Response to comments by reviewer #1 and reviewer #2 on "The contribution of air temperature and ozone to mortality rates during hot weather episodes in eight German cities during the years 2000 and 2017" by Alexander Krug et al.

We sincerely thank you for the overall feedback of our work as well as the constructive comments on the manuscript. This is highly appreciated. We reply to the reviewer comments below. Reviewer comments are in black and italic, authors' responses in blue. Please find the marked-up version of the manuscript at the end of this document.

Anonymous Referee #1

Received and published: 2 June 2020

Reviewer 1, Comment 1: "I have a comment regarding the period of the analysis. The study is performed to annual time series, and the authors tested long-term annual trends. But, given the strong seasonality of MDA8, which usually reaches the highest values in summer, I would expect the most important interaction HWE and MDA8 in summer. Did the authors take into consideration this?"

Answer: The method used in this study regresses between both process variables of air temperature magnitude (TA_{Mag}) and mean 8-hourly average ozone concentration ($MDA8_{M}$) as well as mean mortality rates as effect variable. Regressions are calculated only between the process and the effect during previously detected episodes of the whole analyzed period from 2000 to 2017. Although it was not aim of this study to investigate the effects of seasonal variances in air temperature or ozone concentrations, we fully agree with your expectation of increasing interaction during episodes of highest values of both air temperature and ozone. An indicator of possible higher impacts of interaction can be seen in Fig. 3 in the manuscript. At least four cities (Leipzig, Cologne, Frankfurt and Stuttgart) show increasing explained variance (r^2) of the interaction term with increasing air temperature threshold (TA_{Thres}). As episodes of exceeding high threshold values are likely to occur in mid-summer, results reveal the most interaction during these episodes (high r^2). Lower TA_{Thres} include an increasing number of episodes which are more likely to occur in early or late summer. A lower r^2 for the interaction term of these episodes can be seen in Fig. 3 of the manuscript. Concerning the other investigated cities, a lower r^2 of the interaction term for episodes of lower TA_{Thes} is less visible, which is mainly due to lower values of the explained variances of these three variables. Yet, it cannot be excluded.

Reviewer 1, Comment 2. "Line 83: The analysis of HWE is based on daily average of air temperature (TA), and I understand that as in other studies, TA can be a suitable predictor. However, I was wondering if the authors have tested maximum temperature instead."

Answer: The decision to select daily average air temperature as predictor for mortality rates has been mainly made based on results of studies that are cited in section 2.1.1. According to your comment, we tested daily minimum air temperature (TN) and daily maximum air temperature (TX) as predictor variables in the regressions as well. The results for all investigated cities are displayed below and are also included in the appendix of the revised manuscript. They reflect that TX is less suitable than TN and TA to predict mortality rates during hot weather episodes (HWE), considering all cities. TN and TA show higher values of r^2 than TX. This confirms results of the cited studies in section 2.1.1. and leads to our decision to use TA in our study. Furthermore, it reflects in a more general view, that night-time air temperature plays an important role for urban populations. TA reflects the thermal situation of the entire day compared to TN or TX. In addition to this, TA better captures the urban heat island effect, which is commonly most pronounced in the first phase of the night and therefore not at the time of TN occurrence, commonly shortly before sunrise. According to these points, we selected TA as thermal predictor for mortality in this study. Following your suggestion, we enhanced the section 2.1.1 for this aspect.

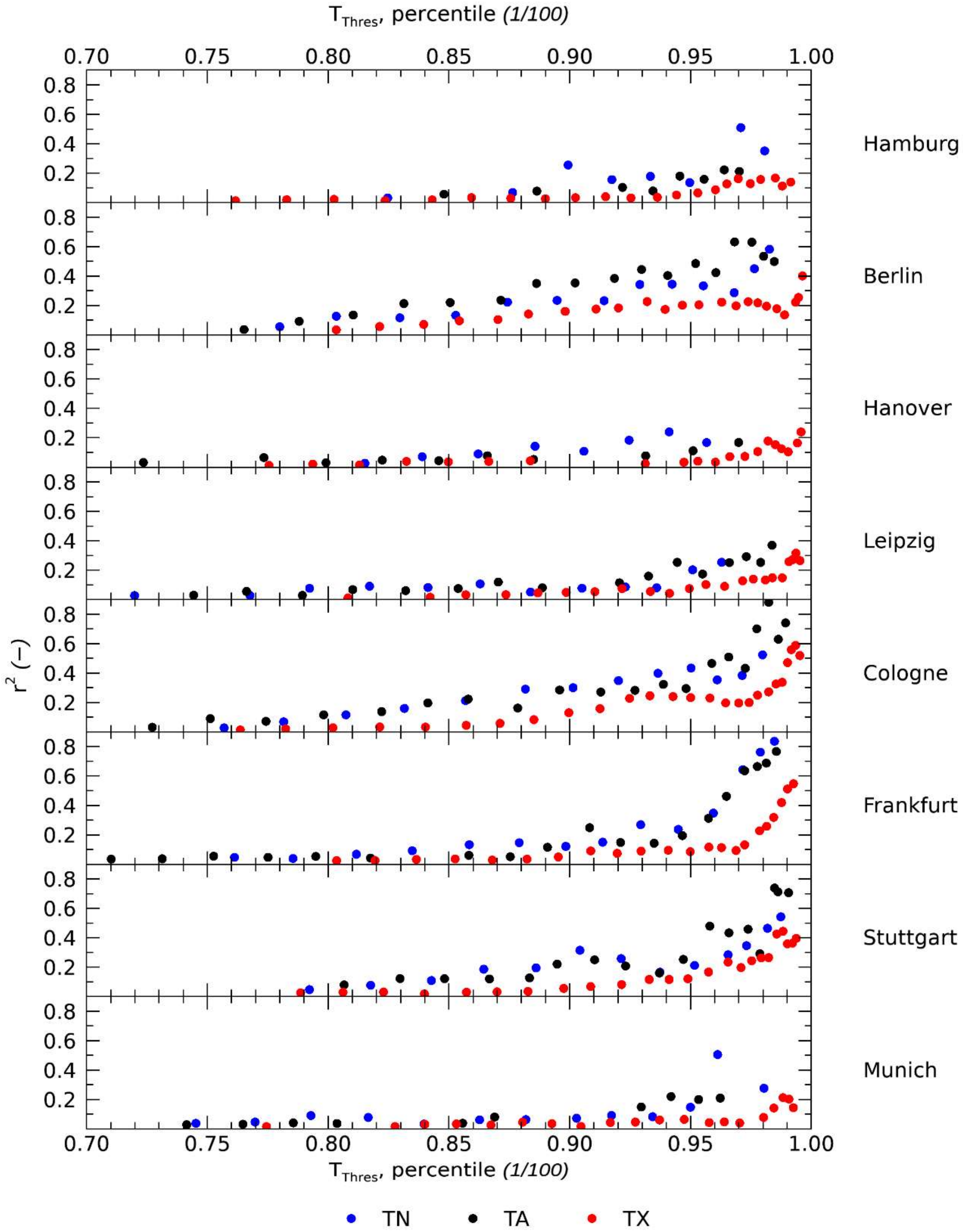

Figure 1: Comparison of regression analysis based on different predictor variables daily minimum air temperature (TN, blue), daily average air temperature (TA, black) and daily maximum air temperature (TX, red). Each panel displays results for one city. X axis: percentile of the respective air temperature distribution, y axis: explained variance (r²) of regression models.

Reviewer 1, Comment 3. "Line 233. In Berlin, it is observed a higher contribution from $MDA8_M$ at the lower TA_{Thres}, which is somehow surprising, since I would expect a higher contribution from MDA8 at higher TA_{Thres}. Why? The authors mention that it could due to stagnant conditions (dry, sunny days..) in early summer, but this is only observed in Berlin, do the authors have further explanations?"

Answer: In Fig. 3 of the manuscript, the light gray bars reflect the part of the variance of the mean mortality rate during episodes which can be explained by the variance of $MDA8_M$. Although all episodes were detected via air temperature thresholds, the regressions reveal that the variance of the mortality rate cannot only be explained by the variance of the air temperature magnitude (TA_{Mag}), but mostly by the variance of $MDA8_M$. This is visible not only in results for Berlin, but also for Stuttgart and Cologne. The reason for this can be similarly discussed as we did in the answer to your comment RC1. Lower TA_{Thres} capture more episodes, which occur in early or late summer. Especially in early summer, MDA8 can reach high values due to intense solar radiation and high photo-oxidative production rate. MDA8 values of up to 170 µg m^3 for episodes of $TA_{Thres} \geq 16$ °C can be seen in Fig. 4. With increasing TA_{Thres}, the explained variance of $MDA8_M$ decreases and the air temperature becomes the most pronounced factor in explaining the variance of the mortality rate during these episodes. This does not mean, however, that MDA8 is not relevant for mortality rates during episodes of higher TA_{Thes} in which the highest MDA8 concentrations may occur (Fig. 4). As shown in Fig. 3, the explained variance of $MDA8_M$ appears as a statistically inseparable part (the interaction term) of the variance of the air temperate magnitude (TA_{Mag}).

The specific contribution of TA_{Mag}, $MDA8_M$ and their interaction to mortality rates is spatially highly heterogeneous. Not only meteorological factors such as wind or humidity may influence the city specific relationship between these three variables. The topography or the emission rate of precursors through vegetation as well as population-specific factors (e.g. demography, socio-economy) may influence the city-specific relationship as well. This makes it more difficult to deduce similarities among different cities especially for the role of ozone. This fact mainly follows the results of other studies focusing on the relationship of air temperature, ozone and mortality, as cited and discussed in the manuscript. We considered this comment in the discussion in section 4.2 in the revised version of the manuscript to make this clearer to the reader.

Technical corrections:

1. *Line 128. It should be 0.5 °C.*

Changed.

2. *Line 173. “Except for Berlin and Cologne,* r^2 *is < 20 % for HWE with* $TA_{Thres} < 95^{th}$ *percentile”, is that correct? I can see from figure 2 that* r^2 *is larger for lower* TA_{Thres}*.*

We removed this sentence.

3. *Line 180. “these HWE can partly explained”, it should be “these HWE can be partly explained”*

We corrected this sentence.

4. *Line 228. “MDA8 explains more of the mortality rate at low* TA_{Thres} *than* TA_{Mag}*”. I think it should be added where (e.g. Berlin), and refer to the figure to help the reader.*
5. *Line 230. As in my previous comment: “A lower TAThres captures more HWE. . .” where? All cities?*

This section (4.2) was revised according to your and the second reviewer’s specific and technical comments. Now, this section should be clearer.

