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Assessing the effectiveness of the heat health warning system in preventing mortality in 15 German cities: A difference-in-differences approach

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ABSTRACT

Background: Heatwaves pose significant risks to human health. Implementing heat health warning systems (HHWS) has been widely adopted as a preventive measure. However, the effectiveness of the German HHWS in reducing mortality during heat episodes across different cities has scarcely been researched.

Objective: This study aimed to assess the effect of HHWS on mortality during heat episodes in 15 major cities in Germany and explore city-specific factors influencing the effectiveness of heat alerts.

Methods: Daily all-cause mortality data during the warm-season months (May to September) from 1993 to 2020 were linked with heat alert data and meteorological information. A difference-in-differences approach was employed to estimate the city-specific effects of heat alerts on mortality. In the second stage, *meta*-regression models were used to pool the city-specific estimates and examine the heterogeneity across cities.

Results: Substantial variation in the city-specific associations was observed, with some cities exhibiting significant reductions in mortality during heat episodes after the HHWS implementation while others showed no significant effect. The pooled relative risk (RR) from the second-stage analysis, based on the *meta*-variables averaged across all cities studied, suggested no overall significant protective effect of heat alerts on mortality (RR = 1.00, 95 % CI: 0.98 to 1.01). However, when controlling for the *meta*-variables *recreational area per person*, *total population*, and *population density*, we found a significant but small protective effect of heat alerts across all cities studied (RR = 0.85, 95 % CI: 0.75 to 0.97).

Conclusion: According to our results, the effectiveness of heat alerts varied considerably across the cities, suggesting the importance of considering city-specific factors, such as population size, population density, and the presence of blue and green urban infrastructure. Understanding these factors can help improve the effectiveness of HHWS and tailor interventions to address the specific characteristics of different urban areas within heat-health action plans.

1. Introduction

Heatwaves constitute a growing public health concern in the context of climate change, as they are globally increasing in intensity, frequency, and duration (Hess et al. 2023; Mücke and Litvinovitch 2020; Perkins-Kirkpatrick and Lewis 2020; Romanello et al. 2022). Exposure to extreme heat and the associated heat stress can cause adverse effects on human health and increase morbidity and mortality (Ebi et al. 2021). Risk groups include young children, adults older than 65 years, people with pre-existing cardiopulmonary and other chronic diseases, as well as

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outdoor workers (An der Heiden et al. 2020; Basagaña et al. 2011; Ebi et al. 2021; Sheffield et al. 2018). The extreme heatwave 2003 was associated with more than 70,000 premature deaths across 12 European countries (Robine et al. 2008). It highlighted the impact of extreme heat on mortality and the need for public health interventions to mitigate heat-related adverse health effects (Mücke and Litvinovitch 2020; Robine et al. 2008; Toloo et al. 2013). In Germany, the highest amount of heat-related deaths for the last three decades occurred in 1994, with 10,100 (95 % CI: 8,100 to 12,400) heat-related deaths, followed by 2003, with 9,500 deaths (95 % CI: 7,200 to 12,000) (Winklmayr et al. 2022). In the summer of 2022, one of the hottest seasons on record in Europe, Germany recorded one of the highest summer heat-related mortality numbers, with an estimated 8,173 heat-related deaths (95 % CI: 5,374 to 11,018) (Ballester et al. 2023). Huber et al. (2024) estimated heat-related deaths in Germany for the summer of 2022 at 9,100 (95 % CI: 7,300 to 10,700), using daily mortality and temperature data, whereas previous studies of the Robert Koch Institute (RKI) estimated the heat-related excess mortality at 4,500, using data on a weekly basis (Winklmayr and an der Heiden 2022).

As a result of the 2003 heatwave, the World Health Organization (WHO) Regional Office for Europe introduced a guidance on heat-health action plans (HHAP) in 2008 in order to protect human health from adverse heat affects through a portfolio of prevention and protection measures at different levels (Matthies et al. 2008). One key component of a HHAP is an accurate and timely heat health warning system (HHWS). Based on meteorological forecasts, a HHWS serves as tool to alert the public about temperature conditions that pose a risk to health. Consequently, the HHAP lead body and stakeholders shall be informed by the HHWS to trigger response actions according to the warning level as defined in the HHAP (Matthies et al. 2008; WHO Regional Office for Europe 2021). By 2019, 16 European HHWS had been reviewed (Basarin et al. 2020; Casanueva et al. 2019; Matzarakis et al. 2020). The HHWS in Germany was developed by the German Weather Service (Deutscher Wetterdienst, DWD) and implemented in 2005 (Matzarakis 2016; Matzarakis et al. 2020).

To assess the human thermal stress, the DWD calculates the thermal index perceived temperature (PT) based on the numerical weather forecast, using a standardized "Klima-Michel" or "Klima-Michel Senior", for elderly people, to model all mechanisms of energy exchange between human body and thermal environment. Short-term heat acclimatization is considered by adjusting the thermal stress thresholds through stored PT values of the past 30 days (Casanueva et al. 2019; Matzarakis et al. 2020). Since 2007, the HHWS was extended to include a building simulation model to estimate the nocturnal indoor thermal conditions, as most people spent the night indoors (Pfafferott and Becker 2008). For cities with more than 100,000 inhabitants an urban heat island effect (UHI) was added to the meteorological forecast to represent the nocturnal conditions of urban areas more precise (Matzarakis et al. 2020). The automatically generated warning proposals are published only with the confirmation and with possible adjustments of a biometeorologist. The heat health warnings for German counties are directed at governmental authorities, ministries of the federal states, nursing homes, and the general public. The heat alerts are disseminated electronically via the internet, subscription newsletters, smartphone applications, and On the DWD website (https://www.dwd.de), heat alerts are displayed in maps linked to explanatory text. This text provides information on the expected intensity of heat stress, the affected altitude range, additional details for the elderly and urban areas when relevant, and recommendations for health-protective behavior. This textual information is also part of all mentioned dissemination ways. The warning also provides information on the duration (number of days) the heat alert has been active. Additionally, mass media (radio and television) can broadcast the warning, making it more widely known to the public. This usually prompts conventional and electronic print media to publish further reports and offer advice on how to protect one's own health as well as that of others in need of care (Matzarakis et al. 2020). A smartphone application was introduced in 2012/2013, as the general weather app (Warnwetterapp) of the German Weather Service. A more specific application focusing on potentially adverse health impacts (named "Gesundheitswetterapp") followed in 2020. The heat warnings are also included in the Emergency Information and Warning App (NINA) of the Federal Office of Civil Protection and Disaster Assistance. More information about the updated German HHWS can be found elsewhere (Matzarakis et al. 2020).

For Germany there is a harmonized guidance for the implementation of HHAPs since 2017 (Federal Ministry for the Environment Nature Conservation Building and Nuclear Safety 2017) and a national heat protection plan issued by the Federal Ministry of Health since 2023 (Federal Ministry of Health 2023). Even though Germany has a implemented and updated HHWS, which could be used in HHAPs as already existing system (Matthies et al. 2008), HHAPs or public health actions following heat alerts are still not systematically and comprehensively implemented across federal states, municipalities and cities (Janson et al. 2023; Kaiser et al. 2021; Matthies-Wiesler et al. 2021). Due to the scarcity of comprehensive data on implemented HHAPs or public health actions following heat alerts, our study explicitly accounts for the HHWS only.

Urban populations are especially exposed to heat due to the urban heat island (UHI) effect, which represents the temperature difference (sometimes up to 10 °C) between an urban area and the surrounding rural areas (Hannemann et al. 2023; Menberg et al. 2013). In Germany, up to 68.1 % of the population lives in urban areas (Taubenböck et al. 2022), and the degree of urbanization is expected to increase further in the coming decades (United Nations (UN) 2018). During extreme heat events, the local UHI effect is superimposed on the regional temperature, increasing the severity of the extreme event (Gabriel and Endlicher 2011). In addition, UHI can affect the association between high temperatures and mortality (Cuerdo-Vilches et al. 2023; Goggins et al. 2012). It is, therefore, of particular interest to investigate the protective effect of HHWS on mortality during heat episodes in urban populations (Gabriel and Endlicher 2011).

Despite implementing the HHWS and other measures to protect human health from heat, high temperatures in the warm-season months still take their toll on human health and mortality. Therefore, it is essential to evaluate the effectiveness of the HHWS on mortality during heat episodes and to identify socioeconomic and environmental factors that might modify the effect. While some previous studies examined the association between HHWS (Heudorf and Schade 2014; Morabito et al. 2012; Toloo et al. 2013) or HHAPs (de'Donato et al. 2018; Fouillet et al. 2008; Heudorf and Schade 2014) and mortality, mainly by pre-post analyses, very few studies used a quasi-experimental design to estimate the effect of HHWS or HHAPs on mortality. A quasi-experimental method already applied in this context is the difference-in-differences (DID) approach. The results of studies using a DID approach range from protective effects to no detectable effect of heat alerts or HHAPs on mortality in Canadian and US cities (Benmarhnia et al. 2016; Weinberger et al. 2018; Wu et al. 2023). In particular, HHAPs appear to have a greater protective impact for specific subgroups, such as people 65 years and older (Benmarhnia et al. 2016). Varying effects were also evident at the city level (Weinberger et al. 2018). To the best of our knowledge, no such studies exist for Germany or any other European country.

