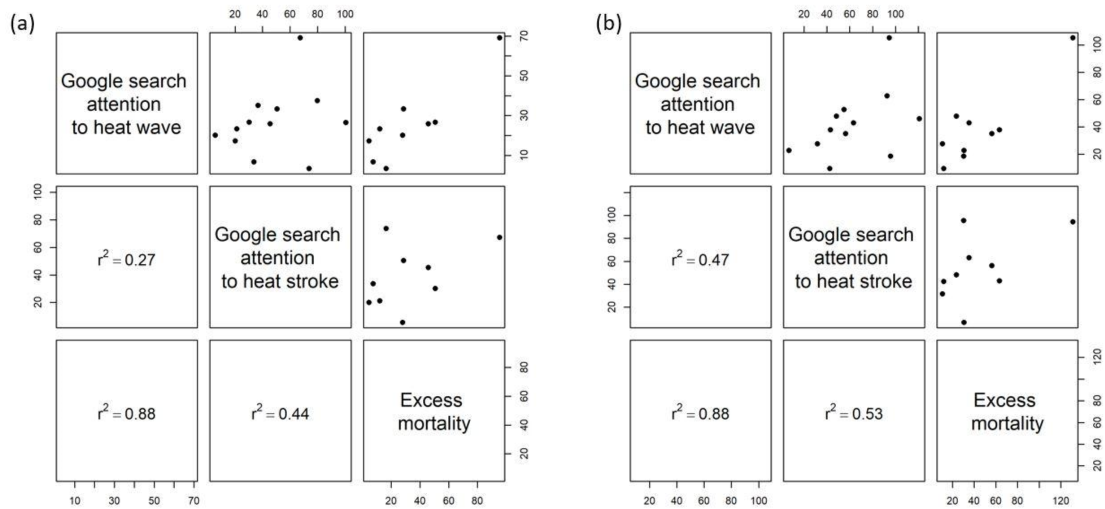

Figure S5. Agreement between the number of hot days detected through Google search attention to *heat wave*, Google search attention to h*eat stroke* and excess mortality: (a) 50 % of population is affected by hot temperatures (b) 25 % of population is affected by hot temperatures