Anonymous Referee #2

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Reviewer 2, Comment 1: "A major concern is related to the choice of Multiple Linear Regression (MLR) and the fact that all conclusions are based on the MLR test statistics assuming a normal distribution of the data. Crude mortality rates usually do not follow a normal distribution. If they do, please show results of normality testing. Mortality rates are count data and a Poisson distribution can be used as underlying distributional assumption in the scope of generalized linear models."

Answer: The majority of epidemiological studies use generalized linear models to investigate the effect of air temperature or air quality on death counts. Crude death counts typically follow Poisson distributions which excludes the use of common linear regression analyzes. In contrast to this common approach, the underlying method of this study differs in two major points. Firstly, the method does not use crude death counts as effect variable. The mortality rate is used instead, which describes the number of deaths per population unit (mortality) as rate per time unit (day). Secondly, we do not investigate the overall relationship of daily air temperature values, ozone concentrations and death counts. Only episodes of variable duration of at least three days are investigated. For these episodes we assume a normal distribution for values of mortality rates of the investigated cites. Therefore, the method allows the use of simple or multiple regressions. A distribution histogram for the investigated cities as well as a table presenting results of the Shapiro-Wilk-Test is attached below.

We do not claim our method to be better than other approaches nor the best in terms to investigate air temperature or air quality effects on death counts or mortality rates, yet it allows a more precise identification of episodes of potentially hazardous atmospheric conditions for the public. Based on your comment we extended the section 2.1 for this aspect.

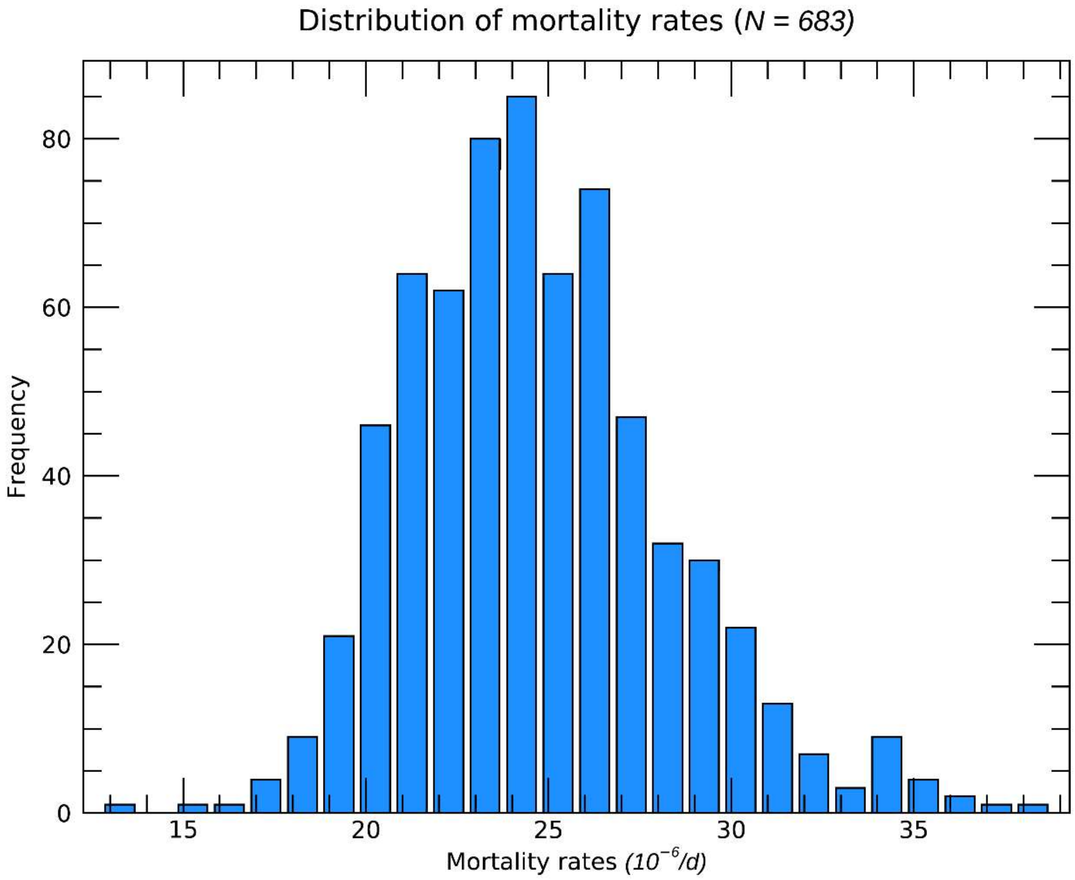

Figure 2: Exemplary distribution of mean mortality rates during episodes exceeding 20 °C (daily average air temperature, TA) for at least three consecutive days. The sample contains episode-specific mean mortality rates of all cities. According to the Shapiro-Wilk-Test this distribution differs significantly from a normal distribution ($p < 0.05$).

The table below provides results of the Shapiro-Wilk-Test for normality concerning mortality rates during respective hot weather episodes (HWE). The table contains all statistically significant models (t-test) of the univariate linear regression as used in the study (see sections 2.2.1, 3.1 and Fig. 2 in the manuscript). Results show inconclusive results of normal (50,4 % of all tested combinations) and significant non-normal (49,6 % of all tested combinations) tested distributions dependent on city and model-specific air temperature threshold. In conclusion, we keep the assumption of a near-normal distribution, acknowledging that our method is not the one ideal approach, or better than others, for investigations using mortality data. However, in terms of our research questions it delivers sufficient information about how to detect and characterize HWE as aimed in this study.

Table 1. Results of the Shapiro-Wilk-test for normal distribution of the mean mortality rate during hot weather episodes (HWE) exceeding TA_{Thres}. $p < 0.05$ (*) means not-normally distributed. City: city name, TA_{Thres}: Threshold temperature of the model, N episodes: number of episodes, W: W-value of the Shapiro-Wilk-test, W_α: critical value.

City	**TA_{Thres}**	**N episodes**	**W**	**W_α**	**$p < 0.05$**
Hamburg	17.0	127	0.979	0.979	*
Hamburg	18.0	93	0.981	0.973	
Hamburg	19.0	59	0.978	0.960	
Hamburg	19.5	51	0.976	0.955	
Hamburg	20.0	47	0.969	0.952	
Hamburg	20.5	38	0.977	0.942	
Hamburg	21.0	35	0.975	0.938	
Hamburg	21.5	26	0.977	0.922	
Berlin	17.0	147	0.985	0.982	
Berlin	17.5	145	0.988	0.982	
Berlin	18.0	138	0.967	0.981	*
Berlin	18.5	133	0.965	0.980	*
Berlin	19.0	121	0.961	0.979	*
Berlin	19.5	116	0.954	0.978	*
Berlin	20.0	100	0.920	0.975	*
Berlin	20.5	86	0.903	0.971	*
Berlin	21.0	74	0.919	0.967	*
Berlin	21.5	67	0.928	0.964	*
Berlin	22.0	61	0.940	0.961	*
Berlin	22.5	47	0.906	0.952	*
Berlin	23.0	34	0.850	0.937	*
Berlin	23.5	28	0.865	0.926	*
Berlin	24.0	22	0.834	0.911	*
Berlin	24.5	16	0.872	0.887	*
Berlin	25.0	12	0.891	0.861	
Hanover	15.0	145	0.995	0.982	
Hanover	16.0	160	0.993	0.983	
Hanover	16.5	155	0.989	0.983	
Hanover	17.0	140	0.997	0.981	
Hanover	17.5	128	0.992	0.980	
Hanover	18.0	116	0.985	0.978	
Hanover	18.5	98	0.995	0.974	
Hanover	20.0	62	0.989	0.962	
Hanover	21.0	40	0.981	0.945	
Hanover	22.0	24	0.910	0.917	*
Leipzig	16.0	139	0.991	0.981	
Leipzig	16.5	153	0.989	0.983	

Leipzig	17.0	151	0.993	0.982	
Leipzig	17.5	148	0.994	0.982	
Leipzig	18.0	129	0.991	0.980	
Leipzig	18.5	118	0.988	0.978	
Leipzig	19.0	113	0.979	0.978	
Leipzig	19.5	101	0.973	0.975	*
Leipzig	20.5	66	0.976	0.964	
Leipzig	21.0	59	0.970	0.960	
Leipzig	21.5	47	0.944	0.952	*
Leipzig	22.0	38	0.949	0.942	
Leipzig	22.5	32	0.938	0.934	
Leipzig	23.0	21	0.927	0.908	
Leipzig	23.5	20	0.948	0.904	
Leipzig	24.0	15	0.924	0.882	
Cologne	16.5	149	0.973	0.982	*
Cologne	17.0	150	0.972	0.982	*
Cologne	17.5	149	0.975	0.982	*
Cologne	18.0	142	0.991	0.981	
Cologne	18.5	125	0.990	0.979	
Cologne	19.0	116	0.986	0.978	
Cologne	19.5	114	0.971	0.977	*
Cologne	20.0	98	0.912	0.974	*
Cologne	20.5	78	0.934	0.968	*
Cologne	21.0	67	0.879	0.964	*
Cologne	21.5	57	0.894	0.959	*
Cologne	22.0	50	0.915	0.954	*
Cologne	22.5	43	0.919	0.948	*
Cologne	23.0	34	0.863	0.937	*
Cologne	23.5	32	0.893	0.934	*
Cologne	24.0	22	0.839	0.911	*
Cologne	24.5	17	0.874	0.892	*
Cologne	25.0	11	0.832	0.855	*
Cologne	25.5	8	0.946	0.823	
Cologne	26.0	6	0.896	0.792	
Frankfurt	16.5	150	0.978	0.982	*
Frankfurt	17.0	146	0.974	0.982	*
Frankfurt	17.5	143	0.981	0.981	*
Frankfurt	18.0	146	0.964	0.982	*
Frankfurt	18.5	146	0.966	0.982	*
Frankfurt	19.0	130	0.969	0.980	*
Frankfurt	20.0	109	0.914	0.976	*
Frankfurt	20.5	100	0.840	0.975	*