To address this research gap (Heudorf and Schade 2014), we used a DID approach combined with random forest classification to assess the effects of heat alerts on all-cause mortality in Germany's 15 most populated cities. Our specific aims were (i) to examine whether the city-specific DID estimators suggest a protective effect of heat alerts on mortality during heat episodes in the respective city, and (ii) to pool the city-specific effects and examine potential heterogeneity between the city-specific estimators based on city-specific socioeconomic and environmental characteristics as well as the presence of geographical dependencies.

2. Materials and methods

2.1. Data sources

2.1.1. Mortality data

We used the daily counts of all-cause deaths from the Research Data Centres of the German Statistical Offices for the 15 largest German cities between 1993 and 2020 (Berlin, Bremen, Cologne, Dortmund, Dresden, Duisburg, Dusseldorf, Essen, Frankfurt am Main, Hamburg, Hannover, Leipzig, Munich, Nuremberg, and Stuttgart). There were no missing values for the study period.

2.1.2. Meteorological data

We obtained daily observations of mean, minimum, and maximum air temperature (°C), mean relative humidity (%), and daily mean specific humidity (gram of water vapor/ kilogram of humid air) for each city measured at DWD stations from 1993 to 2020 (Deutscher Wetterdienst (DWD) 2023) (Table A.1). The thermal index perceived temperature (PT) is an important thermal index used in the German HHWS (Matzarakis et al. 2020). As neither the PT data nor the exact PT calculation models were available to us, we calculated the daily apparent temperature (Kalkstein and Valimont 1986; Steadman 1979) for daily mean and maximum air temperature using an algorithm of Lanzinger et al. (Lanzinger et al. 2016). We consider the apparent temperature the best available approximation of PT. All meteorological variables utilized in the analyses, including the number of missing values, are summarized in Table A.2 (Matzarakis et al. 2020).

2.1.3. Heat alert data (2005–2020)

Official heat alerts for each city were also obtained from the DWD for 2005 to 2020 on daily basis. Except for Hannover (Hannover region) and Munich (city with a district), all districts in which the cities were located were urban. The dataset included information on the district name, the corresponding federal state, the date of the heat alert, and the warning level (1 = strong and 3 = extreme heat stress). As the thresholds for the warning levels were region-specific and took acclimatization into account, we only distinguished between days with and without heat alerts (Casanueva et al. 2019; Deutscher Wetterdienst (DWD), 2021). No further distinction was made according to the warning level.

2.1.4. Metavariables (city-level characteristics)

We obtained annual records of ten socioeconomic variables from the INKAR database for each city from 1995 to 2020 and five environmental variables per city from 2016 to 2020 (Bundesinstitut für Bau- Stadt- und Raumforschung (BBSR) 2023) (for details, see Table A.3). For the years 1993 and 1994, we extrapolated the following variables: total number of inhabitants, the proportion of inhabitants aged 65 years and older (in %), and mean life expectancy of a newborn in years, based on the mean change observed in the subsequent two years. Additionally, we included the German Index of Socioeconomic Deprivation (GISD) as a socioeconomic variable, which is based on the three dimensions of occupation, education, and income from the INKAR database (Michalski et al. 2022).

2.2. Study design and statistical analysis

We used an extended two-stage design for environmental research to firstly estimate the city-specific effects of heat alerts on all-cause mortality during heat episodes by a DID approach and secondly pool these city-specific effects in a *meta*-regression (Sera and Gasparrini 2022).

2.2.1. Difference-in-differences approach (first-stage analyses)

In the DID approach, all-cause mortality for the population of each city was compared before and after HHWS implementation in 2005 on so-called 'eligible' (hot) and 'non-eligible' (non-hot) days during the warm season (May to September). After implementing the HHWS (2005–2020), eligible days corresponded to days with a heat alerts forecast, and days were classified as non-eligible if no heat alert forecast was issued on this day. For the classification of eligible and non-eligible days before the implementation of the HHWS (1993–2004), we implemented a random forest classification algorithm, based on observed meteorological data. Based on a set of meteorological variables, the algorithm identified eligible (hot) days on which heat alerts would have most likely been issued if the HHWS had already been implemented at the time (for details, see Appendix A. Random forest classification and Fig. A.1). The effect of the heat alerts on the all-cause daily death count per city was estimated as the difference in daily mortality between eligible days and non-eligible days before the HHWS implementation compared to the difference between eligible days and non-eligible days after HHWS implementation. Therefore, the counterfactual quantity of interest was the difference in the daily death count between eligible days and non-eligible days that would have been observed during 2005–2020 if the HHWS had not been implemented (Benmarhnia et al. 2016).

Key assumptions of the DID analysis are that i) the implementation of the HHWS was the only intervention that might have caused a change in the association between heat and mortality before and after HHWS implementation, and that ii) before the HHWS implementation, eligible and non-eligible days have parallel trends in the outcome mortality. The second assumption means that the trend in the mortality observed during non-eligible days is a good approximation of the counterfactual trend in the mortality, which would have been observed during eligible days without HHWS implementation (Abadie and Cattaneo 2018; Alari et al. 2021). The trends in pre-HHWS period are optimally parallel, but presumably not congruent, as the eligible days are expected to be hotter with a subsequent more death attributable to heat than non-eligible days. To test the parallel trend assumption in the DID analyses, we plotted the daily mortality for eligible and non-eligible days during the pre-HHWS and post-HHWS periods, including linear trendlines for each group (Fig. A.2). If the lines appeared to be approximately parallel in the pre-HHWS period, we assumed the parallel trend assumption to be fulfilled for the respective city (Wing et al. 2018). Subsequently, in the second-stage analyses, a distinction was made between all cities and the subset of cities appearing to fulfill the parallel trend assumption.

City-specific DID quasi-Poisson models with an offset (total number of inhabitants per year) were used to estimate the effect of heat alerts on daily all-cause death counts. Based on previous literature, the models were adjusted for temporal patterns (day of the week, year, day of the year, and date), daily mean temperature, and relative humidity (Barreca 2012; Benmarhnia et al. 2016). We incorporated relative humidity as a control variable instead of specific humidity (Davis et al. 2016) due to much fewer missing values and a weaker correlation with mean temperature compared to specific humidity (Fig. A.3). The formula for the DID main model per city is provided in Appendix A (formula DID main model).

The DID estimate represents the adjusted interaction term between the estimated effect of eligible versus non-eligible days, and the estimated effect of the pre-HHWS (1993–2004) versus post-HHWS (2005–2020) period. To estimate non-parametric 95 % confidence intervals (CI) and variance for the adjusted DID estimates, we employed bootstrapping with 1000 samples (Carpenter and Bithell 2000). To provide a simplified interpretation of the results, we report the relative risks (RR). A RR of less than one indicates a decrease in daily mortality attributable to heat alerts, interpreted as evidence that due to alerts people protect themselves or are protected adequately from heat. If the HHWS is ineffective in reducing mortality during heat episodes, for example, by not reaching vulnerable people with heat alerts, the RR would be greater than or equal to one.

2.2.2. Meta-regression (second-stage analyses)

In the second stage, we used *meta*-regression models to pool the city-specific DID estimates and to examine (part of) the observed heterogeneity across the cities and potential geographical dependencies. In all second-stage models, the city-specific DID estimators of the first-stage analyses were used as outcome variables, and the models were fitted using maximum likelihood estimation (MLE).

We compared four different *meta*-regression models (Model 0 to Model 3). Model 0 was a basic *meta*-regression model with no predictors, only intercepts, and one random effect per city to account for potential differences between the cities. Model 1 included two levels of random effects (cities nested within federal states) to examine the presence of geographical dependencies, specifically whether cities within the same federal state (Bundesland) exhibited more similarity than cities in different federal states. Model 2 was a mixed-effect regression model, adding fixed-effect *meta*-variables to model 0 to identify environmental and socioeconomic factors that possibly explain a quota of heterogeneity by being associated with the effectiveness of heat alerts on mortality. We employed a stepwise procedure, guided by the Akaike information criterion (AIC), to select the best set of 16 *meta*-variables. In the analyses described, the arithmetic mean of all given values in the study period per city was included for each of the 16 environmental and socioeconomic (meta-) variables (for more detailed information, refer to Table A.4). Model 3 was the same as Model 2, but with two levels of random effects (as in Model 1). We assessed heterogeneity in all four models using the Cochrane Q Test of Heterogeneity. Considering that the variables *population* and *population density* could be correlated (Figs. A4 and A.5), we additionally examined the presence of multicollinearity by calculating the variance inflation factor (VIF) for models 2 and 3. The final second-stage model was selected based on AIC and Bayesian information criterion (BIC).

The DID effect estimate pooled across cities (expressed as RR) was the prediction from the final *meta*-regression model based on the averages of the selected *meta*-variables across cities. We also reported the intercept of the final model as an alternative pooled estimator, which controls for the identified *meta*-variables.