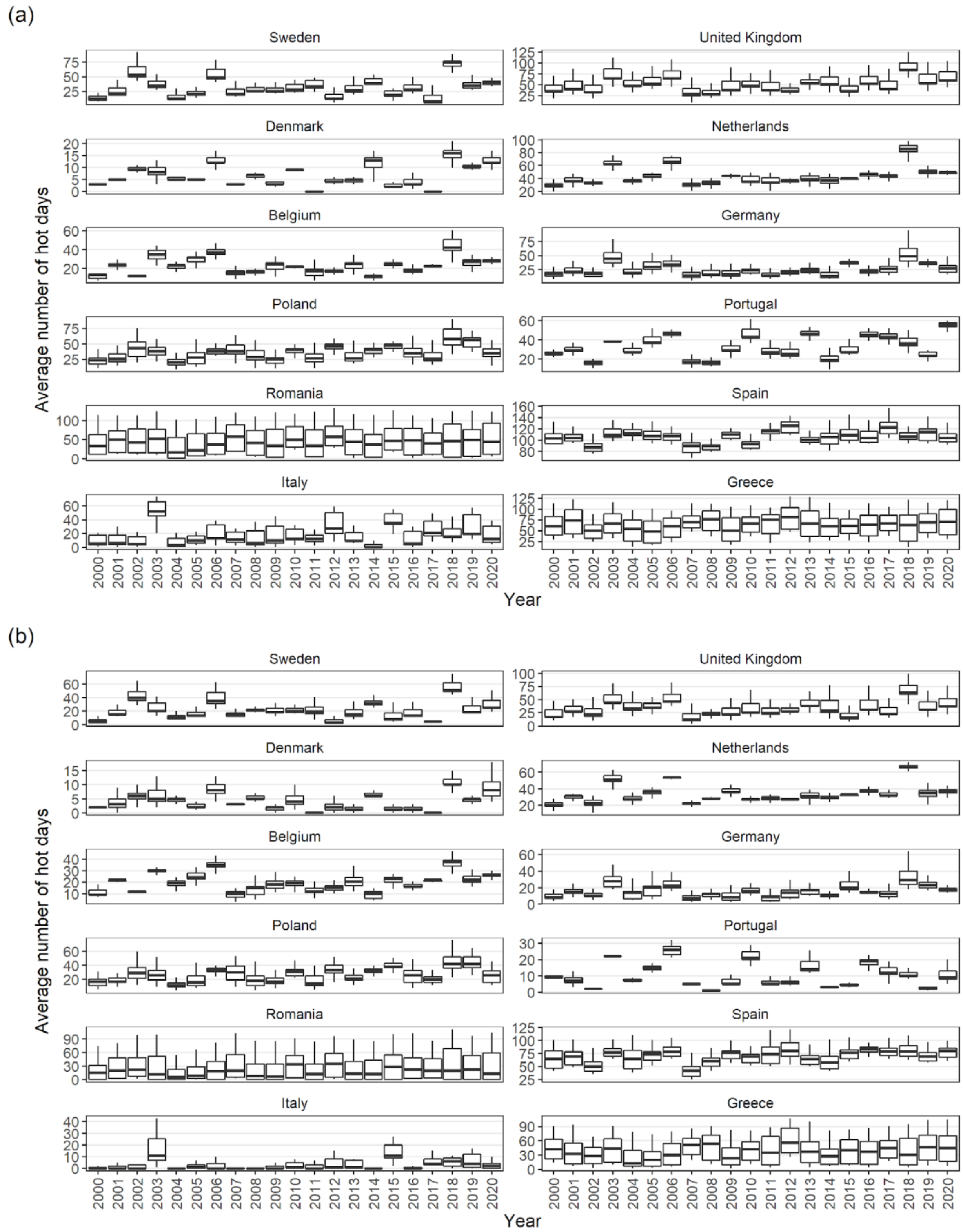

Figure S6. Number of societally relevant hot days per year calculated for Google search attention to heat wave and affecting (a) 25 % and (b) 50% of population