Frankfurt	21.0	94	0.790	0.973	*
Frankfurt	21.5	80	0.830	0.969	*
Frankfurt	22.0	65	0.797	0.963	*
Frankfurt	22.5	54	0.808	0.957	*
Frankfurt	23.0	41	0.810	0.946	*
Frankfurt	23.5	39	0.776	0.944	*
Frankfurt	24.0	31	0.829	0.932	*
Frankfurt	24.5	25	0.781	0.920	*
Frankfurt	25.0	19	0.815	0.901	*
Frankfurt	25.5	14	0.859	0.875	*
Frankfurt	26.0	9	0.819	0.834	*
Stuttgart	18.0	131	0.989	0.980	
Stuttgart	18.5	116	0.982	0.978	
Stuttgart	19.0	111	0.990	0.977	
Stuttgart	19.5	101	0.961	0.975	*
Stuttgart	20.0	92	0.985	0.973	
Stuttgart	20.5	86	0.967	0.971	*
Stuttgart	21.0	76	0.960	0.968	*
Stuttgart	21.5	65	0.952	0.963	*
Stuttgart	22.0	58	0.962	0.959	
Stuttgart	22.5	48	0.955	0.952	
Stuttgart	23.0	36	0.952	0.940	
Stuttgart	23.5	31	0.904	0.932	*
Stuttgart	24.0	20	0.971	0.904	
Stuttgart	24.5	15	0.968	0.882	
Stuttgart	25.0	13	0.943	0.869	
Stuttgart	25.5	11	0.917	0.855	
Stuttgart	26.0	8	0.934	0.823	
Munich	16.0	164	0.987	0.984	
Munich	16.5	149	0.993	0.982	
Munich	17.0	143	0.976	0.981	*
Munich	17.5	132	0.984	0.980	
Munich	19.0	114	0.987	0.977	
Munich	19.5	107	0.995	0.976	
Munich	21.5	58	0.984	0.959	
Munich	22.0	51	0.969	0.955	
Munich	22.5	36	0.975	0.94	
Munich	23.0	26	0.971	0.922	

Reviewer 2, Comment 2: "Furthermore, some of the conclusions have to be reconsidered. At page 11, lines 2018-2019 it is stated that the effect of air temperature on mortality is stronger in comparison to the effect of ozone. I disagree with this conclusion, because only events with high temperature have been selected and MLR is tuned towards this variable. These events do not necessarily go along with the ozone concentrations relevant for mortality."

Answer: According to numerous investigations, ozone concentrations are highly relevant for public health and mortality. It is not the aim or conclusion of this study to weaken the importance of ozone concentrations. Our results underline quite the opposite; the found interaction underlines that during HWE not only elevated air temperature affects mortality rates. The interaction between air temperature and ozone concentrations as a statistically non-separable portion of the explained variance of mortality rates plays an important role during HWE. The statement you mentioned in your comment refers to the comparison of single proportions of each variable (air temperature magnitude, TA_{Mag} and $MDA8_{M}$) to mortality rates. In particular, episodes detected via high TA_{Thres}, TA_{Mag} explain more of the variance of the mortality rate that $MDA8_{M}$ (see Fig. 3 in the manuscript). We also investigated lower TA_{Thres} down to the 70th percentile, in which $MDA8_{M}$ reaches higher values for the explained variance compared to TA_{Mag}. Nevertheless, we reconsidered the statements in section 4.2 according to your concerns.

Reviewer 2, Comment 3: "At lines 228ff. you notice that a lower TA_{Thres} captures more HWE in which air temperature is relatively low, but ozone concentrations can reach high values. This suggests that the typical non-linear relationship between temperature and ozone has an impact within your analysis. This should also be further investigated."

Answer: Our results show that the relative contribution of TA_{Mag}, $MDA8_{M}$ and their interaction depends on the distinct TA_{Thres} which identifies HWE (Fig. 3). In our opinion, different r^2 for TA_{Mag} and $MDA8_{M}$ among different TA_{Thres} indicate a potential non-linearity between air temperature and MDA8. Otherwise, as shown in Fig. 4 in the manuscript, the relationship between HWE and MDA8 shows a linearity for each TA_{Thres}, based on the position of the median, the 25th and the 75th percentile. Therefore, the interpretation of the role of air temperature and ozone concentrations strongly relates to the distinct TA_{Thres} and thus the identification of potential hazardous episodes. Your comment is a truly interesting point for further investigations. However, in terms of our research questions and aims we see no need to extent our study to this point. Yet, your point will be taken into account in future work.

Technical corrections:

1. *General comment: English should be revised by a native speaker.*

We checked the manuscript and made several corrections.

2. *Page1, line 21: replace "excessive mortality rates" by "excess mortality rates".*

Replaced.

3. *Page2, line 28: Please add NOx as further precursors.*

Added.

4. *Page2, line 50: replace "exposition" by "exposure".*

Replaced.

5. *Page 5, line 127: remove "Firstly".*

Removed.

6. *Section 2.2.2: add results of the F-test of the overall significance of the regression models.*

All models of the multiple regression are now tested for overall statistical significance with a F-test. This led to minor changes in Fig. 3 and Fig 4. in the manuscript, but with no consequences for any results or conclusions. Furthermore, we adjusted sections 2.2.2 and 3.2 for this point.

7. *Page 7, line 180: correct to "can partly be explained"*

Corrected.

The contribution of air temperature and ozone to mortality rates during hot weather episodes in eight German cities during the years 2000 and 2017

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Abstract. Hot weather episodes are globally associated with increased mortality. Elevated ozone concentrations occurring simultaneously contribute to mortality during these episodes, yet to what extent both stressors are linked to increased mortality rates varies from region to region.

This study analyzes time series of observational data of air temperature and ozone concentrations for eight German cities during the years 2000 and 2017. By using an event-based risk approach, various air temperature thresholds were explored for each city to detect hot weather episodes which are statistically associated with increased mortality. Multiple linear regressions were calculated to investigate the relative contribution of air temperature and ozone concentrations to mortality rates during these episodes, including their interaction. Results were compared for their similarities and differences among the investigated cities.

In all investigated cities hot weather episodes, linked to increased mortality rates, were detected. Results of the multiple linear regression further point towards air temperature as the major stressor explaining mortality rates during these episodes by up to 60 %, and ozone concentrations by up to 20 %. The strength of this association both for air temperature and ozone varies across the investigated cities. An interactive influence was found between both stressors, underlining their close relationship. For some cities, this interactive relationship explained more of the observed variance in mortality rates than each individual stressor alone.

We could show that during hot weather episodes, not only air temperature affects urban populations. Concurrently high ozone concentrations also play an important role for public health in German cities.

1 Introduction

Hot weather episodes (HWE) cause more human fatalities in Europe than any other natural hazard (EEA, 2019). HWE are typically characterized by elevated air temperature and can last for several days or weeks, depending on respective threshold values that are used to identify such days. Numerous investigations found ~~excessive~~ excess mortality rates during days of elevated air temperature (Curriero et al., 2002; Anderson and Bell, 2009; Gasparrini and Armstrong, 2011; Gasparrini et al., 2015). Increases in morbidity rates, hospital admissions and emergency calls are also associated with elevated air temperatures (Bassil et al., 2009; Karlsson and Ziebarth, 2018).

In addition, HWE are linked to increased tropospheric ozone concentrations (Shen et al., 2016; Schnell and Prather, 2017; Phalitnonkiat et al., 2018). Zhang et al. (2017) and Schnell and Prather (2017), e.g., found for North America that the probability is up to 50 % that both air temperature and ozone concentrations reach their 95th percentile simultaneously. Ozone as a secondary air pollutant is formed by ~~oxidation~~ photochemical reactions of volatile organic compounds and nitrogen oxides. Increased air temperature and high solar radiation intensify this formation (Camalier et al., 2007; Varotsos et al., 2019). Correlations between both environmental stressors are mostly described as linear (Steiner et al., 2010). A variety of geographic and meteorological factors may influence this relationship, such as the presence of precursors, local-specific wind patterns or the humidity content of the lower atmosphere (Steiner et al., 2010). At the upper end of the respective air temperature and ozone concentration distributions the direct linkage between the two stressors is discussed to be even more complex (Steiner et al., 2010; Shen et al., 2016). Despite this linkage, elevated ozone concentrations alone have also been associated with adverse health effects (Bell, 2004; Hůnová et al., 2013; Bae et al., 2015; Díaz et al., 2018; Vicedo-Cabrera et al., 2020). The close linkage of both environmental stressors makes it necessary to account for their confounding influence on each other, in order to investigate distinctive health effects of each of these two stressors. But beyond the consideration of both environmental stressors as separated elements, their co-occurrence may lead to even higher rates of excess mortality (Burkart et al., 2013; Vanos et al., 2015; Scortichini et al., 2018; Krug et al., 2019). Some studies also indicate an interactive effect, which is larger than the sum of their individual effects (Cheng and Kan, 2012; Burkart et al., 2013; Analitis et al., 2018).

Studies which investigate regional differences in the relation between HWE and ozone concentrations revealed differences in the air-temperature-ozone relationship (e.g., Shen et al., 2016; Schnell and Prather, 2017; Phalitnonkiat et al., 2018) and in terms of their individual and combined effects on mortality (Filleul et al., 2006; Burkart et al., 2013; Analitis et al., 2014; Breitner et al., 2014; Tong et al., 2015; Analitis et al., 2018; Scortichini et al., 2018). Some studies report a North-South gradient in the air-temperature-mortality relationship, indicating that populations of northern regions are more sensitive to heat compared to southern regions, which are more affected by cold (e.g., Burkart et al., 2013; Scortichini et al., 2018). However, the influencing effect of elevated ozone concentrations is shown to be more differentiated. While some studies report a greater influence of elevated ozone concentrations for more heat-affected regions (Anderson and Bell, 2011; Scortichini et al., 2018), other studies discuss that regional differences are a result of location-specific physiological, behavioral, and ~~social-economic~~ socio-economic characteristics, as well as the specific level of ~~exposition~~ exposure across various cities (Anderson and Bell, 2009, 2011; Burkart et al., 2013; Breitner et al., 2014). For Germany, most studies investigated the effect of air temperature during HWE on mortality for different regions (Gabriel and Endlicher, 2011; Scherer et al., 2013; Muthers et al., 2017; an der Heiden et al., 2019). Breitner et al. (2014) investigated short-term effects of air temperature on mortality and modifications by ozone in three cities in southern Germany. But, to our knowledge, a national multi-city study exploring the impacts of HWE on mortality across different German cities has not been carried out so far. In addition, how ozone concentrations contribute to mortality rates during HWE are inconclusive for different cities in Germany and world-wide, as described above.

A prior study for Berlin, Germany (Krug et al., 2019), identified HWE and episodes of elevated ozone concentrations with a risk-based approach for the period 2000 to 2014. Whereas ozone concentrations alone only showed a weak relationship to mortality rates, the co-occurrence with elevated air temperatures amplified mortality rates in Berlin. On the basis of these results, main focus of this study lies on the identification of HWE in multiple cities in Germany and to investigate how air temperature and ozone concentrations contribute to mortality rates during these. Furthermore, the analysis period is extended up until 2017.