2.2.3. Sensitivity analyses

As a sensitivity analysis, we first tested an alternative definition, only based on observed data, of "eligible" and "non-eligible" days to assess the robustness of the chosen approach. For this purpose, we defined "eligible" days only based on the random forest classification for the entire study period (warm-season months of 1993–2020). Second, we were more restrictive in defining non-eligible days by considering only days on which temperature and relative humidity were above predefined thresholds. The thresholds were the minimum values of daily mean, minimum, and maximum temperature, as well as of relative humidity of the "eligible" days throughout the study period. Third, we defined shorter study periods, specifically the warm-season months of May to September, for *a)* three years (2002–2007); *b)* five years (2000–2009); and *c)* 10 years (1995–2014) before and after HHWS implementation in 2005. Fourth, to test the potential impact of years with extreme heat exposure, we excluded *a)* all and *b)* one of the six years with the highest counts of heat-related deaths from 1993 to 2020 (specifically, 1994, 2003, 2006, 2015, 2018, 2019) according to (Winklmayr et al. 2022).

We tested several modifications to assess the quasi-Poisson first-stage model's robustness. These included fitting the first-stage model a) without any adjustments (basic DID model), b) adjusting only for temporal patterns, c) adjusting for temporal patterns, relative humidity, and daily maximum temperature, d) adjusting for temporal patterns, relative humidity, and the running mean of the mean temperature of the previous three days. Furthermore, we fitted our first-stage model e) without an offset, and f) additionally adjusted, besides temporal patterns, relative humidity, and mean temperature, for the proportion of inhabitants 65 years and older and the life expectancy in years. The DID estimators obtained from the sensitivity analyses were pooled using the same *meta*-regressions as in the main second-stage model. Finally, we performed two linear regression models as a complementary analysis with the daily mortality rate per 100,000 inhabitants as the outcome variable (dividing the number of daily deaths by the population per city). One linear regression model was fitted without any adjustments (basic DID model). The second linear model included adjustments for temporal patterns, mean temperature, and relative humidity, similar to the main quasi-Poisson model.

All analyses were conducted using R software (version 4.2.3). For second-stage analyses, the R package 'mixmeta' was used (Sera et al. 2019).

3. Results

3.1. Descriptive statistics

During the study period from 1993 to 2020, a total of 1,731,269 all-cause deaths occurred in the warm-season months of May to September. The average number of daily deaths was 26.9 for all cities, ranging from a minimum of 3 deaths per day to a maximum of 266 deaths. Munich had the lowest mean mortality rate (2.51 per 100,000 inhabitants) throughout the study period, while Essen had the highest mortality rate, followed by Leipzig and Nuremberg (3.67, 3.41, and 3.21 per 100,000 inhabitants). Within the study period, a percentage of 5.66 % eligible days (3,635 out of 64,260 days) occurred. The mean yearly number of eligible days was higher in the post-HHWS period (144 days) compared to the pre-HHWS period (112 days) (Table 1). Among the 15 cities, Hamburg had the fewest number of eligible days (164 days), followed by Bremen (178 eligible days). In contrast, Stuttgart had the highest number of eligible days (355 days), with Frankfurt having the second-highest number (334 eligible days). Among eligible and non-eligible days, the arithmetic means and interquartile ranges of daily mean, maximum and minimum temperature were very similar in the pre- and post-HHWS period (Table 1). Descriptive statistics for each city, including the actual number of heat warnings issued, are outlined in Tables A.5 to A.19 in the Appendix.

In the graphical assessment of the parallel trend assumption during the pre-HHWS period, we observed very similar trends in mortality on eligible and non-eligible days for the cities of Bremen, Duisburg, Essen, Frankfurt, Hannover, Munich, and Nuremberg. Conversely, the assumption appeared to be violated for Berlin, Cologne, Dortmund, Dresden, Dusseldorf, Hamburg, Leipzig, and Stuttgart. Outliers in both groups of eligible and non-eligible days appeared to affect the trendlines and limited the conclusiveness of the graphical verification of the parallel trend assumption (Fig. A.2). Consequently, our subsequent analyses differentiated between all cities and the seven cities with very similar mortality trends before 2005.

3.2. City-specific effects of heat alerts on mortality

Among the 15 cities analyzed, six cities showed RRs of less than one, while the RRs of nine cities were greater than or equal to one (Fig. 1; Table A.20). Notably, Berlin exhibited a statistically significant RR of less than one (RR = 0.95, 95 % CI: 0.91 to 0.99, p-value < 0.01), suggesting a significant reduction in mortality due to heat alerts. Additionally, Frankfurt (RR = 0.94, 95 % CI: 0.88 to 1.00, p-value < 0.05) and Hamburg (RR = 0.95, 95 % CI: 0.90 to 1.00, p-value < 0.05) demonstrated significant RRs of less than one, while Duisburg showed a significant RR greater than one (RR = 1.09, 95 % CI: 1.01 to 1.18, p-value < 0.05). Among the seven cities fulfilling the parallel trends assumption, two cities had RRs of less than one, while five cities had RRs greater than or equal to one. Specifically, Frankfurt exhibited a statistically significant RR of less than one, and Duisburg showed a significant RR greater than one.

3.3. Pooled effects of heat alerts on mortality

The basic *meta*-regression random effects models (Model 0) produced pooled estimates without adjustment for city-specific characteristics, representing the average association between heat alerts and mortality

Table 1
Descriptive statistics pre- and post-heat health warning system (HHWS) period for eligible and non-eligible days.

Variables *, **, ***	Pre-HHWS period (1993–2004)				Post-HHWS period (2005–2020)			
	Non-eligible days (n = 26,152)		Eligible days (n = 1,339)		Non-eligible days (n = 34,424)		Eligible days (n = 2,296)	
Number of days per year	2,179.3		111.6		2,151.5		143.5	
Daily number of all-cause deaths (IQR)	26.9	(15.0–29.0)	31.1	(17.0–31.0)	26.6	(15.0–29.0)	30.5	(18.0–33.0)
Mean temperature [°C (IQR)]	16.1	(13.6–18.9)	24.6	(23.6–25.9)	16.6	(14.0–19.1)	24.6	(23.1–26.1)
Maximum temperature [°C (IQR)]	21.0	(17.8–24.5)	31.6	(30.2–33.2)	21.7	(18.5–24.9)	31.8	(29.7–33.7)
Minimum temperature [°C (IQR)]	11.6	(9.2–13.9)	17.7	(16.4–18.8)	11.6	(8.9–13.9)	17.5	(16.0–18.8)
Relative humidity [% (IQR)]	72.0	(64.0–81.0)	58.0	(51.0–66.0)	72.0	(63.6–80.0)	59.0	(52.0–68.0)
Apparent temperature [°C (IQR)]	22.0	(17.9–26.6)	36.2	(34.5–38.3)	23.0	(18.8–27.4)	36.8	(34.3–39.2)

* Median values, followed by the interquartile range (IQR), are provided for each continuous variable except the daily number of all-cause deaths.
** For daily number of all-cause deaths, mean values are provided, followed by the interquartile range (IQR).
*** For number of days per year, mean values are provided.

across the 15 and seven cities. This basic model showed a moderate heterogeneity across all cities and the seven cities fulfilling the parallel trend assumption (Table 2). The observed heterogeneity cannot be accounted for by grouping into federal states (Model 1) since the multilevel models (Model 1) showed similar or higher heterogeneity compared to the basic models (Model 0). The final second-stage model, explaining most of the observed heterogeneity, was the stepwise selected multiparameter model (Model 2). It included the metavariables *recreational area per person*, *total population*, and *population density* as predictors for all cities and the metavariables *water area* and *total population* for the subset of the seven cities (Table 2). No protective effect was found for the pooled RR predicted based on the average of the identified *meta*-variables, neither for all cities (RR = 1.00, 95 % CI: 0.98 to 1.01) nor the seven cities fulfilling the parallel trend assumption (RR = 1.01, 95 % CI: 0.98 to 1.03). By contrast, a significant but small protective pooled effect (intercept of the final second-stage model) was found across all cities (RR = 0.85, 95 % CI: 0.75 to 0.97) and the subgroup of the seven cities (RR = 0.90, 95 % CI: 0.81 to 0.99), when adjusting for the identified city-specific *meta*-variables.