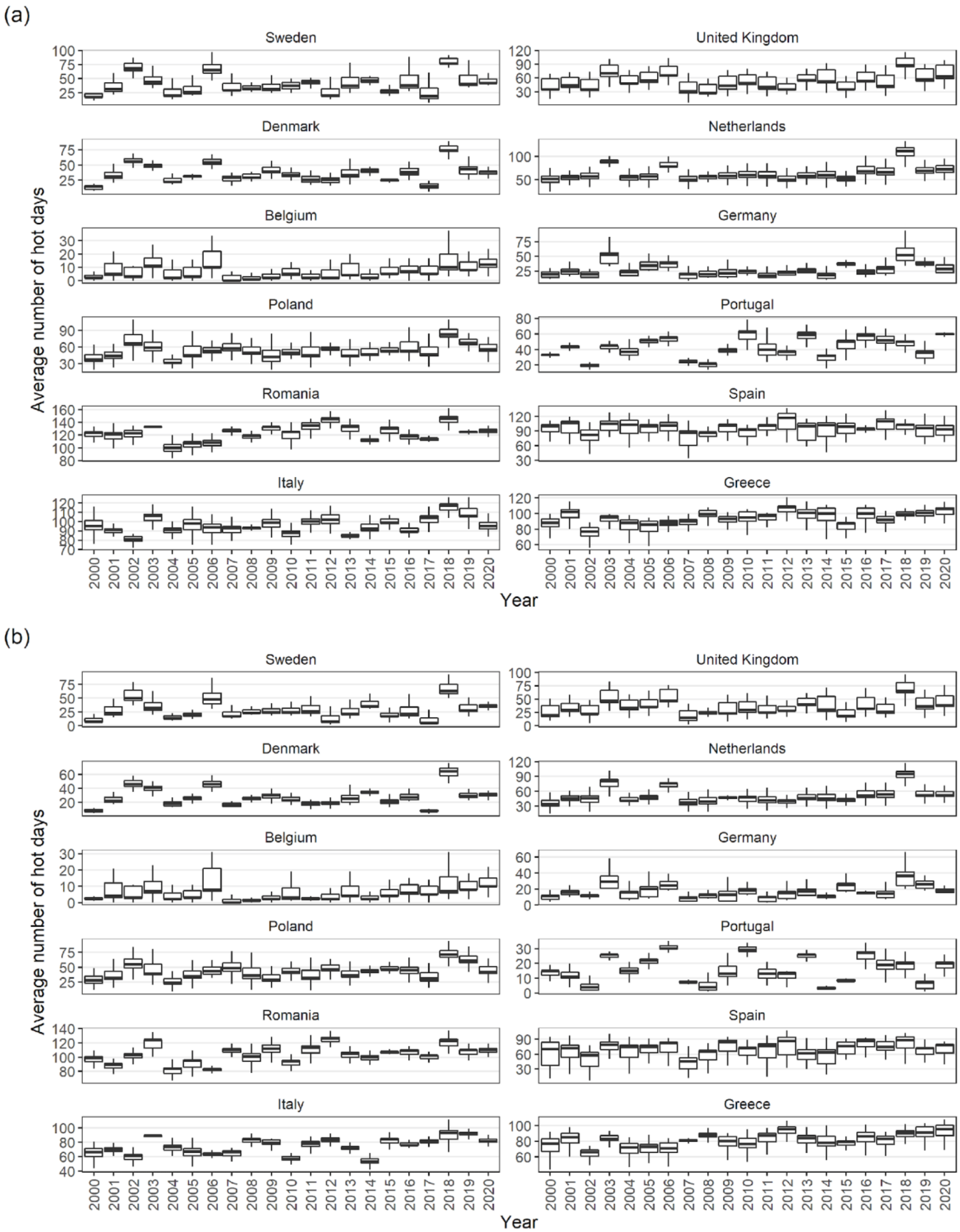

Figure S7. Number of societally relevant hot days per year calculated for Google search attention to heat stroke and affecting (a) 25 % and (b) 50% of population