Main goals of this study are (a) to identify HWE that show statistical relations to mortality rates for eight of the largest German cities and (b) to compare these cities in terms of their location-specific relation of air temperature and ozone concentrations onto mortality rates. This study is structured by the following research questions:

1. Do other German cities, likewise Berlin, show a significant relationship between HWE and their specific mortality rates?
2. How does this relationship differ in terms of city-specific threshold values and the relative contribution of air temperature and ozone concentrations during HWE to the overall explained variance of the mortality rate?

2 Data and methods

2.1 Data

The period analyzed in this study are 18 years from 2000 to 2017. Eight cities are investigated (in the order of their population): Berlin, Hamburg, Munich, Cologne, Frankfurt (Main), Stuttgart, Leipzig and Hanover (Fig. 1, Table 1). While the first six are the six most populous cities in Germany, the latter two were included in this study to ensure spatially relatively homogeneous distribution of the investigated cities in Germany. The analyzed cities comprise 10.3 million inhabitants at the end of 2017, which were 12.5 % of the entire German population at this time (DESTATIS, 2019). The smallest city in terms of population (Hanover) has > 500 000 inhabitants, while the largest (Berlin) has > 3.5 million (Table 1).

2.1.1 Air temperature

Air temperature data at daily resolution was obtained from the German Weather Service (DWD, 2019). The selection of measurement sites was based on the availability of data covering the entire analysis period. For cities with more than one measurement site the site closest to the city center and to the co-located ozone measurement site was selected. An overview of the selected measurement sites including their meta data is given in Table A1 and Fig. A1 in the appendix. We ~~use daily~~ tested daily minimum (TN), maximum (TX) and average air temperature (TA) from each station ~~. Previous studies found this~~ as predictor variables for mortality rates. The results for all investigated cities are displayed in Fig. A2 in the appendix. Considering all cities and thresholds, TN and TA performed better than TX. This confirms results of previous studies that found TA to be a suitable predictor for the air-temperature-mortality relationship and a suitable indicator for the city's diurnal thermal conditions, compared to ~~maximum or minimum air temperature~~ TX or TN (Hajat et al., 2006; Anderson and Bell, 2009; Vaneckova et al., 2011; Yu et al., 2010; Scherer et al., 2013; Chen et al., 2015).

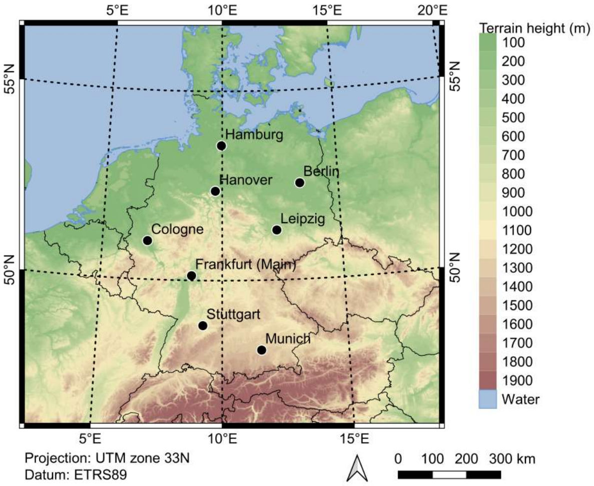

Figure 1. Location of investigated cites. Topographic map is based on GTOPO30 data retrieved from European Environment Agency (EEA, 2016)

2.1.2 Ozone concentrations

Data of hourly ozone concentrations were obtained from the German Environment Agency (UBA). These data stem from the air quality monitoring networks of the German federal states. To select one ozone monitoring station per city the same criteria as for the selection of TA measurement sites were applied (closest to city center and to TA site). Only "urban background" stations were selected, as the ozone concentrations should be "representative of the exposure of the general urban population" (EU, 2008). The daily maximum eight-hour moving average (MDA8) was calculated from hourly values for all selected sites, which is the widely used metric for ozone monitoring for human health purposes (WHO, 2006; EU, 2008).

2.1.3 Population data

Time series of annual population counts were obtained for each city from the German Federal Bureau of Statistics (DESTATIS, 2019). The German census of 2011 revealed an error between 1 % and 5 % to the previously available annually updated version of the population time series for the selected cities, based on the prior census in 1990. Therefore, population time series were corrected based on the assumption that the error (a) increases over time and (b) correlates with the strength of the annual migration of each city. An error term was calculated for each year of the census period from 1990 to 2010 as the annual proportion of the total error (derived from the difference in the two census data in 2011). Each error term was further weighted by the proportion of the annual migration size from total migration size during the census period. This weighted error term was then subtracted from the annual population size. Years 2012 to 2017 were likewise corrected based on afore-mentioned assumptions. Annual time series were then linearly interpolated to daily values for each city.

2.1.4 Mortality data

Daily values of deaths for each city were provided by the German Federal Bureau of Statistics (DESTATIS, 2019). We intentionally consider all-cause and all-age total death counts of the whole city in this study, as the main goal is to explore the process which could have an effect (e.g. mortality) as a city-wide variable without any pre-assumption of disease-specific and heat-related health effects. For that reason, we do not want to exclude any death counts from the analysis that might be related to TA or MDA8. Mortality rates were calculated by dividing daily death counts by daily interpolated population counts.

Each time series of TA, MDA8, population and mortality rate were tested for a long-term annual trend. Whereas for TA and MDA8 no significant long-term trend could be detected over the analysis period, mortality rates in all cities showed a significant ($p < 0.05$, double-sided t test) negative annual trend. This trend was corrected for to avoid any misinterpretation of the variance in the time series.

2.2 Methods

The methodological approach used in this study follows the concept of risk evaluation by the Intergovernmental Panel on Climate Change (IPCC) (IPCC, 2012). This concept was adopted for an explorative event-based risk analysis, which is explained in detail by Scherer et al. (2013) and used in previous works to deduce two risk-based definitions of heat waves (Fenner et al., 2019) or to quantify heat-related risks and hazards (Jänicke et al., 2018). This approach was also used to analyze the co-occurrence of HWE and episodes of elevated ozone concentrations in Berlin (Krug et al., 2019). The main advantage of this approach is that it explores time series without any pre-assumptions concerning threshold value, length or existing relation between potentially hazardous episodes (here described with TA) and an effect variable (here the mortality rate). In order to identify HWE with a significant relation to mortality rates, the approach as described in ~~(Krug et al., 2019)~~ Krug et al. (2019) was applied. In ~~this~~ that prior study, time series of TA and MDA8 were explored separately and the episodes, described as "events", were afterwards classified as temporally separated or co-occurring events of elevated TA and MDA8. Deviating from that approach, only HWE as characterized by elevated TA and identified by various threshold values are analyzed in this study. MDA8 is treated as an additional stressor during HWE and analyzed as described in Sect. 2.2.2.

2.2.1 Detection of HWE

~~Firstly, time~~ Time series of TA for each city were searched for HWE as the occurrence of at least three consecutive days exceeding a certain TA threshold value (TA_{Thres}). TA_{Thres} was iteratively increased in 0.5 °C steps within the range 10 °C to 30 °C. Secondly, at each TA_{Thres} TA magnitude (TA_{Mag}) was calculated for each HWE as the accumulated sum of the difference of daily TA and respective TA_{Thres} over the whole length of the HWE (sum of degree days above TA_{Thres}). Thirdly, univariate linear regressions were calculated between TA_{Mag} as predictor variable (logarithmized) and mean mortality rates during the HWE plus a maximum number of lag days (to account for possible lag effects in mortality rates after HWE) as the dependent variable over the whole study period. Regression models thus consist of a unique combination of TA_{Thres} and maximum lag days. Models for each TA_{Thres} were tested for a lag effect of maximum 0 to 7 days. Afterwards, the lag effect was fixed to four days, which was the mean lag effect across the analyzed cities. All presented results are based on this number (four). Episode-specific mean mortality rates of each model were tested for normal distribution (not shown). Results indicate inconclusive findings of normal and significant non-normal tested distributions dependent on city and model-specific TA_{Thres}. In conclusion, we keep the assumption of a quasi-normal distribution of mean mortality rates during HWE, acknowledging that our method is not the one ideal approach, or better than others, for any investigations using mortality data. However, in terms of our research questions it delivers sufficient information about detection and characterization of HWE as aimed in this study. The base mortality rate for each model is provided as the mortality rate for zero TA_{Mag} (y-intercept of the regression model), indicating conditions of no thermal stress. This approach was also sensitivity-tested for seasonal variances in the mortality rate by the use of a seasonal de-trended, LOESS-smoothed (Cleveland, 1979) mortality time series instead of the crude mortality rate. Differences are negligible, which shows that the original approach chosen is insensitive to seasonal variances. In addition, HWE occur usually during the summer month when mortality rates are low. For each regression model, the explained variance (r^2) was calculated. Error probabilities were calculated with a double-sided t-test. Regression models which were not statistically significant ($p >$ 0.05) or comprised less than five HWE over the study period were discarded from further analyses. Error estimates for each regression model were calculated as the standard error of the regression coefficient (RE_{RC}) and of the base mortality rate (RE_{BR}). Regressions were also calculated for HWE with a minimum duration of consecutive days different from three (1 to 5 days). The chosen minimum duration of three days yielded best results in terms of r^2, RE_{BR}, and RE_{RC}.

2.2.2 Multiple linear regressions

After detection of HWE, mean MDA8 (MDA8_{M}) were calculated for the total duration of each HWE. Multiple linear regressions (MLR) were then calculated using the ordinary least square error method with TA_{Mag} and MDA8_{M} of each HWE as predictor variables for mean mortality rates (as described in Sect. 2.2.1). The overall explained variance (r^2) and adjusted explained variance (r^2_{adj}) as well as the explained variance for each single variable ($r^2_{\text{TA}_{\text{Mag}}}$ and $r^2_{\text{MDA8}_{\text{M}}}$) were calculated. An interaction term ($r^2_{\text{TA}_{\text{Mag}},\text{MDA8}_{\text{M}}}$) was also estimated as a cross-product effect of both predictor variables. ~~Statistical~~ Overall statistical significance is assumed for an error probability of $p < 0.05$, calculated with a ~~double-sided t-test~~F-test.