3.4. Sensitivity analyses results

The random forest classification analyses and the analyses with restrictions in the group of non-eligible days did not result in substantial changes in the effects compared to the main model. The only difference concerned the pooled RR (intercept of the *meta*-regression model) for the seven cities, which was no longer significant using a more restrictive definition of non-eligible days (Fig. 2; Table A.21 and A.22). Shortening the study periods led to a smaller pooled RR for all cities, whereas the pooled RR for the seven cities meeting the parallel trend assumption showed little changes (Fig. 2; Tables A.23 to A.25). When excluding the six years with the highest number of heat-related deaths from 1993 to 2020, the pooled RR of the seven cities remained robust, while the pooled RR of all cities lost significance (Table A.26). When excluding each of the six years with extreme heat episodes in turn, the exclusion of 2003 and 1994 revealed the greatest changes in effect size on city-level. The exclusion of 2003 revealed an RR increase, especially in Cologne, Dortmund, Dusseldorf, Frankfurt, and Stuttgart. The exclusion of 1994 revealed an RR increase, especially in Berlin, Bremen, Dresden, and Hamburg (refer to Tables A.27 to A.32 and Fig. A.7). The pooled RR remained robust, when excluding each of the six years, except for 2003, where the pooled RR of all and the seven cities lost significance. Nevertheless, the pooled RR of the cities fulfilling the DID assumptions demonstrated consistently high robustness in the sensitivity analyses, with pooled RR (intercept of the *meta*-regression model) ranging from 0.85 (95 % CI: 0.76 to 0.96) to 0.92 (95 % CI: 0.83 to 1.02).

We tested several modifications of the first-stage quasi-Poisson model, and the city-specific and pooled results remained highly consistent (Fig. A.6; Tables A.33 to A.38), indicating the robustness of our first-stage model. The results of the additional linear analyses further confirmed the robustness of the city-specific findings. Although the effect sizes of the DID estimators from the linear models could not be directly compared to the quasi-Poisson models, it was evident that the same city-specific estimators became significant, and the effect directions were highly similar (see Tables A.39 and A.40).

4. Discussion

This study is one of the first comprehensive studies examining the impact of heat alerts on mortality in 15 major German cities. The results of the first-stage analyses revealed substantial heterogeneity in the effectiveness of the HHWS in preventing deaths on hot days across cities. This variability was evident in both the full set of cities and the subgroup of cities fulfilling the parallel trends assumption of the difference-in-differences (DID) approach. Our pooled findings indicated no significant overall protective effect, or a significant but small protective effect of heat alerts on all-cause mortality across the studied cities.

These inconsistent results align with previous conflicting evidence on the effectiveness of HHWS in preventing mortality. Some studies have reported a reduced heat-related mortality after implementing a heat alert system (Fouillet et al. 2008; Heudorf and Schade 2014; Morabito et al. 2012) or heat prevention plans (de'Donato et al. 2018; Hess et al. 2018; Martínez-Solanas and Basagaña 2019; Schifano et al. 2012). By contrast, a study from Adelaide, for example, provided no evidence of a reduction in mortality but a significant reduction in morbidity after implementing a heat alert system (Nitschke et al. 2016). However, these studies may be susceptible to confounding due to factors changing over time, other than the implementation of heat alert systems or heat health action plans (HHAPs), such as structural adaptation measures (for example, higher air conditioning prevalence), changes in baseline health status, or shifting in socioeconomics (Weinberger et al. 2021; Weinberger et al. 2018). To avoid this form of confounding, a few studies, including this one, compared days with and without heat alerts while adjusting for time-varying factors (Benmarhnia et al. 2016; Weinberger et al. 2021; Weinberger et al. 2018). Two of these studies examined the effectiveness of National Weather Service heat alerts in preventing mortality in 20 US cities and among adults aged 65 and over in the United States. Both studies found no evidence of an association between heat alerts and reduced mortality, except for Philadelphia (Weinberger et al. 2021; Weinberger et al. 2018).

In addition to our study, a DID approach has been applied in a Canadian and a Korean study (Benmarhnia et al. 2016; Heo et al. 2019). While in the Canadian study the effect of heat action plans (HAPs) on mortality was assessed, stratified by sex, age, and socioeconomic status (Benmarhnia et al. 2016), the Korean study focused on the effect of a heat wave warning system on all-cause mortality across various subgroups (Heo et al. 2019). Given these methodological differences, direct comparisons between our findings and those of these studies are limited. The Canadian study reported that the reduction in mortality attributable to HAPs was more pronounced among elderly people and residents of low-education neighborhoods (Benmarhnia et al. 2016). In contrast, in the Korean study evidence was found for a decrease in all-cause

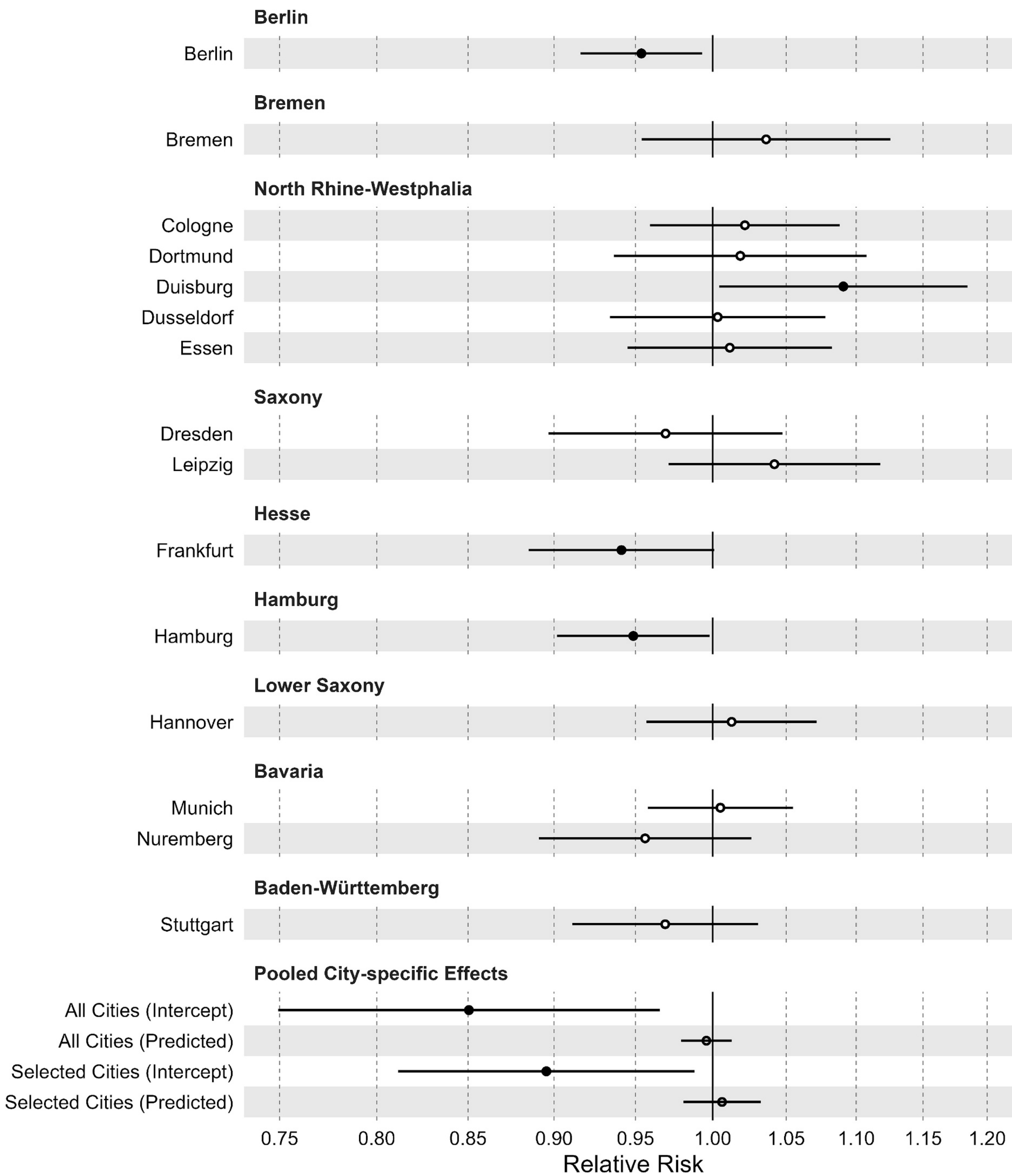

Fig. 1. City-specific and pooled estimates of relative risk (RR) from the first-stage quasi-Poisson models and the second-stage *meta*-regression (bottom), for all cities and the seven cities fulfilling the DID parallel trends assumption (selected cities), with 95 % confidence intervals. RR < 1 suggests that the implementation of the heat health warning system (HHWS) reduced all-cause mortality during heat episodes. RR ≥ 1 suggests no protective effect of the HHWS. Filled symbols show significant estimates ($p < 0.05$), open symbols non-significant results.

mortality for the subgroup of people aged 19–64 without education (−0.144 deaths per 1,000,000 people, 95 % CI: −0.227 to −0.061) and for children aged 0–19 (−0.555 deaths per 1,000,000 people, 95 % CI: −0.993 to −0.117). Unlike our study and the Canadian study, the Korean study did not compare pre- and post-implementation periods of the heat alert or HAP in DID analyses. Instead, Heo et al. (2019) used the discrepancy between the alerts and the monitored temperature, distinguishing between correct and incorrect forecast.