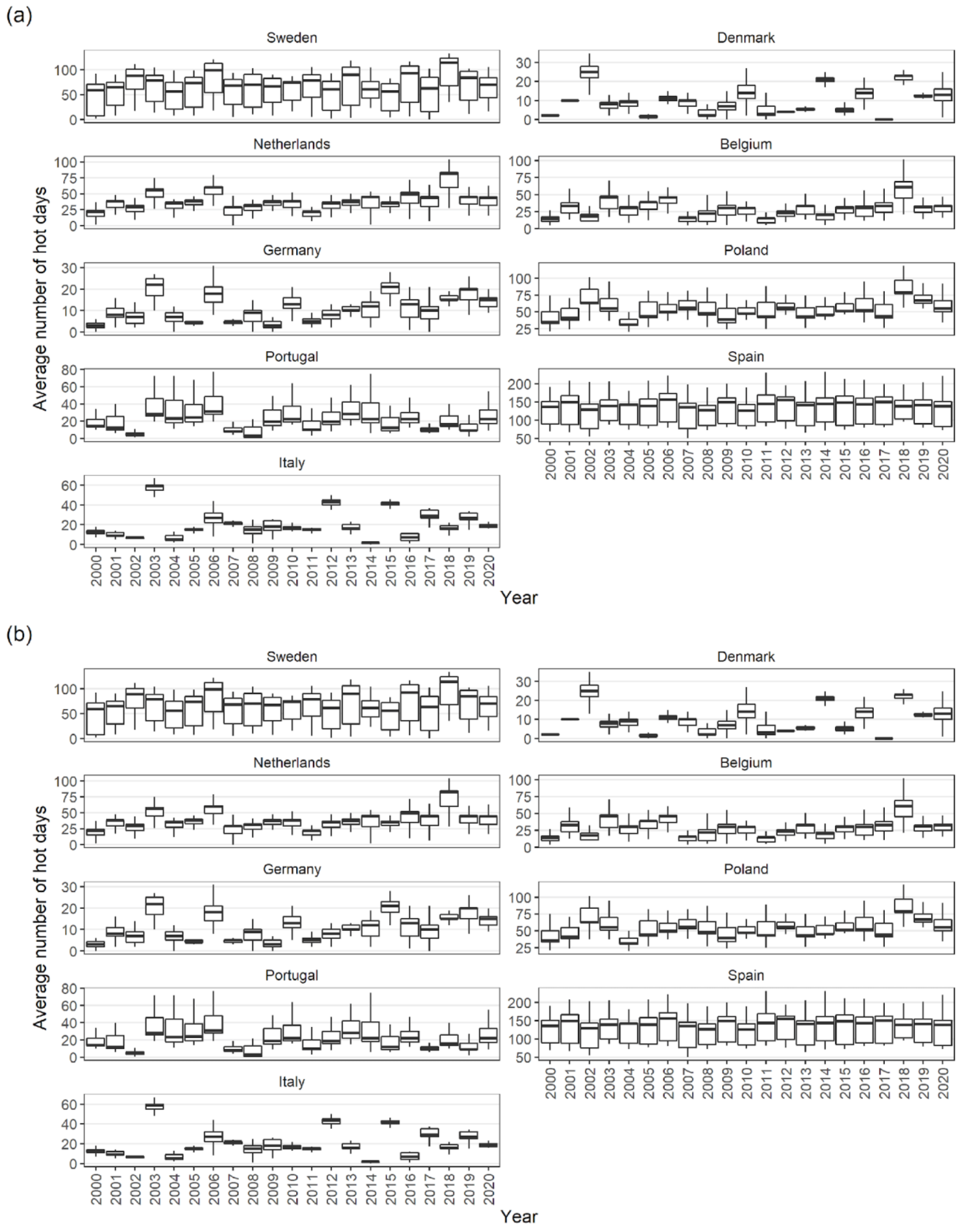

Figure S8. Number of societally relevant hot days per year calculated for excess mortality and affecting (a) 25 % and (b) 50% of population

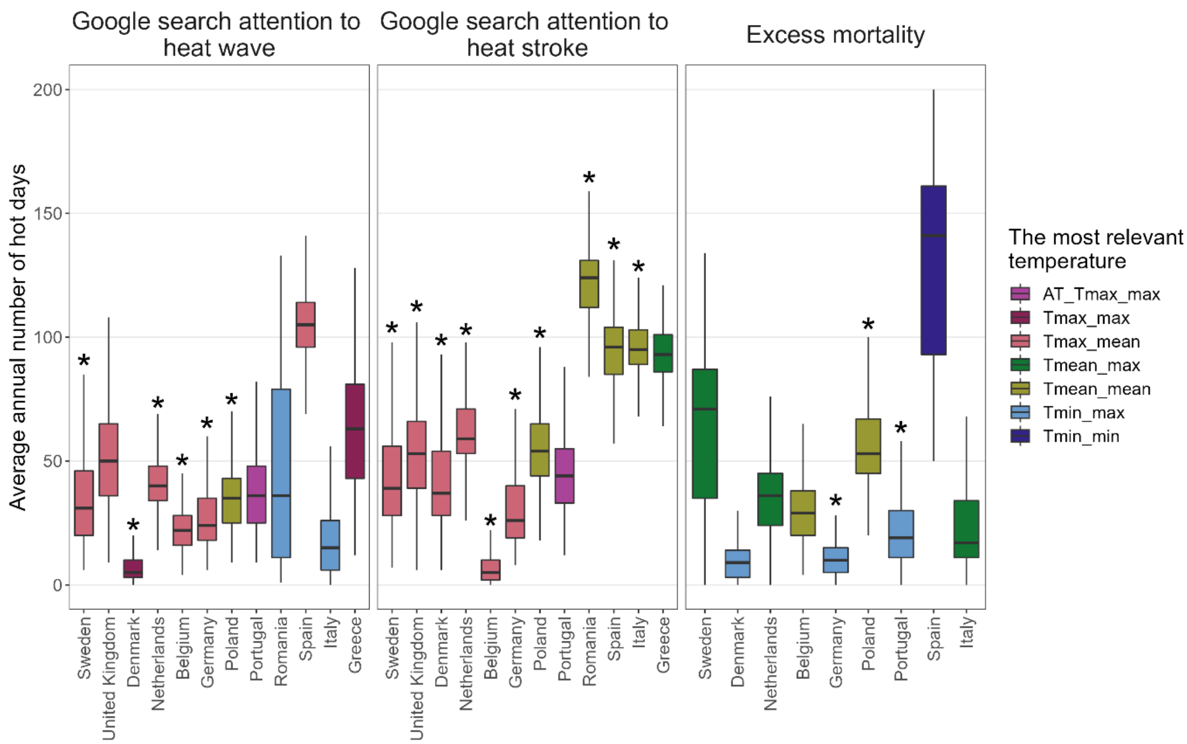

Figure S9. Average annual number of hot days during 2010-2020 affecting 25 % of the population of each country. Countries are ordered from cold (left) to warm (right) climate. Colors indicate the most influential temperature variable for each country and societal response metric. * indicates $r^2 \geq 0.5$ for Google attention to *heat wave* or *heat stroke*, and $r^2 \geq 0.2$ for excess mortality