3 Results

Table 1 shows statistics for TA and MDA8 during the analysis period for each city. The 50th percentile of TA ranges from 10.0 °C in Hamburg to 11.9 °C in Cologne. For the analyzed cities, the highest recorded maximum TA is 31.1 °C in Cologne and the lowest 28.2 °C in Hamburg. The 50th percentile of the MDA8 concentration varies between 55.3 µg m^{-3} in Frankfurt and 65.3 µg m^{-3} in Leipzig. In two cities, Frankfurt and Cologne, by far the absolute highest MDA8 concentrations were recorded during the study period ($>$ 240 µg m^{-3}, Table 1).

Table 1. Overview of city-specific statistics of the population (census corrected) at 31 December 2017. Statistics of air temperature and ozone concentrations are based on data from selected measurement sites during the years 2000 to 2017 (Table A1, Fig. A1). Cities are sorted from north to south, P refers to percentile. Sources: Population data: (DESTATIS, 2019), air temperature: (DWD, 2019), ozone concentrations: German Environment Agency (UBA), based on original data from air quality monitoring networks of the German federal states.

City	Population				Air temperature (daily average, °C)			Ozone (MDA8, µg m^{-3})		
	Total (No.)	under 18 (%)	over 65 (%)	Density (No. per km^2)	50th P	95th P	Max	50th P	95th P	Max
Hamburg	1 800 865	17.7	18.7	2385	10.0	20.3	28.2	56.3	101.7	192.1
Berlin	3 542 728	17.5	19.6	3976	10.5	22.4	30.5	58.0	117.9	192.6
Hanover	529 957	15.8	19.0	2594	10.4	21.0	29.0	61.6	114.9	208.0
Leipzig	573 070	17.1	20.8	1924	10.3	21.8	29.0	65.3	123.5	198.3
Cologne	1 079 186	17.1	17.4	2665	11.9	22.6	31.1	56.8	121.4	240.1
Frankfurt	741 978	17.8	15.8	2988	11.6	23.2	30.7	55.3	122.7	240.5
Stuttgart	625 658	16.5	18.1	3018	11.1	22.7	30.3	62.3	129.1	203.7
Munich	1 451 696	16.6	17.8	4672	10.4	22.4	29.5	61.7	120.2	185.6

3.1 Regression analysis

Figure 2 presents results of the univariate regression analysis. For all cities, the analysis yields statistically significant results between TA$_{\mathrm{Mag}}$ and mean mortality rates during HWE for a variety of TA$_{\mathrm{Thres}}$. In all cities, statistically significant models are characterized by a minimum absolute TA$_{\mathrm{Thres}}$ between 16 °C and 18 °C (Fig. 2, left panel). Results of all cities show generally increasing r^2 with increasing TA$_{\mathrm{Thres}}$. Yet, differences across cities can be seen in the range of TA$_{\mathrm{Thres}}$ and r^2 of the regression models. Highest values for r^2 are obtained for Berlin, Cologne, Frankfurt and Stuttgart with values of more than 60 % for HWE of high TA$_{\mathrm{Thres}}$. Cities with generally high TA (Table 1) also yield highest values of r^2. This may be a result of the absence of HWE identified by higher TA$_{\mathrm{Thres}}$ in cities like Hamburg, Hanover, Leipzig and Munich compared to the others. For all cities, increased mortality rates during HWE with TA$_{\mathrm{Thres}}$ $\leq$ 22 °C can be explained by around 20 % of TA$_{\mathrm{Mag}}$. Values of RE$_{\mathrm{BR}}$ are low for each city ($<$ 0.2) but show an increase towards higher TA$_{\mathrm{Thres}}$. Values of RE$_{\mathrm{RC}}$ are heterogeneous across different models as well as across different cities.

Whereas the range of absolute TA$_{\mathrm{Thres}}$ of significant models varies across the cities, a percentile-based order reveals a more similar pattern in terms of threshold-r^2 relationship across the cities (Fig. 2, right panel). For HWE with TA$_{\mathrm{Thres}}$ $>$ 95th percentile of the year-round TA distribution in 2000 to 2017, at least 20 % of the mortality rate can be explained by TA$_{\mathrm{Mag}}$ across all cities. ~~Except for Berlin and Cologne, r^2 is $<$ 20 % for HWE with TA$_{\mathrm{Thres}}$ $<$ 95th percentile. However, an~~ An increase in r^2 can be observed for all cities for HWE with TA$_{\mathrm{Thres}}$ $>$ 94th percentile.

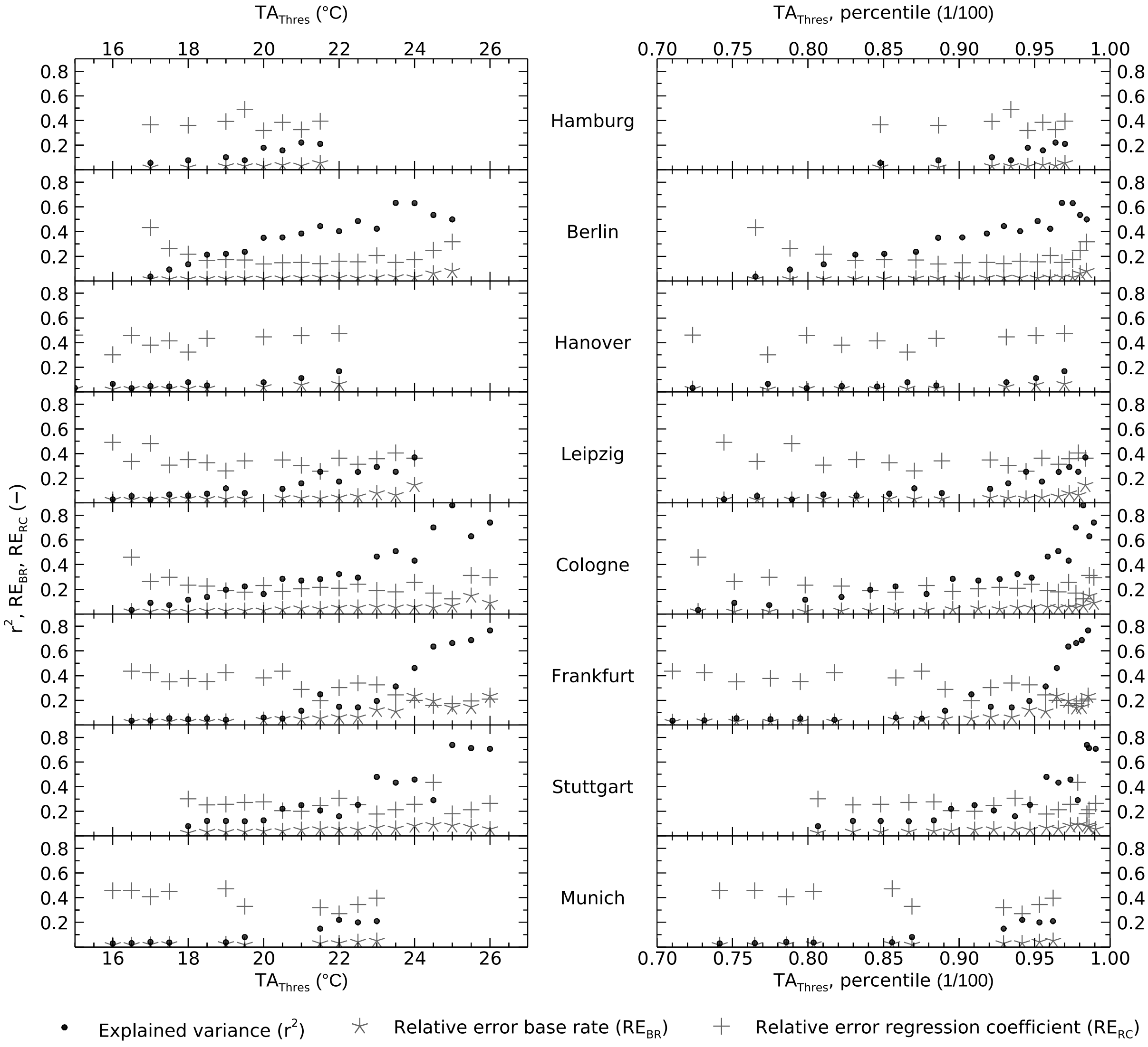

Figure 2. Statistically significant results ($p < 0.05$, t test) from the univariate regression analysis with TA$_{Mag}$ as predictor variable for each city. Left panel x axis: absolute threshold value for HWE detection (TA$_{Thres}$), right panel x axis: percentile of TA$_{Thres}$ referring to the whole analysis period 2000 to 2017. y axis: explained variance of the models (r^2), relative errors of the base rate (RE$_{BR}$) and the regression coefficient (RE$_{RC}$), respectively.

3.2 Multiple linear regression analysis

Results of the multiple linear regression and partitioning of r^2 are shown in Fig. 3. Generally, highest values are obtained for $r^2_{\mathrm{TA_{Mag}}}$, increasing with increasing $\mathrm{TA_{Thres}}$. This can be observed for almost all cities, while $r^2_{\mathrm{TA_{Mag}}}$ values vary between cities. In particular, for HWE identified by higher $\mathrm{TA_{Thres}}$ values variance in $\mathrm{TA_{Mag}}$ alone explains at least 20 % up to 60 % of the mortality rates in Berlin, Cologne, Frankfurt and Stuttgart. Other cities show overall lower values of $r^2_{\mathrm{TA_{Mag}}}$. Results also reveal that in all cities the variance of mortality rates during these HWE can partly be explained by the variance of $\mathrm{MDA8_M}$, independently from $\mathrm{TA_{Mag}}$. Particularly in Berlin, but also in Hanover and Stuttgart, mortality rates during HWE identified by high $\mathrm{TA_{Thres}}$ cannot solely be explained by $\mathrm{MDA8_M}$. However, this applies not to Frankfurt, where $r^2_{\mathrm{MDA8_M}}$ values reach higher values compared to $r^2_{\mathrm{TA_{Mag}}}$, and in addition increase with increasing $\mathrm{TA_{Thres}}$ (Fig. 3(f)). Differences between cities are also observable for the interaction term between both variables ($r^2_{\mathrm{TA_{Mag}},\mathrm{MDA8_M}}$). Whereas some cities show only marginal values (Hamburg, Hanover, Munich), the others show an increasing interaction term with increasing $\mathrm{TA_{Thres}}$, reaching up to 60 % in Frankfurt. A different pattern for the interaction term is visible for Berlin. Highest values of $r^2_{\mathrm{TA_{Mag}},\mathrm{MDA8_M}}$ are obtained for medium $\mathrm{TA_{Thres}}$ with declining trend towards higher $\mathrm{TA_{Thres}}$.