Our observations of heterogeneous city-specific effects were consistent with studies from the US, which also observed heterogeneous effects of heat alerts on mortality in different spatial units (Weinberger et al. 2018; Wu et al. 2023). More specifically, the estimated effect of HHWS on mortality for Frankfurt was in qualitative agreement with Heudorf and Schade (2014), who found a decreased excess mortality during heat waves after the implementation of a HHWS and HHAP in that city. Further evidence on initial evaluations of the HHWS is given for the state of Hessen (where Frankfurt is located), showing that the HHWS effectively reduced hospital admissions among residents of elderly care and nursing homes with heat-related symptoms (Koppe 2009). Although the DWD uniformly disseminated the heat alerts via various channels

Table 2

Results of the second-stage random-effects *meta*-regression models: Basic and final multiparameter models based on city-specific difference-in-differences (DID) estimators for all cities and the seven cities fulfilling the DID parallel trend assumption (selected cities).

Model	Coefficient	Relative Risk	95 % CI*	p-Value*	I-squared	AIC	BIC
Basic model (all cities)	(Intercept)	0.99	[0.97,1.01]	0.41	35.24 %	− 50.46	− 49.04
Final model (all cities)	(Intercept)**	0.85	[0.75,0.97]	< 0.05	0.00 %	− 57.40	− 53.86
	Recreational area	1.00	[1.00,1.01]	< 0.01			
	Population	1.00	[1.00,1.00]	< 0.01			
	Population density	1.00	[1.00,1.00]	0.06			
Basic model (selected cities)	(Intercept)	1.00	[0.97,1.03]	0.90	43.18 %	− 20.29	− 20.40
Final model (selected cities)	(Intercept)**	0.90	[0.81,0.99]	< 0.05	0.00 %	− 23.98	− 24.20
	Water area	1.02	[1.01,1.03]	< 0.01			
	Population	1.00	[1.00,1.00]	0.12			

* Parametric 95% confidence interval and p-value of the relative risk of each estimate.

** Intercepts of the final models represent the pooled estimates.

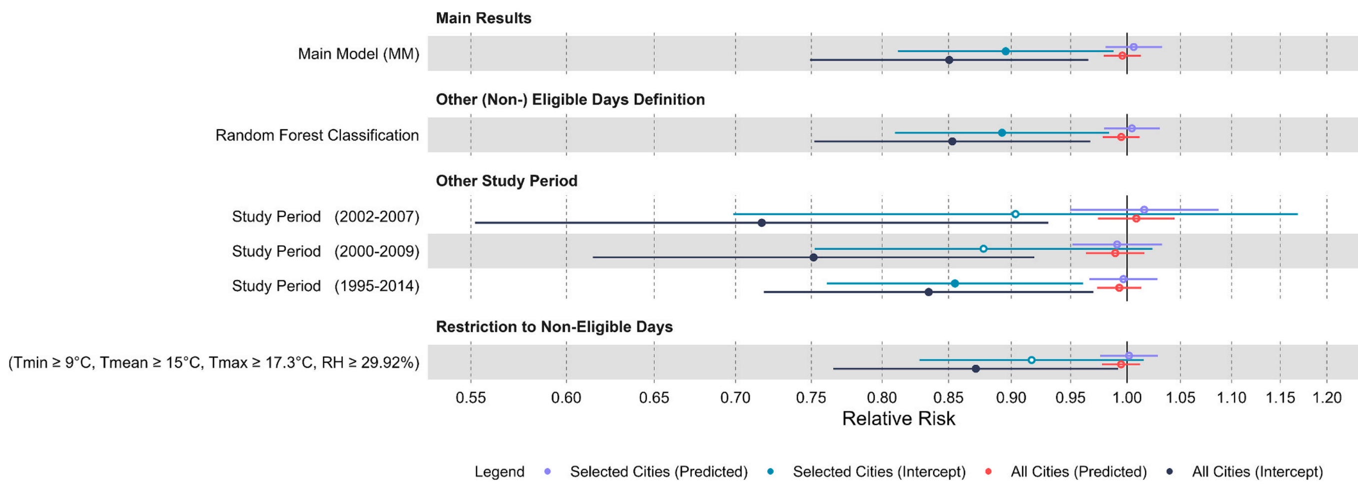

Fig. 2. Pooled relative risks (RR) of the sensitivity analyses for all cities (intercepts of the meta regression: black, predicted RR based on the average of the meta variables across all cities: red) and the seven cities fulfilling the DID parallel trends assumption (intercepts: turquoise, predicted RR: purple), with 95 % confidence intervals. Filled symbols show significant estimates ($p < 0.05$), open symbols non-significant results.

(Matzarakis et al. 2020), where interested parties could directly inform themselves, there were differences in heat alert dissemination at the state level. For example, an evaluation study by the German Federal Environment Agency of Germany found that only six federal German states disseminated heat alerts to healthcare facilities at their own responsibility (Capellaro and Sturm 2015). However, we could not explain the observed heterogeneity with more similarity for cities nested within the same state.

Another factor that may contribute to the observed heterogeneity in the first-stage results is the local implementation and quality of HHAP or other designated concepts with measures to protect human health from heat effects. Although all 15 cities have published measures for the protection of human health against heat, it cannot be assumed that all measures have actually been implemented (Hannemann et al. 2023). In addition, there is a significant heterogeneity in the comprehensiveness and scope of the published measures (Hannemann et al. 2023; Winklmayr et al. 2023). Even though there is no detailed information available on which actions have been put in place and where, it can be assumed that some heat health action was carried out beyond the mere heat health warning. This lack of this information may be based in the lack of a clearly defined responsibilities in heat health protection on national, federal and local levels and the resulting heterogeneity of approaches and measures in Germany (Matthies-Wiesler et al. 2021). This means, that it cannot be disentangled in how far the identified effects of heat alerts on mortality during heat episodes are linked to the HHWS and the alerts alone, or whether they are connected to the way the heat alerts are disseminated and integrated with respective heat health actions, such as information campaigns. It can also be expected that general awareness and understanding of heat related health risks have increased in the population over the last 20 years, since the HHWS has first been established. While these aspects go beyond the scope of this study, further research can help to differentiate the effects of HHWS alerts with regard to their coverage in reaching the population and the connection with respective heat health messages and measures. Hence, investigations assessing the awareness, knowledge, attitude and practice of the population, including vulnerable population groups, can shed more light on potential factors influencing the effectiveness of heat alerts. One example of such an investigation is the PACE study, providing information on public awareness and perception of heat-related health risks (Lehrer et al. 2024). Furthermore, the existing HHAPs and heat health measurements have yet to be evaluated; therefore, the effect of these on heat-related mortality and morbidity remains unclear (Blättner et al. 2020; Hannemann et al. 2023).

Our *meta*-analysis suggested that the city-specific proportion of water area and recreational area per person (predominantly green area), in addition to population size and population density, may be associated to the effectiveness of heat alerts on mortality, explaining a large part of the observed heterogeneity in city-specific effects. Comparing these second-stage results with other results in similar contexts is difficult because of the lack of comparable studies. In the study of Weinberger et al. (Weinberger et al. 2018), second-stage *meta*-regression models were applied to explain variability in heat alert effectiveness across 20 US cities but with different city-level characteristics. Thereby, no association was found between the metavariables mean daily maximum heat index, air conditioning prevalence, percent of inhabitants 65 years and older, percent of heat alerts published as excessive heat warnings, and the effectiveness of heat alerts (Weinberger et al. 2018). Previous studies on the modification of heat-related mortality by urban green or blue (water) indicated a protective effect of these variables on heat-related mortality (Burkart et al. 2016; Choi et al. 2022). In contrast, a study from Hong Kong found no significant protective effects of green and blue infrastructure on heat-related mortality risk (Song et al. 2022). Still, assuming the general protective effects of green and blue infrastructure on heat-related mortality in the studied cities, this could lower the effect of heat alerts on mortality on heat days. These theoretical considerations could explain our results: the more green and blue infrastructure were present, the higher the RR, because the population was comparatively well protected from heat independent of the existence of a HHWS. Regarding population size, it is remarkable that cities with more inhabitants are better positioned to receive external funding, including EU funds, to initiate and implement measurements (Hannemann et al. 2023; Otto et al. 2021) to protect human health from heat, which might increase the protective effect of heat alerts. However, the variables *population size* and *population density* showed inconsistent effects in terms of direction and significance in the final second-stage models.

One strength of this study is the application of a DID design, which is generally well-established in public health research (Dimick and Ryan 2014; Wing et al. 2018). Although the DID approach is not a perfect replacement for randomized experiments, it can help understand the causal relationship between heat alerts and mortality on heat days (Wing et al. 2018). In applying the approach, one of the most challenging tasks is to assess the credibility of the assumption of common trends (Wing et al. 2018). Unlike the studies from Montreal and Korea (Benmarhnia et al. 2016; Heo et al. 2019), we sought to validate the parallel trends assumption with graphical evidence, following the approach of a study of Alari et al. (2021). The graphical verification indicated that for eight of the 15 cities, the city-specific trends in mortality in eligible and non-eligible days were not approximately parallel in the pre-HHWS period (1993–2004). Contrary to the study of Alari et al. (2021), we did not exclude these cities from further analysis. However, we reported the results separately, as the year-to-year variation of mortality during eligible and non-eligible days was high, which was consistent with observations on mortality during heat episodes in the respective period in Germany (Winklmayr et al. 2022). A second strength of our study is that we devoted more attention to sensitivity analyses, assessing the key assumptions that support the research design's internal validity, as the year-to-year mortality variation was high (Wing et al. 2018). Overall, the city-specific and pooled effects appeared robust in sensitivity analyses, especially the estimator of the seven cities, where the graphical evaluation supported the given parallel trends assumption. However, the sensitivity analyses generally supported a high internal validity of the applied DID models, especially for the selected cities (Wing et al. 2018).