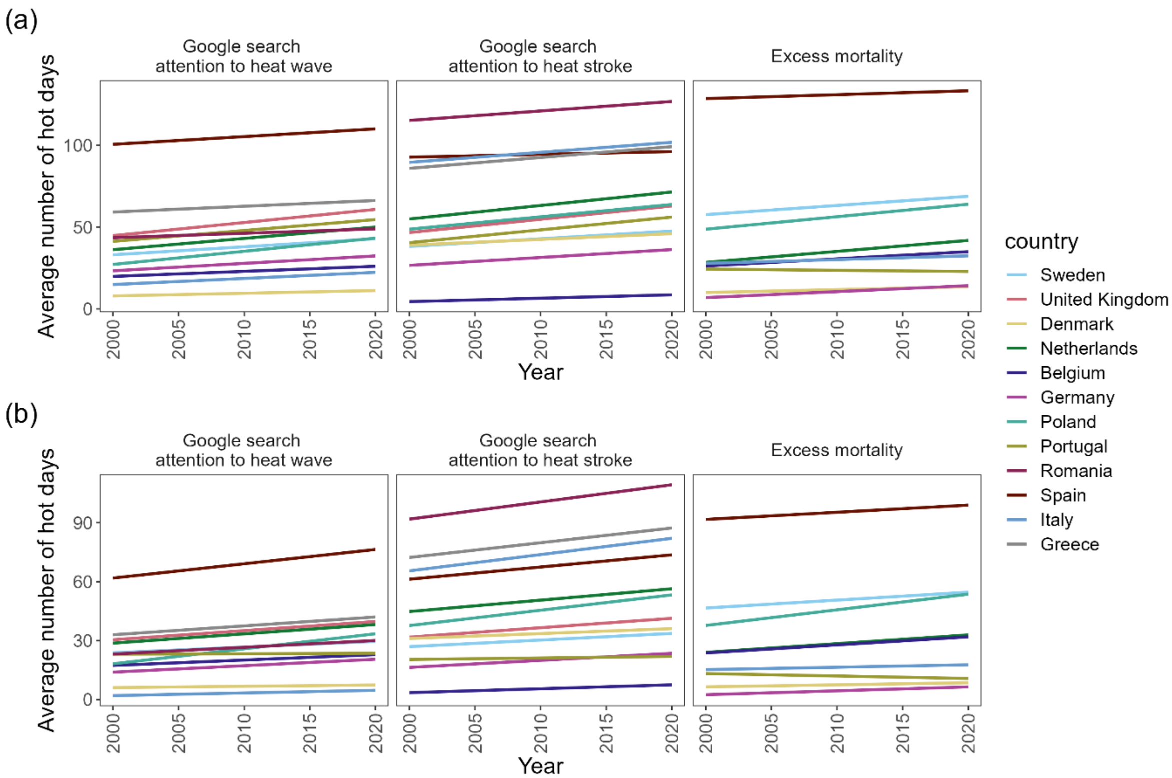

Figure S10. Linear trend estimates of societally relevant hot days per year affecting (a) 25 % and (b) 50% of population