4 Discussion

4.1 Relationship between $\mathrm{TA_{Mag}}$ and mortality rates

The method used in this study allowed for an explorative identification and investigation of HWE, associated with an effect on mortality. In contrast to other investigations in the field of environmental epidemiology, the aim of this study was not to estimate air temperature or ozone related deaths. One of the main goals of this study was to identify HWE in multiple German cities, that are associated with increased mortality. In all cities, the strength of this association (r^2) increases with increasing $\mathrm{TA_{Thres}}$. This is generally comparable with results from other investigations that show greater impact on mortality for more intense HWE (e.g., Anderson and Bell, 2011; Tong et al., 2015).

However, the specific relationship between an absolute $\mathrm{TA_{Thres}}$ and associated r^2 is affected by the specific TA distribution of each city and selected measurement site. Regression analyses were undertaken based on data of one selected measurement site per city, representing the atmospheric conditions of each city. Yet, it must be noted that data at these sites are not only influenced by city-wide characteristics, but also by characteristics of the closest environment at each site. Therefore, $\mathrm{TA_{Thres}}$ is affected by the distinct air temperature distribution of the selected measurement site and might differ for other locations. The usage of absolute $\mathrm{TA_{Thres}}$ might thus be ambiguous for an inter-city comparison.

~~Throughout involved~~ Across the investigated cities, an increase of r^2 was obtained around the 95th percentile of each city-specific TA distribution. This is also reported by the multi-city risk evaluation of various heat wave definitions for Australian cities (Tong et al., 2015). The use of relative $\mathrm{TA_{Thres}}$ to identify HWE is thus suggested for studies investigating multiple cities to take into account possible differences in TA distributions and acclimatization of the population to the local-specific air temperature distribution (Anderson and Bell, 2009, 2011; Tong et al., 2015). The use of the 95th percentile could thus

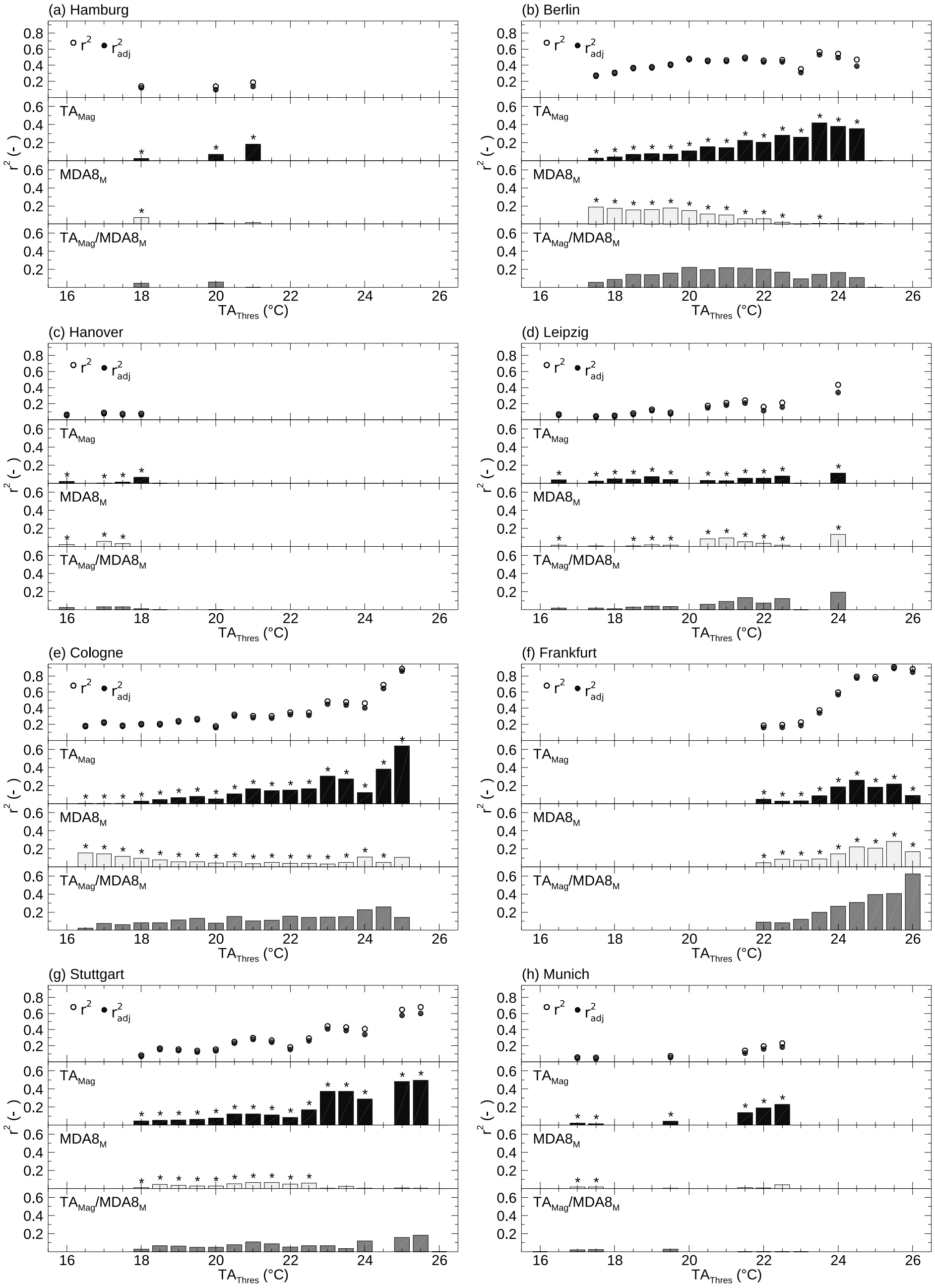

Figure 3. Results of the multiple linear regression (MLR) analysis between the predictor variables $\mathrm{TA_{Mag}}$ and $\mathrm{MDA8_M}$ and the mean mortality rate during HWE as independent variable. Each panel shows results for one city and different $\mathrm{TA_{Thres}}$ (x axis). Top row of each panel shows overall r^2 (empty circles) and r^2_{adj} (filled circles) of MLR models. Partitioned r^2 (y axis) are shown in the lower three rows for the predictors $\mathrm{TA_{Mag}}$ (top, black), $\mathrm{MDA8_M}$ (middle, light gray) as well as the interaction term of $\mathrm{TA_{Mag}}$ and $\mathrm{MDA8_M}$ (bottom, dark gray). Only results of overall statistically significant (F-test, $p < 0.05$) MLR models are displayed. Statistical significance of each predictor variable ($p < 0.05$) is marked with a star above each bar.

be interpreted as one possibility to identify HWE that capture most of the mortality effect. It has to be stressed, though, that results also reveal statistically significant regression models for HWE identified with $\mathrm{TA}_{\mathrm{Thres}}$ lower than the 95th percentile. Such HWE, identified via $\mathrm{TA}_{\mathrm{Thres}} < 95$th percentile, should thus likewise be considered as health relevant.

4.2 Relative contribution of $\mathrm{TA}_{\mathrm{Mag}}$ and $\mathrm{MDA8}_{\mathrm{M}}$ to mortality rates

Similar aspects as discussed above for the local dependence of air temperature measurements have to be noted also for ozone measurements. A comparison of regression analyses with the same method and based on data from different ozone measurement sites in Berlin was executed in ~~(Krug et al., 2019)~~Krug et al. (2019). The ozone measurement site that was used in this study differs from ~~the~~ that prior study. Yet, the data used here (Berlin Neukölln) revealed similar performance in terms of r^2 (Krug et al., 2019), but is the closest to the co-located TA measurement site (Berlin-Tempelhof).

The second goal of this study was to investigate how ozone concentration contributes to mortality rates during HWE. MLR results between the predictors $\mathrm{TA}_{\mathrm{Mag}}$, $\mathrm{MDA8}_{\mathrm{M}}$ and mean mortality rates show that the latter is explained across all cities by up to 60 % by the variance of $\mathrm{TA}_{\mathrm{Mag}}$. $\mathrm{MDA8}_{\mathrm{M}}$ alone partly explains mortality rates during HWE by up to 20 % in the investigated cities. This is in agreement with results of other studies which show that the effect of air temperature on mortality ~~is stronger~~ plays a major role in comparison to the effect of ozone (e.g., Scortichini et al., 2018; Krug et al., 2019). ~~$\mathrm{MDA8}_{\mathrm{M}}$ alone partly explains~~ Yet, it also underlines that besides air temperature, also ozone is a highly important factor explaining mortality rates during HWE~~by up to 20 % in the investigated cities. Except of Frankfurt, this is mostly visible for HWE that are identified with low $\mathrm{TA}_{\mathrm{Thres}}$~~. Figure 4 shows that during HWE, MDA8 (per day) can reach values of up to 190 $\mu\mathrm{g\,m^{-3}}$ (e.g. Fig. 4(e), Cologne). This exceeds the target value of 120 $\mu\mathrm{g\,m^{-3}}$ set by the European Union to protect human health (EU, 2008). More than 50 % of the days during HWE identified via $\mathrm{TA}_{\mathrm{Thres}} < 20$ °C or even lower (depending on respective city) even fall below the ozone guideline value recommended by the World Health Organization (WHO) of 100 $\mu\mathrm{g\,m^{-3}}$ (WHO, 2006). Associated adverse mortality effects during days with MDA8 values lower than the WHO guideline value for ozone were also found in the prior study focusing on Berlin (Krug et al., 2019) and in other studies and for other regions, e.g. Spain (Díaz et al., 2018) or cities in the United Kingdom (Atkinson et al., 2012; Powell et al., 2012).

However, the relative contribution of both $\mathrm{MDA8}_{\mathrm{M}}$ and $\mathrm{TA}_{\mathrm{Mag}}$ varies between cities and different $\mathrm{TA}_{\mathrm{Thres}}$. Particularly, in Berlin and Cologne (Fig. 3), $\mathrm{MDA8}_{\mathrm{M}}$ explains more of the mortality rate at low $\mathrm{TA}_{\mathrm{Thres}}$ than $\mathrm{TA}_{\mathrm{Mag}}$. ~~A~~ This may be due to the fact that, in general, lower $\mathrm{TA}_{\mathrm{Thres}}$ ~~captures~~ capture more HWE in which air temperature is relatively low, but ozone concentrations can reach high values. This may occur during dry, sunny days in early summer with high photo-oxidative production rate, which promote the formation of ozone (Monks, 2000; Otero et al., 2016). This is also shown and discussed in ~~(Krug et al., 2019)~~ ~~.~~ Krug et al. (2019). The reason why the high contribution of $\mathrm{MDA8}_{\mathrm{M}}$ to mortality rates at low $\mathrm{TA}_{\mathrm{Thres}}$ can only be observed in Berlin and Cologne remains hypothetical. We suspect that differences between cities regarding meteorological factors such as wind or humidity, topography, the emission rate of precursors through vegetation as well as population-specific factors (e.g. demography, socio-economy) may lead to this finding. Further in-depth investigations to understand these differences would allow for a better understanding and would thus be of high value, yet go beyond the scope of this study.