The most important limitation of our study was that we were unable to analyze subgroups or further outcomes, for example cause-specific mortality or hospital admission due to the aggregated mortality data. Other studies have shown that specific subgroups vulnerable to heat, such as children and older adults, seem to benefit more from heat alerts (Benmarhnia et al. 2016; Heo et al. 2019). As the first-stage analyses do not require any adjustments for age or sex to determine the city-specific DID estimators, these are still valid given the DID assumptions. The results point out that the estimator for the seven cities, where the graphical evaluation supported the given parallel trends assumption, was more robust than the all-cities estimator. This could indicate a violation of the DID assumptions for the eight cities, where the graphical evaluation did not support the parallel trends assumption, may leading to a biased all-cities estimator. Additionally, a possible prediction error, resulting from the fact that alerts are issued based on weather forecasts, could have contributed to biases in the DID estimators (Heo et al. 2019). Further studies are needed to examine this prediction error and its impact on the effect of heat warnings on mortality. Another important limitation of our study was that we did not analyze lagged effects. While there is a risk of ecological fallacies due to the partly high level of aggregation (Roumeliotis et al. 2021), this study provides initial evidence of city-level characteristics that modify the effect of heat alerts on mortality during heat episodes. We were unable to address the heat-health action plans (HHAP) in the analyzed cities and could not determine to what extent the inhabitants are informed about heat alerts and respective preventive and protective measures. Nevertheless, we focused on one core element indicated by the WHO for the successful implementation of HHAPs: The HHWS (Matthies et al. 2008; WHO Regional Office for Europe 2021; WMO and WHO 2015). Further research is required to explore this further.

5. Conclusion

Our research concludes that the implementation of a heat health warning system (HHWS) in Germany in 2005 has contributed to a significant but small decrease in mortality during heat episodes across 15 German cities, once inter-city differences in the number of inhabitants, population density and the presence of blue and green urban infrastructure are controlled for. However, our first-stage results indicate considerable heterogeneity in the city-specific effects of heat alerts, ranging from significant protective effects to significant ineffectiveness. Our results can be useful for cities and municipalities when developing and implementing HHAPs. They suggest that the effect of city-specific factors together with heat alerts need to be considered when developing measures for the core element of long-term urban planning to reduce heat exposure. Future research will need to elucidate whether HHWSs unfold their effectiveness without respective heat health measures as part of a HHAP. Our study contributes to moving forward the efforts in heat health protection and underlines the need to develop and implement HHWS as part of HHAP and in combination with heat health actions at local level. Similar study approaches could potentially contribute to the evaluation of the effectiveness of overall HHAPs in terms of reducing mortality during heat episodes.

CRediT authorship contribution statement

Hanna Feldbusch: Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Alexandra Schneider:** Writing – review & editing. **Franziska Matthies-Wiesler:** Writing – review & editing. **Andreas Matzarakis:** Writing – review & editing. **Annette Peters:** Writing – review & editing. **Susanne Breitner-Busch:** Writing – review & editing, Methodology, Conceptualization. **Veronika Huber:** Writing – review & editing, Methodology, Data curation, Conceptualization.

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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.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envint.2025.109746.

Data availability

The data that has been used is confidential.

References

Abadie, A., Cattaneo, M.D., 2018. Econometric methods for program evaluation. Ann. Rev. Econ. 10, 465–503. https://doi.org/10.1146/annurev-economics-080217-053402.

Alari, A., Schwarz, L., Zabrocki, L., Le Nir, G., Chaix, B., Benmarhnia, T., 2021. The effects of an air quality alert program on premature mortality: a difference-in-differences evaluation in the region of Paris. Environ. Int. 156, 106583. https://doi.org/10.1016/j.envint.2021.106583.

An der Heiden, M., Muthers, S., Niemann, H., Buchholz, U., Grabenhenrich, L., Matzarakis, A., 2020. Heat-related mortality. Dtsch. Arztebl. Int. 117, 603–609. https://doi.org/10.3238/arztebl.2020.0603.

Ballester, J., Quijal-Zamorano, M., Méndez Turrubiates, R.F., Pegenaute, F., Herrmann, F.R., Robine, J.M., Basagaña, X., Tonne, C., Antó, J.M., Achebak, H., 2023. Heat-related mortality in Europe during the summer of 2022. Nat. Med. https://doi.org/10.1038/s41591-023-02419-z.

Barreca, A.I., 2012. Climate change, humidity, and mortality in the United States. J. Environ. Econ Manage. 63, 19–34. https://doi.org/10.1016/j.jeem.2011.07.004.

Basagaña, X., Sartini, C., Barrera-Gómez, J., Dadvand, P., Cunillera, J., Ostro, B., Sunyer, J., Medina-Ramón, M., 2011. Heat waves and cause-specific mortality at all ages. Epidemiology 22, 765–772. https://doi.org/10.1097/EDE.0b013e31823031c5.

Basarin, B., Lukić, T., Matzarakis, A., 2020. Review of biometeorology of heatwaves and warm extremes in Europe. Atmosphere 11, 1276. https://doi.org/10.3390/atmos11121276.

Benmarhnia, T., Bailey, Z., Kaiser, D., Auger, N., King, N., Kaufman, J.S., 2016. A difference-in-differences approach to assess the effect of a heat action plan on heat-related mortality, and differences in effectiveness according to sex, age, and socioeconomic status (Montreal, Quebec). Environ. Health Perspect. 124, 1694–1699. https://doi.org/10.1289/ehp203.

Blättner, B., Janson, D., Roth, A., Grewe, H.A., Mücke, H.-G., 2020. Gesundheitsschutz bei hitzeextremen in deutschland: was wird in ländern und kommunen bisher unternommen? Bundesgesundheitsbl. Gesundheitsforsch. Gesundheitsschutz 63, 1013–1019. https://doi.org/10.1007/s00103-020-03189-6.

Bundesinstitut für Bau- Stadt- und Raumforschung (BBSR). Laufende Raumbeobachtung des BBSR - INKAR. 2023. https://www.inkar.de/.

Burkart, K., Meier, F., Schneider, A., Breitner, S., Canário, P., Alcoforado, M.J., Scherer, D., Endlicher, W., 2016. Modification of heat-related mortality in an elderly urban population by vegetation (Urban Green) and proximity to water (urban blue): evidence from Lisbon, Portugal. Environ Health Perspect 124, 927–934. https://doi.org/10.1289/ehp.1409529.

Capellaro, M., Sturm, D., 2015. Evaluation of Information Systems Relevant to Climate Change and Health. Volume 1: Adaption to Climate Change: Evaluation of Existing National Information Systems (UV-Index, Heat Warning System, Airborne Pollen and Ozone Forecasts) from a Public Health Perspective – How to Reach Vulnerable Populations. Umwelt und Gesundheit 2015;3:1-144.

Carpenter, J., Bithell, J., 2000. Bootstrap confidence intervals: when, which, what? A practical guide for medical statisticians. Stat. Med. 19, 1141–1164. https://doi.org/10.1002/(sici)1097-0258(20000515)19:9.

Casanueva, A., Burgstall, A., Kotlarski, S., Messeri, A., Morabito, M., Flouris, A.D., Nybo, L., Spirig, C., Schwierz, C., 2019. Overview of existing heat-health warning systems in Europe. Int. J. Environ. Res. Public Health 16, 2657. https://doi.org/10.3390/ijerph16152657.

Choi, H.M., Lee, W., Roye, D., Heo, S., Urban, A., Entezari, A., Vicedo-Cabrera, A.M., Zanobetti, A., Gasparrini, A., Analitis, A., Tobias, A., Armstrong, B., Forsberg, B., Íñiguez, C., Åström, C., Indermitte, E., Lavigne, E., Mayvaneh, F., Acquaotta, F., Sera, F., Orru, H., Kim, H., Kyselý, J., Madueira, J., Schwartz, J., Jaakkola, J.J.K., Katsouyanni, K., Diaz, M.H., Ragettli, M.S., Pascal, M., Ryti, N., Scovronick, N., Osorio, S., Tong, S., Seposo, X., Guo, Y.L., Guo, Y., Bell, M.L., 2022. Effect modification of greenness on the association between heat and mortality: a multi-city multi-country study. EBioMedicine 84, 104251. https://doi.org/10.1016/j.ebiom.2022.104251.

Cuerdo-Vilches, T., Díaz, J., López-Bueno, J.A., Luna, M.Y., Navas, M.A., Mirón, I.J., Linares, C., 2023. Impact of urban heat islands on morbidity and mortality in heat waves: observational time series analysis of Spain's five cities. Sci. Total Environ. 890, 164412. https://doi.org/10.1016/j.scitotenv.2023.164412.