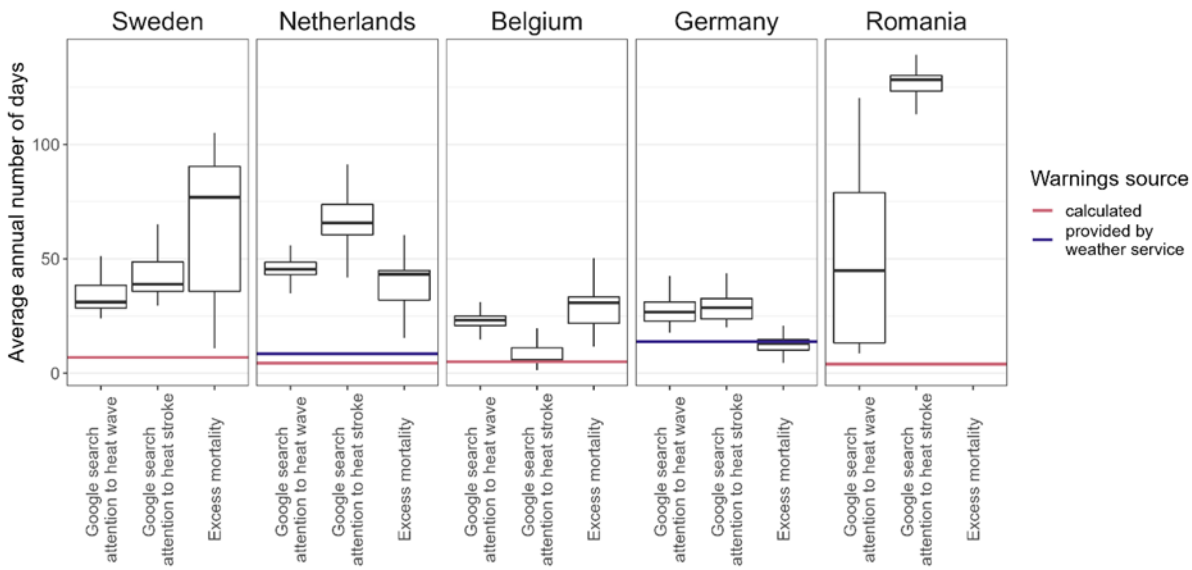

Figure S11. Average annual number of societally relevant hot days (boxes) and heat warnings (horizontal lines) affecting 50% of the country's population. Computed for the time period 2010-2020. The number of days with warnings is calculated using official heat warnings definitions (red lines) or/and heat warnings provided by the national weather service or a public health institution (blue lines).