With increasing TA$_{\mathrm{Thres}}$ a declining contribution of MDA8$_{\mathrm{M}}$ ~~alone~~ to the mortality rate is observable (particularly visible in Berlin and Cologne, but except for Frankfurt, Fig. 3(b)~~and~~ , (e) and (f), respectively). ~~An~~ But besides this decreasing contribution of MDA8$_{\mathrm{M}}$, an increasing contribution of ozone as reflected in the interaction term ($r^2_{\mathrm{TA_{Mag}},\mathrm{MDA8_M}}$) ~~explaining mortality rates~~ can be observed in all cities. This interaction is most pronounced in Berlin, Cologne, Frankfurt, Stuttgart and Leipzig~~and indicates that ozone contributes to mortality rates~~. It indicates that during HWE identified by higher TA$_{\mathrm{Thres}}$ ~~. Towards HWE identified by higher TA$_{\mathrm{Thres}}$ air temperature becomes the more dominant factor explaining mortality rates and the variance of MDA8$_{\mathrm{M}}$ is directly linked to the variance of TA$_{\mathrm{Mag}}$~~ozone contributes to mortality rates mostly as a statistically inseparable part of the air temperature effect. Similar conclusions were drawn by ~~(Burkart et al., 2013) and is~~ Burkart et al. (2013) and they are basically comparable to results that the mortality effect of ozone is strengthened during days of elevated air temperature and HWE (Vanos et al., 2015; Analitis et al., 2018; Scortichini et al., 2018).

4.3 Inter-city differences

Strongest associations between TA$_{\mathrm{Mag}}$ as well as MDA8$_{\mathrm{M}}$ and mortality rates were found for Berlin, Cologne, Frankfurt and Stuttgart. These cities are also those in which highest values of the 50th and 95th percentile and the maximum ~~air temperature~~ TA are recorded (Table 1). Based on absolute TA$_{\mathrm{Thres}}$, it is not clear if the lower effect observed in Hamburg, Hanover, Leipzig and Munich are reasoned by the absence of HWE with TA$_{\mathrm{Thres}} > 24$ °C (Leipzig, Munich) or TA$_{\mathrm{Thres}} > 22$ °C (Hamburg, Hanover), which occur in other cities and show strongest relationships to mortality rates.

Heterogeneities across cities were obtained not only for city-specific absolute TA$_{\mathrm{Thres}}$ but also for their respective values of r^2, which is also reported in other studies investigating other cities across Europe (e.g., Filleul et al., 2006; Baccini et al., 2011; Burkart et al., 2013; Breitner et al., 2014; Analitis et al., 2018; Scortichini et al., 2018). City-specific peculiarities such as demographic or socio-economic characteristics at the community level may cause these differences (Stafoggia et al., 2006; Anderson and Bell, 2011; Baccini et al., 2011). For instance, differences in age structure may influence the results. Elderly people were shown to be more vulnerable to heat (Yu et al., 2010; Scherer et al., 2013; Benmarhnia et al., 2015). Thus, a higher ratio of elderly people may strengthen the mortality rate during HWE. The ratio of the elderly over 65 years are in fact heterogeneous among the involved cities (Table 1)~~but~~. Yet, a linkage to city-specific relation to the effect on mortality rates cannot be deduced. Heterogeneities across cities may also be caused by local-specific geographical characteristics. The close distance to the North and Baltic Sea, associated with a maritime climate, may prevent Hamburg from air temperatures that lead to higher impacts on mortality rates as observed for other cities. Similarly, Munich is not only the city situated at the highest altitude in this study but also closest to the Alps, which may influence ~~the~~ local weather conditions and lead to weather characteristics resulting in weaker relations between high air temperature and mortality rates. However, these reasons remain hypothetical and do not explain the low impacts in Hanover and Leipzig. To sum up, differences between cities are conceivable to be an overlay of city-specific characteristics, such as demographic and geographic factors.

Results of this study underline the complexity to find similarities across different cities to determine appropriate criteria to identify hazardous episodes in terms of a health-related adverse effect, if there was such an effort. Some cities show a strong relationship between TA$_{\mathrm{Mag}}$ and mortality rates, but these are also the cities experiencing highest air temperatures in this

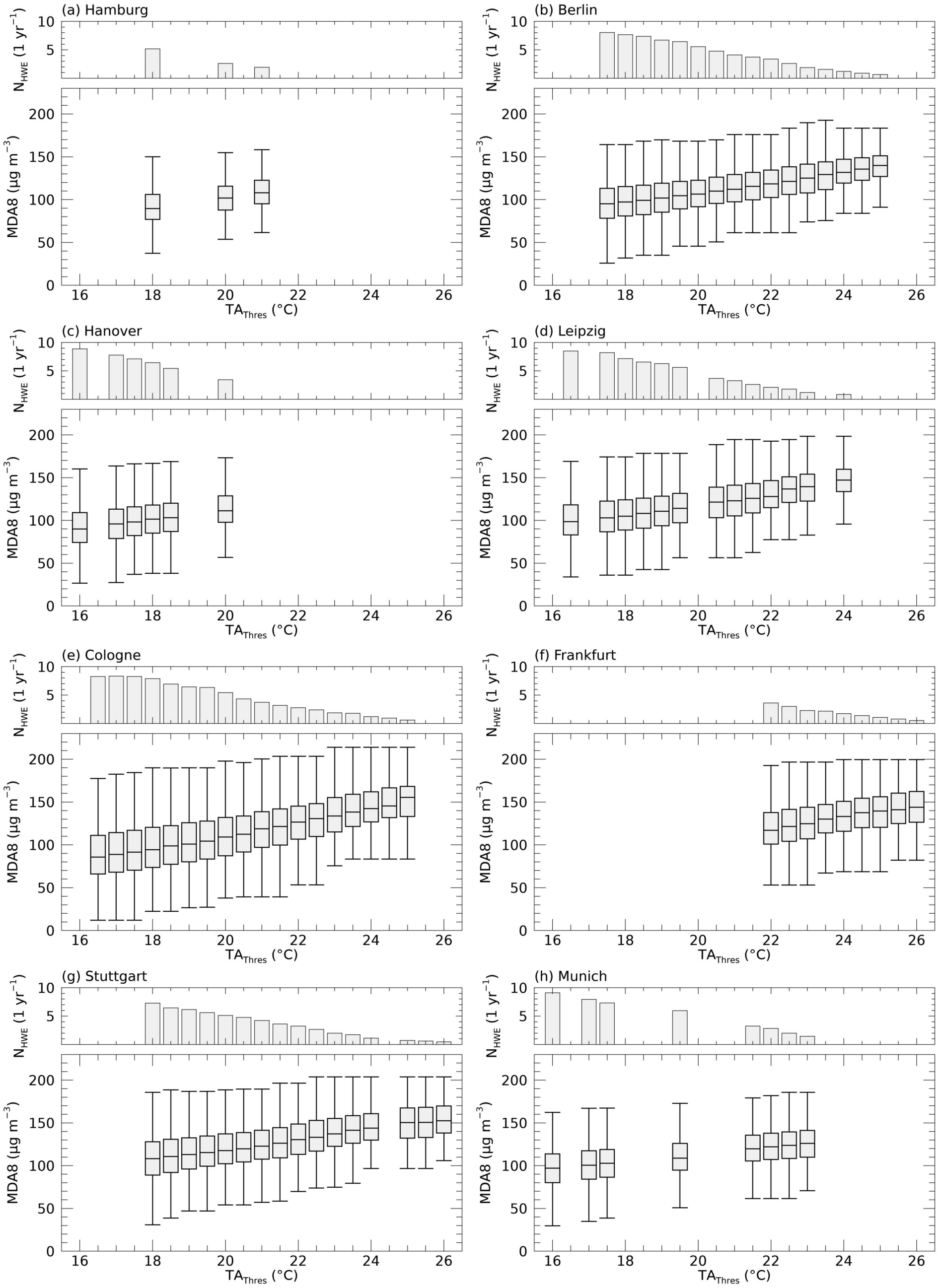

Figure 4. Top row of each panel: average number of HWE per year (y axis), detected per TA_{Thres} (x axis). Bar-whisker plots display daily values of MDA8 during detected HWE. Boxes refer to the range between the 25th and 75th percentile (inter quartile range IQR), median values are given as solid lines, and whiskers are the minimum and maximum values excluding outliers (less than Q1-1.5·IQR, greater that Q3+1.5·IQR). Only results of overall statistically significant ~~regression~~ (F-test, $p < 0.05$) MLR models are shown.

study (Table 1). Moreover, the strength of this relationship also varies across cities for equal TA_{Thres} values. However, most similarities arise by comparing results based on their local-specific percentile of the air temperature distribution rather than using absolute thresholds. This further also includes the interactive contribution of ozone.

Further research is needed to investigate local characteristics in more detail such as geographic drivers, socio-economic or socio-demographic factors which may affect the air-temperature-ozone-mortality relationship. These may cause local heterogeneities. Further, some studies also identified other air pollutants that affect mortality during HWE. Especially, concentrations of particulate matter were also found to be increased during episodes of hot and dry weather (Tai et al., 2010; Schnell and Prather, 2017; Kalisa et al., 2018). Enhanced emission of secondary fine particles during hot weather conditions accompanied with reduced air movement may lead to this increased concentration especially in urban areas. Further, particulate matter is also associated with adverse mortality effect and is thus additionally relevant to human health during HWE (Burkart et al., 2013; Analitis et al., 2014; Schnell and Prather, 2017; Analitis et al., 2018).

5 Conclusions

This study investigated mortality rates during HWE in eight cities in Germany from 2000 to 2017. HWE were identified with a risk-based approach as a result of regressions between daily average air temperature above a threshold and mean mortality rates during these episodes. HWE and thereby statistically significant regressions were detected in all selected cities for various air temperature thresholds. Results reveal a strong increase in the association around the 95th percentile of the local-specific air temperature distribution. Apart from air temperature, ozone concentrations were shown to contribute to mortality rates during HWE. While air temperature was identified to be the dominant factor for elevated mortality rates, ozone concentrations alone contribute to those by up to 20 %. Additionally, results reveal that the effect of both stressors on mortality cannot be separated in many cases, highlighting their strong interaction. Especially for HWE identified via higher threshold values of air temperature, ozone mostly contributes to mortality rates ~~as statistically inseparable interaction with~~ statistically inseparable from air temperature. To which extend air temperature and ozone explain mortality rates differs across cities and for various air temperature thresholds. Some cities show weak associations, while the contributions of both stressors to mortality rates are more pronounced in others.