Davis, R.E., McGregor, G.R., Enfield, K.B., 2016. Humidity: a review and primer on atmospheric moisture and human health. Environ. Res. 144, 106–116. https://doi.org/10.1016/j.envres.2015.10.014.

de'Donato, F., Scortichini, M., De Sario, M., de Martino, A., Michelozzi, P., 2018. Temporal variation in the effect of heat and the role of the Italian heat prevention plan. Public Health 161, 154–162. https://doi.org/10.1016/j.puhe.2018.03.030.

Deutscher Wetterdienst (DWD). Historische Hitzewarnungen in Deutschland, Version v001. 2021. https://opendata.dwd.de/climate_environment/health/historical_alerts/heat_warnings/.

Deutscher Wetterdienst (DWD). Daily station observations (temperature, pressure, precipitation, sunshine duration, etc.) for Germany. 2023. https://opendata.dwd.de/climate_environment/CDC/observations_germany/climate/daily/kl/.

Dimick, J.B., Ryan, A.M., 2014. Methods for evaluating changes in health care policy: the difference-in-differences approach. J. Am. Med. Assoc. 312, 2401–2402. https://doi.org/10.1001/jama.2014.16153.

Ebi, K.L., Capon, A., Berry, P., Broderick, C., de Dear, R., Havenith, G., Honda, Y., Kovats, R.S., Ma, W., Malik, A., Morris, N.B., Nybo, L., Seneviratne, S.I., Vanos, J., Jay, O., 2021. Hot weather and heat extremes: health risks. Lancet 398, 698–708. https://doi.org/10.1016/s0140-6736(21)01208-3.

Federal Ministry for the Environment Nature Conservation Building and Nuclear Safety. Recommendations for Action. Heat Action Plans to protect human health. 2017. https://www.bmuv.de/WS4443-1.

Federal Ministry of Health. Hitzeschutzplan für Gesundheit des BMG. 2023. https://www.bundesgesundheitsministerium.de/fileadmin/Dateien/3_Downloads/H/Hitzeschutzplan/230727_BMG_Hitzeschutzplan.pdf.

Fouillet, A., Rey, G., Wagner, V., Laaidi, K., Empereur-Bissonnet, P., Le Tertre, A., Frayssinet, P., Bessemoulin, P., Laurent, F., De Crouy-Chanel, P., Jougla, E., Hémon, D., 2008. Has the impact of heat waves on mortality changed in France since the European heat wave of summer 2003? A study of the 2006 heat wave. Int. J. Epidemiol. 37, 309–317. https://doi.org/10.1093/ije/dym253.

Gabriel, K.M.A., Endlicher, W.R., 2011. Urban and rural mortality rates during heat waves in Berlin and Brandenburg, Germany. Environ. Pollut. 159, 2044–2050. https://doi.org/10.1016/j.envpol.2011.01.016.

Goggins, W.B., Chan, E.Y., Ng, E., Ren, C., Chen, L., 2012. Effect modification of the association between short-term meteorological factors and mortality by urban heat islands in Hong Kong. PLoS One 7, e38551. https://doi.org/10.1371/journal.pone.0038551.

Hannemann, L., Janson, D., Grewe, H.A., Blättner, B., Mücke, H.-G., 2023. Heat in German cities: a study on existing and planned measures to protect human health. J. Public Health. https://doi.org/10.1007/s10389-023-01932-2.

Heo, S., Nori-Sarma, A., Lee, K., Benmarhnia, T., Dominici, F., Bell, M.L., 2019. The use of a quasi-experimental study on the mortality effect of a heat wave warning system in Korea. Int. J. Environ. Res. Public Health 16, 2245. https://doi.org/10.3390/ijerph16122245.

Hess, J.J., Errett, N.A., McGregor, G., Busch Isaksen, T., Wettstein, Z.S., Wheat, S.K., Ebi, K.L., 2023. Public health preparedness for extreme heat events. Annu. Rev. Public Health 44, 301–321. https://doi.org/10.1146/annurev-publhealth-071421-025508.

Hess, J.J., Lm, S., Knowlton, K., Saha, S., Dutta, P., Ganguly, P., Tiwari, A., Jaiswal, A., Sheffield, P., Sarkar, J., Bhan, S.C., Begda, A., Shah, T., Solanki, B., Mavalankar, D., 2018. Building resilience to climate change: pilot evaluation of the impact of india's first heat action plan on all-cause mortality. J. Environ. Public Health 2018, 7973519. https://doi.org/10.1155/2018/7973519.

Heudorf, U., Schade, M., 2014. Heat waves and mortality in Frankfurt am Main, Germany, 2003-2013: what effect do heat-health action plans and the heat warning system have? Z. Gerontol. Geriatr. 47, 475–482. https://doi.org/10.1007/s00391-014-0673-2.

Huber, V., Breitner-Busch, S., He, C., Matthies-Wiesler, F., Peters, A., Schneider, A., 2024. Heat-related mortality in the extreme summer of 2022: an analysis based on daily data. Dtsch Arztebl Int 2024. https://doi.org/10.3238/arztebl.m2023.0254.

Janson, D., Kaiser, T., Kind, C., 2023. Analyse von Hitzeaktionsplänen und gesundheitlichen Anpassungsmaßnahmen an Hitzeextreme in Deutschland. Umwelt Und Gesundheit. https://doi.org/10.60810/openumwelt-7319.

Kaiser, T., Kind, C., Dudda, L., Klimawandel, S.K., 2021. Hitze und Gesundheit: stand der gesundheitlichen Hitzevorsorge in Deutschland und Unterstützungsbedarf der Bundesländer und Kommunen. UMID - Umwelt + Mensch Informationsdienst. https://www.umweltbundesamt.de/sites/default/files/medien/4031/publikationen/umid_01-2021-beitrag_3_hitze.pdf.

Kalkstein, L.S., Valimont, K.M., 1986. An evaluation of summer discomfort in the United States using a relative climatological index. Bull. Am. Meteorol. Soc. 67, 842–848. https://doi.org/10.1175/1520-0477(1986)067<0842:AEOSDI>2.0.CO;2.

Koppe, C., 2009. The heat health warning system of the german meteorological service. UMID Special Issue Climate Change and Health 3, 39–43.

Lanzinger, S., Schneider, A., Breitner, S., Stafoggia, M., Erzen, I., Dostal, M., Pastorkova, A., Bastian, S., Cyrys, J., Zscheppang, A., Kolodnitska, T., Peters, A., 2016. Ultrafine and fine particles and hospital admissions in central Europe. Results from the UFIREG study. Am. J. Respir. Crit. Care Med. 194, 1233–1241. https://doi.org/10.1164/rccm.201510-2042OC.

Lehrer, L., Geiger, M., Sprengholz, P., Jenny, M., Temme, H.L., Shamsrizi, P., Eitze, S., Betsch, C., 2024. Study protocol of the planetary health action survey PACE: a serial cross-sectional survey to assess the readiness to act against climate change. BMJ Open 14. https://doi.org/10.1136/bmjopen-2024-091093.

Martínez-Solanas, È., Basagaña, X., 2019. Temporal changes in temperature-related mortality in Spain and effect of the implementation of a Heat Health Prevention Plan. Environ. Res. 169, 102–113. https://doi.org/10.1016/j.envres.2018.11.006.

Matthies-Wiesler, F., Herrmann, M., Schulz, C., Gepp, S., Jung, L., Schneider, A., Breitner-Busch, S., 2021. The Lancet Countdown on Health and Climate Change - Policy Brief für Deutschland. The Lancet Countdown on Health and Climate Change, the German Medical Association, Institute of Epidemiology of Helmholtz Zentrum Muenchen, Charite Universitaetsmedizin Berlin, Potsdam Institute for Climate Impact Research (PIK). https://www.klimawandel-gesundheit.de/wp-content/uploads/2021/10/20211020_Lancet-Countdown-Policy-Germany-2021_Document_v2.pdf.

Matthies, F., Bickler, G., Marin, N.C., Hales, S., 2008. Heat-health action plans: guidance. WHO Regional Office for Europe. https://www.who.int/publications/i/item/9789289071918.

Matzarakis, A., 2016. Das Hitzewarnsystem des Deutschen Wetterdienstes (DWD) und seine Relevanz für die menschliche Gesundheit. Gefahrstoffe 76, 457–460.

Matzarakis, A., Laschewski, G., Muthers, S., 2020. The heat health warning system in Germany—application and warnings for 2005 to 2019. Atmos. 11, 170. https://doi.org/10.3390/atmos11020170.

Menberg, K., Bayer, P., Zosseder, K., Rumohr, S., Blum, P., 2013. Subsurface urban heat islands in German cities. Sci. Total Environ. 442, 123–133. https://doi.org/10.1016/j.scitotenv.2012.10.043.

Michalski, N., Reis, M., Tetzlaff, F., Herber, M., Kroll, L.E., Hövener, C., Nowossadeck, E., Hoebel, J., 2022. German index of socioeconomic deprivation (GISD): revision, update and application examples. J. Health Monit. 2–23. https://doi.org/10.25646/10641.