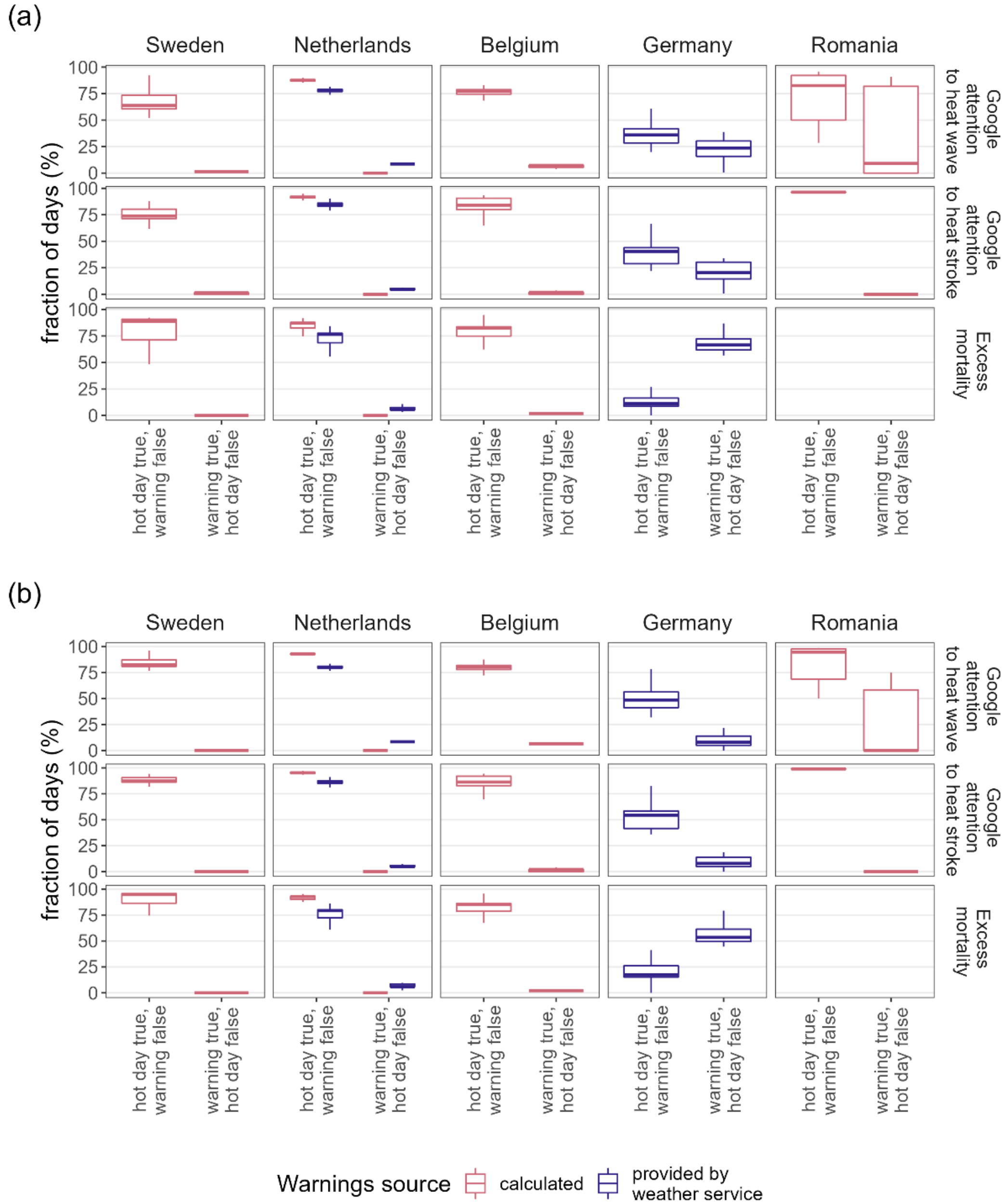

Figure S12. Agreement between heat warnings and societally relevant hot days affecting (a) 25% and (b) 50% of population: "false negative" refers to the fraction of days with no heat warning among all societally relevant hot days, i.e. P (no warning | societal response); "false positive" is the fraction of days with no societal response among all days with a heat warning, i.e. P (no societal response | warning).

Tables

Table S1. Average Google's search engine market share during 2010-2020 (%) (Statcounter GlobalStats 2022).

Country	Average market share of Google's search engine (%)
Sweden	95.3
United Kingdom	91.3
Denmark	96.1
Netherlands	94.5
Belgium	95.6
Germany	94.2
Poland	97.6
Portugal	96.9
Romania	97.2
Spain	96.1
Italy	95.6
Greece	97.4

Table S2. Data sources

Data	Source	Reference	Time period
Google search attention *heat wave*	Google Trends	https://trends.google.com/trends/?geo=DE	2010-2020
Google search attention *heat stroke*	Google Trends	https://trends.google.com/trends/?geo=DE	2010-2020
Press mentions	Factiva, WiSo, Nexis Uni, online webpages. More information in Table S3	https://www.dowjones.com/professional/factiva/ https://www.wiso-net.de/ https://www.lexisnexis.com	2010-2020
Mortality	Eurostat	https://ec.europa.eu/eurostat	2010-2020
Temperature	ERA 5	Hersbach et al. (2020)	2010-2020
Relative humidity	ERA 5	Hersbach et al. (2020)	2010-2020

Table S3. Press data information

country	newspaper	political alignment	format	printed/ online	source	# articles during warm months
Belgium	De Standaard	Liberal-conservative	compact	online	https://www.standaard.be/	51
	De Tijd	business and economics	berliner (middle)	online	https://www.tijd.be/	23
	DH les Sports	-	-	online	https://www.dhnet.be/	62
	L'Avenir	regional press	compact?	online	https://www.lavenir.net/	66
	Le_Soir	progressive, liberalism	berliner (middle)	online	https://www.lesoir.be/	21
Denmark	B.T.	-	tabloid	online	https://www.bt.dk/	17
	Ekstra Bladet	no alignment	tabloid	online	https://ekstrabladet.dk/	15
	Politiken	social liberal	broadsheet	online	https://politiken.dk/	34

Germany	Die Welt	conservatism, liberal conservatism	broadsheet	printed	WiSo	67
	Die Zeit	centrist and liberal	broadsheet	printed	Factiva	34
	Süddeutsche Zeitung	centre-left, left-liberal	nordisch (German format)	printed	Factiva	73
United Kingdom	Daily Mail	right wing	tabloid	printed	Factiva	14
	Daily Mirror	labour	tabloid	printed	Factiva	20
	The Sun	conservative	tabloid	printed	Factiva	7
Greece	Kathimerini	liberal conservatism	broadsheet	online	https://www.kathimerini.gr/	91
	Naftemporiki	-	broadsheet	online	https://www.naftemporiki.gr/	189
	Protothema	conservative liberalism		online	https://www.protothema.gr/	301
Italy	Corriere della Sera	liberalism, centrism,	berliner (middle)	printed	Nexis Uni®	49
	la Repubblica	progressivism	berliner (middle)	online	repubblica.it	286
	La Stampa	liberalism, centrism,	berliner (middle)	printed	Nexis Uni®	87