This study underlines the complexity to deduce one universal threshold value in order to identify potentially hazardous HWE in terms of a health effect. Yet, it also emphasizes that besides air temperature ozone contributes to mortality during HWE in German cities. Future research should focus on city-specific characteristics such as population characteristics or geographical peculiarities, which are likely leading to heterogeneities across cities and which may influence the respective air-temperature-ozone-mortality relationship.

Appendix A

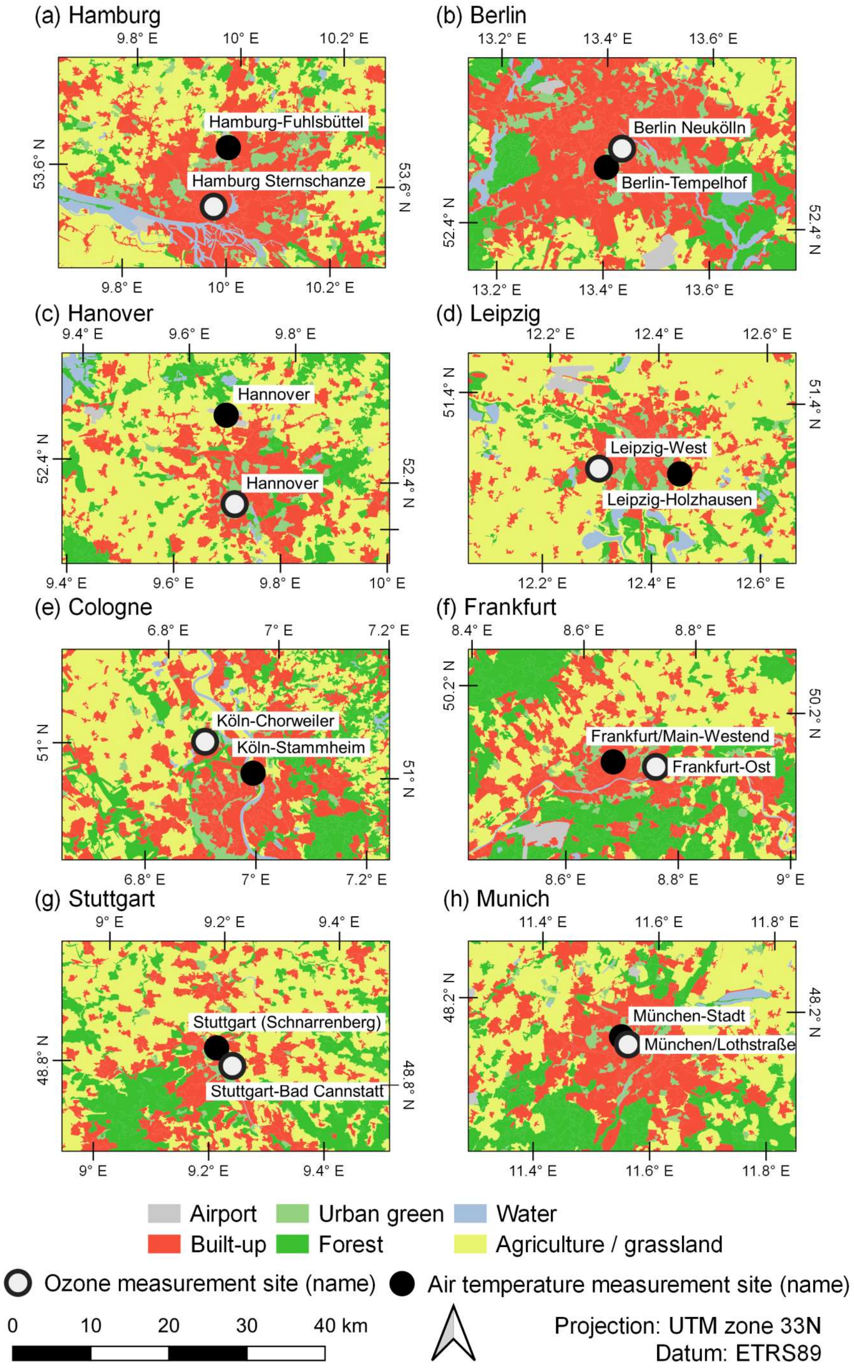

Figure A1. Location of selected air temperature and ozone measurement sites in the investigated cities. Land cover classification is based on CORINE 2018, v20 (EEA, 2019).

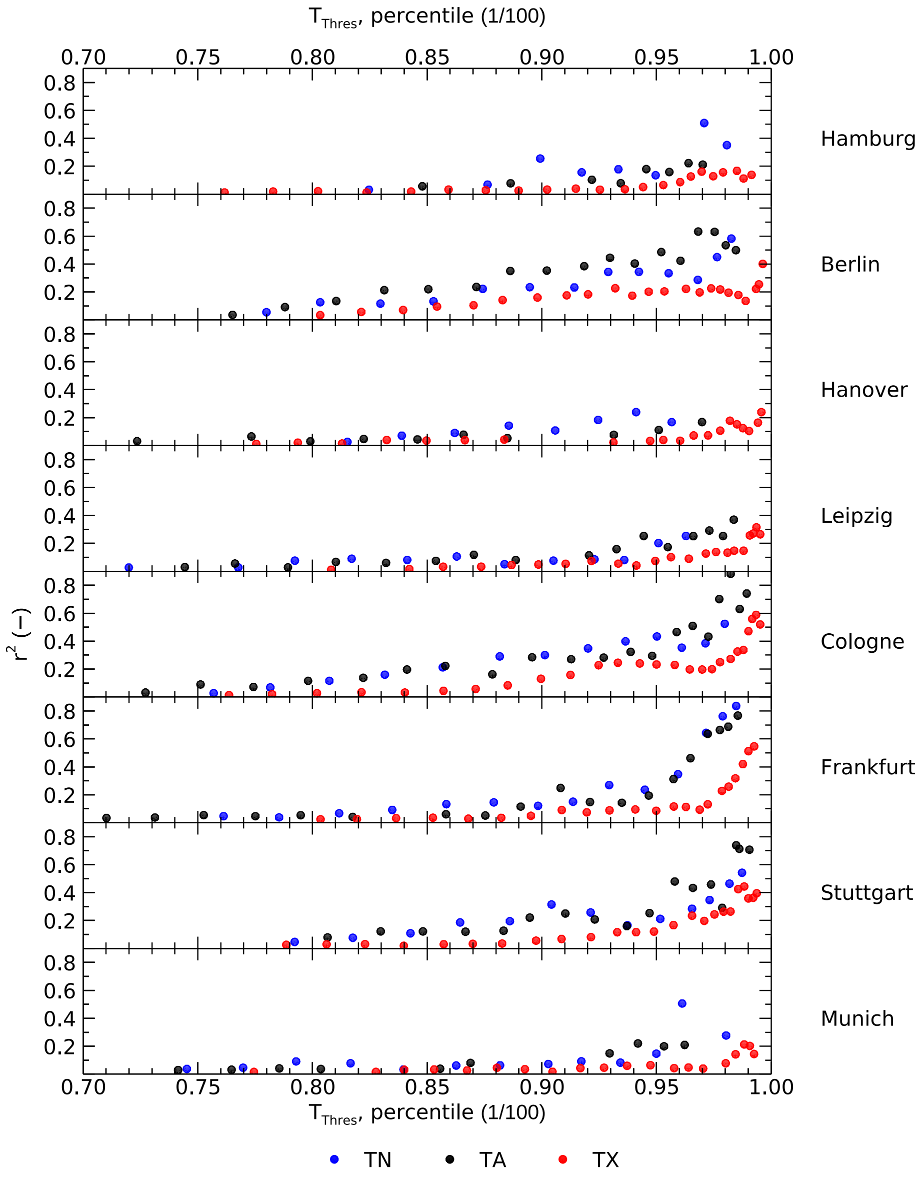

Figure A2. Comparison of regression analysis based on different predictor variables daily minimum air temperature (TN, blue), daily average air temperature (TA, black) and daily maximum air temperature (TX, red). Each panel displays results for one city. X axis: percentile of the respective air temperature distribution, y axis: explained variance (r^2) of regression models.

Table A1. Selected air temperature and ozone measurement sites of each city. Air temperature data were obtained from the German Weather Service (DWD) (DWD, 2019), data of ozone concentrations were obtained by the German Environment Agency (UBA), based on originally measured data of air quality networks of the German federal states.

City	Air temperature measurements				Ozone measurements				
	Site name	Site location		Elevation (m a.m.s.l.)	Site name	Site location		Elevation (m a.m.s.l.)	Horizontal distance between co-located sites (km)
		Longitude (° E)	Latitude (° N)			Longitude (° E)	Latitude (° N)		
Hamburg	Hamburg-Fuhlsbüttel	9.9881	53.6332	14	Hamburg Sternschanze	9.9679	53.5641	15	7.8
Berlin	Berlin-Tempelhof	13.4021	52.4675	48	Berlin Neukölln	13.4308	52.4895	35	3.1
Hanover	Hannover	9.6779	52.4644	58	Hannover	9.7061	52.3629	85	11.5
Leipzig	Leipzig-Holzhausen	12.4462	51.3151	138	Leipzig-West	12.2974	51.3179	115	10.4
Cologne	Köln-Stammheim	6.9777	50.9894	43	Köln-Chorweiler	6.8846	51.0193	46	7.3
Frankfurt	Frankfurt/Main-Westend	8.6694	50.1269	124	Frankfurt-Ost	8.7463	50.1253	100	5.5
Stuttgart	Stuttgart (Schnarrenberg)	9.2000	48.8281	314	Stuttgart-Bad Cannstatt	9.2297	48.8088	235	3.1
Munich	München-Stadt	11.5429	48.1631	515	München/Lothstraße	11.5547	48.1545	521	1.3

Code availability. Code can be made available by the authors upon request.

Author contributions. Alexander Krug conceived the concept, Dieter Scherer and Daniel Fenner gave technical and conceptual support. Dieter Scherer provided the risk-analysis software. Alexander Krug collected the data, carried out the analyses, prepared the original draft of the manuscript and produced the visualizations. All authors gave support in the writing process, discussed the results, and commented on the manuscript. Dieter Scherer and Hans-Guido Mücke supervised the analysis.

Competing interests. The authors declare that they have no conflict of interest.

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