Morabito, M., Profili, F., Crisci, A., Francesconi, P., Gensini, G.F., Orlandini, S., 2012. Heat-related mortality in the Florentine area (Italy) before and after the exceptional 2003 heat wave in Europe: an improved public health response? Int. J. Biometeorol. 56, 801–810. https://doi.org/10.1007/s00484-011-0481-y.

Mücke, H.G., Litvinovitch, J.M., 2020. Heat extremes, public health impacts, and adaptation policy in Germany. Int. J. Environ. Res. Public Health 17. https://doi.org/10.3390/ijerph17217862.

Nitschke, M., Tucker, G., Hansen, A., Williams, S., Zhang, Y., Bi, P., 2016. Evaluation of a heat warning system in Adelaide, South Australia, using case-series analysis. BMJ Open 6, e012125. https://doi.org/10.1136/bmjopen-2016-012125.

Otto, A., Kern, K., Haupt, W., Eckersley, P., Thieken, A.H., 2021. Ranking local climate policy: assessing the mitigation and adaptation activities of 104 German cities. Clim. Change 167, 5. https://doi.org/10.1007/s10584-021-03142-9.

Perkins-Kirkpatrick, S.E., Lewis, S.C., 2020. Increasing trends in regional heatwaves. Nat. Commun. 11, 3357. https://doi.org/10.1038/s41467-020-16970-7.

Pfafferott, J., Becker, P., 2008. Erweiterung des Hitzewarnsystems um die Vorhersage der Wärmebelastung in Innenräumen. Bauphysik 30, 237–243. https://doi.org/10.1002/bapi.200810031.

Robine, J.M., Cheung, S.L., Le Roy, S., Van Oyen, H., Griffiths, C., Michel, J.P., Herrmann, F.R., 2008. Death toll exceeded 70,000 in Europe during the summer of 2003. C. R. Biol. 331, 171–178. https://doi.org/10.1016/j.crvi.2007.12.001.

Romanello, M., Di Napoli, C., Drummond, P., Green, C., Kennard, H., Lampard, P., Scamman, D., Arnell, N., Ayeb-Karlsson, S., Ford, L.B., Belesova, K., Bowen, K., Cai, W., Callaghan, M., Campbell-Lendrum, D., Chambers, J., van Daalen, K.R., Dalin, C., Dasandi, N., Dasgupta, S., Davies, M., Dominguez-Salas, P., Dubrow, R., Ebi, K.L., Eckelman, M., Ekins, P., Escobar, L.E., Georgeson, L., Graham, H., Gunther, S.H., Hamilton, I., Hang, Y., Hänninen, R., Hartinger, S., He, K., Hess, J.J., Hsu, S.C., Jankin, S., Jamart, L., Jay, O., Kelman, I., Kiesewetter, G., Kinney, P., Kjellstrom, T., Kniveton, D., Lee, J.K.W., Lemke, B., Liu, Y., Liu, Z., Lott, M., Batista, M.L., Lowe, R., MacGuire, F., Sewe, M.O., Martinez-Urtaza, J., Maslin, M., McAllister, L., McGushin, A., McMichael, C., Mi, Z., Milner, J., Minor, K., Minx, J.C., Mohajeri, N., Moradi-Lakeh, M., Morrissey, K., Munzert, S., Murray, K.A., Neville, T., Nilsson, M., Obradovich, N., O'Hare, M.B., Oreszczyn, T., Otto, M., Owfi, F., Pearman, O., Rabbaniha, M., Robinson, E.J.Z., Rocklöv, J., Salas, R.N., Semenza, J. C., Sherman, J.D., Shi, L., Shumake-Guillemot, J., Silbert, G., Sofiev, M., Springmann, M., Stowell, J., Tabatabaei, M., Taylor, J., Triñanes, J., Wagner, F., Wilkinson, P., Winning, M., Yglesias-González, M., Zhang, S., Gong, P., Montgomery, H., Costello, A., 2022. The 2022 report of the Lancet Countdown on health and climate change: health at the mercy of fossil fuels. Lancet 400, 1619–1654. https://doi.org/10.1016/s0140-6736(22)01540-9.

Roumeliotis, S., Abd ElHafeez, S., Jager, K.J., Dekker, F.W., Stel, V.S., Pitino, A., Zoccali, C., Tripepi, G., 2021. Be careful with ecological associations. Nephrology (Carlton) 26, 501–505. https://doi.org/10.1111/nep.13861.

Schifano, P., Leone, M., De Sario, M., de'Donato, F., Bargagli, A.M., D'Ippoliti, D., Marino, C., Michelozzi, P., 2012. Changes in the effects of heat on mortality among the elderly from 1998-2010: results from a multicenter time series study in Italy. Environ. Health 11, 58. https://doi.org/10.1186/1476-069x-11-58.

Sera, F., Armstrong, B., Blangiardo, M., Gasparrini, A., 2019. An extended mixed-effects framework for meta-analysis. Stat. Med. 38, 5429–5444. https://doi.org/10.1002/sim.8362.

Sera, F., Gasparrini, A., 2022. Extended two-stage designs for environmental research. Environ. Health 21, 41. https://doi.org/10.1186/s12940-022-00853-z.

Sheffield, P.E., Herrera, M.T., Kinnee, E.J., Clougherty, J.E., 2018. Not so little differences: variation in hot weather risk to young children in New York City. Public Health 161, 119–126. https://doi.org/10.1016/j.puhe.2018.06.004.

Song, J., Lu, Y., Zhao, Q., Zhang, Y., Yang, X., Chen, Q., Guo, Y., Hu, K., 2022. Effect modifications of green space and blue space on heat-mortality association in Hong Kong, 2008-2017. Sci. Total Environ. 838, 156127. https://doi.org/10.1016/j.scitotenv.2022.156127.

Steadman, R.G., 1979. The Assessment of sultriness. Part I: A temperature-humidity index based on human physiology and clothing science. J. Appl. Meteorol. Climatol. 18, 861–873. https://doi.org/10.1175/1520-0450(1979)018<0861:TAOSPI>2.0.CO;2.

Taubenböck, H., Droin, A., Standfuß, I., Dosch, F., Sander, N., Milbert, A., Eichfuss, S., Wurm, M., 2022. To be, or not to be 'urban'? a multi-modal method for the differentiated measurement of the degree of urbanization. Comput. Environ. Urban Syst. 95, 101830. https://doi.org/10.1016/j.compenvurbsys.2022.101830.

Toloo, G., FitzGerald, G., Aitken, P., Verrall, K., Tong, S., 2013. Evaluating the effectiveness of heat warning systems: systematic review of epidemiological evidence. Int. J. Public Health 58, 667–681. https://doi.org/10.1007/s00038-013-0465-2.

United Nations (UN), 2018. World Urbanization Prospects: The 2018 Revision.

Weinberger, K.R., Wu, X., Sun, S., Spangler, K.R., Nori-Sarma, A., Schwartz, J., Requia, W., Sabath, B.M., Braun, D., Zanobetti, A., Dominici, F., Wellenius, G.A., 2021. Heat warnings, mortality, and hospital admissions among older adults in the United States. Environ. Int. 157, 106834. https://doi.org/10.1016/j.envint.2021.106834.

Weinberger, K.R., Zanobetti, A., Schwartz, J., Wellenius, G.A., 2018. Effectiveness of National Weather Service heat alerts in preventing mortality in 20 US cities. Environ. Int. 116, 30–38. https://doi.org/10.1016/j.envint.2018.03.028.

WHO Regional Office for Europe. Heat and health in the WHO European Region: updated evidence for effective prevention. Copenhagen; 2021.

Wing, C., Simon, K., Bello-Gomez, R.A., 2018. Designing difference in difference studies: best practices for public health policy research. Annu. Rev. Public Health 39, 453–469. https://doi.org/10.1146/annurev-publhealth-040617-013507.

Winklmayr, C., an der Heiden, M., 2022. Hitzebedingte Mortalität in Deutschland 2022. Epidemiologisches Bulletin 3–9. https://doi.org/10.25646/10695.3.

Winklmayr, C., Matthies-Wiesler, F., Muthers, S., Buchien, S., Kuch, B., An der Heiden, M., Mücke, H.G., 2023. Heat in Germany: health risks and preventive measures. J. Health Monit. 8, 3–32. https://doi.org/10.25646/11651.

Winklmayr, C., Muthers, S., Niemann, H., Mücke, H.G., Heiden, M.A., 2022. Heat-related mortality in Germany from 1992 to 2021. Dtsch. Arztebl. Int. 119, 451–457. https://doi.org/10.3238/arztebl.m2022.0202.

WMO and WHO. Heatwaves and Health: Guidance on Warning-System Development. In: McGregor G.R., Bessemoulin P., Ebi K., Menne B., eds; 2015.

Wu, X., Weinberger, K.R., Wellenius, G.A., Dominici, F., Braun, D., 2023. Assessing the causal effects of a stochastic intervention in time series data: are heat alerts effective in preventing deaths and hospitalizations? Biostatistics. https://doi.org/10.1093/biostatistics/kxad002.