Netherlands	Telegraaf	conservative and populist style	tabloid	printed	Nexis Uni®	81
	Volkskrant	centre-left	compact	printed	Nexis Uni®	64
Poland	Dziennik Gazeta Prawna	center-right	-	online	https://www.gazetaprawna.pl/	70
	Gazeta Wyborcza	liberalism	compact	online	https://www.wyborcza.pl	42
	Rzeczpospolita	liberal conservatism	compact	online	https://www.rp.pl/	81
Portugal	Expresso	no alignment	berliner (middle)	online	https://www.expresso.pt	59
	Publico	-	tabloid	online	https://www.publico.pt	45
Romania	EVZ.ro	-	broadsheet / now online	online	https://evz.ro/	75
	România Liberă	conservative	broadsheet	online	https://romanialibera.ro/	83
	Ziarul Financiar	-	-	online	https://www.zf.ro/	14
Spain	El Mundo	center-right	compact	printed	Nexis Uni®	61
	El País	center-left	compact	printed	Nexis Uni®	112

	El Periodico: Extremadura	-	-	printed	Nexis Uni®	57
Sweden	Dagens Nyheter	liberal	compact	online	https://www.dn.se/	61
	Goeteborgs Posten	liberal	compact	online	https://www.gp.se/	81
	Svenska Dagbladet	moderate (liberal-conservative)	tabloid	online	https://www.svd.se/	46

Table S4. Search keywords for retrieval press data. For search in the database, connectors AND/OR were used. For the webpage search, only a keyword was used.

Country	Search keyword
Belgium	chaleur extreme (French), extreme hitte (Flemish)
Denmark	ekstrem varme
Germany	Deutschland AND Hitzewelle OR extreme Hitze
Great Britain	Britain OR UK OR U.K. AND Heat wave OR extreme heat
Greece	καύσωνας
Italy	Italia AND ondata di calore OR ondata di caldo OR caldo estremo, ondata di calore
Netherlands	Nederland AND hittegolf OR extreme hitte
Polen	upał
Portugal	calor extremo
Romania	calor extremo
Spain	España AND ola de calor OR calor extremo

Table S5. Temperature abbreviations

Abbreviation	**Meaning**
Tmax_max	Weekly maximum of daily maximum temperature, ˚C
Tmax_mean	Weekly average of daily maximum temperature, ˚C
Tmax_min	Weekly minimum of daily maximum temperature, ˚C
Tmean_max	Weekly maximum of daily average temperature, ˚C
Tmean_mean	Weekly average of daily average temperature, ˚C
Tmean_min	Weekly minimum of daily average temperature, ˚C
Tmin_max	Weekly maximum of daily minimum temperature, ˚C
Tmin_mean	Weekly average of daily minimum temperature, ˚C
Tmin_min	Weekly minimum of daily minimum temperature, ˚C
AT_Tmax_max	Apparent temperature weekly values, calculated based on Tmax_max, ˚C
AT_Tmax_mean	Apparent temperature weekly values, calculated based on Tmax_mean, ˚C

Table S6. Warning criteria used in calculations

country	**Criteria for warning**	**Source**
Belgium	yellow level: Tmax ≥ 32 for at least 3 days; orange level: Tmax ≥ 35 for at least 3 days; red level: Tmax ≥ 40 for at least 3 days	Royal Meteorological Institute of Belgium (2022)
Netherlands	yellow level: Tmax ≥ 27 for at least 4 days or Tmax ≥ 35; orange level: Tmax ≥ 30 and Tmin ≥ 18 for at least 3 days; red level: Tmax ≥ 32 and Tmin ≥ 20 at least 3 days	Koninklijk Nederlands Meteorologisch Instituut (2015)
Sweden	notice: Tmax ≥ 26 for at least 3 days yellow: Tmax ≥ 30 for 3-4 days orange: Tmax ≥ 30 for at least 5 days or Tmax ≥ 33 for at least 3 days	Public Health Agency of Sweden (2022)
Romania	Tmax Alert: Tmax 35–38 °C, Maximum response: Tmax 35–40 °C	Casanueva et al. (2019)

Table S7. Ranking of temperature variables with respect to their explanatory power in the piecewise regression models. r^2 is the average value across all countries and societal variables.

Temperature variable	r^2
Tmax_mean	0.40
AT_Tmax_mean	0.39
Tmean_mean	0.39
Tmean_max	0.37
Tmax_max	0.36
AT_Tmax_max	0.34
Tmin_max	0.32
Tmin_mean	0.30
Tmax_min	0.29
Tmean_min	0.29
Tmin_min	0.23