Original Article

Heat-Related Mortality in the Extreme Summer of 2022

An Analysis Based on Daily Data

Veronika Huber, Susanne Breitner-Busch, Cheng He, Franziska Matthies-Wiesler, Annette Peters, Alexandra Schneider

Institute of Epidemiology, The Institute for Medical Information Processing, Biometry, and Epidemiology (IBE), Medical Faculty, Ludwig-Maximilians-Universität (LMU), München, Germany: Dr. rer. nat. Veronika Huber, Dr. rer. nat. Susanne Breitner-Busch, Prof. Dr. rer. biol. hum. Annette Peters

Institute of Epidemiology, Helmholtz Center Munich – German Research Center for Environmental Health, Neuherberg, Germany: Dr. rer. nat. Veronika Huber, Dr. rer. nat. Susanne Breitner-Busch, Cheng He Ph.D., Dr. phil. Franziska Matthies-Wiesler; Prof. Dr. rer. biol. hum. Annette Peters, Dr. rer. biol. hum. Alexandra Schneider

German Alliance on Climate Change and Health (KLUG e.V.), Berlin, Germany: Dr. phil. Franziska Matthies-Wiesler

Munich Heart Alliance, German Center for Cardiovascular Health (DZHK e.V., partner-site Munich), München, Germany: Prof. Dr. rer. biol. hum. Annette Peters

Summary

Background: Estimating the excess mortality attributable to heat is a central element of the documentation of the consequences of climate change for human health. Until now, estimates of heat-related deaths in Germany by the Robert Koch Institute (RKI) have been based on weekly mortality records.

Methods: Our study is the first to use higher resolution data—i.e. daily all-cause mortality linked to daily mean temperatures—from each of the German federal states to assess the heat-related mortality from 2000 to 2023 in Germany, employing quasi-Poisson models and multivariate meta-regression analyses. We focus our analysis on the extreme summer of 2022.

Results: Our analysis yielded an estimate of 9100 (95% CI: [7300; 10 700]) heat-related deaths in Germany for the summer of 2022, whereas previous studies of the RKI estimated the number of heat-related deaths at 4500 [2100; 7000]. When we set a higher temperature threshold in the definition of the heat risk, we arrived at a figure of 6900 [5500; 8100] heat-related deaths in 2022. In other summers that—similarly to 2022—were characterized by large fluctuations in daily mean temperatures, we also robustly estimated higher numbers of heat-related deaths than the RKI did. The exclusion of reported deaths due to COVID-19 had only a minor effect on our estimates.

Conclusion: Our findings suggest that previous studies based on weekly mortality data have underestimated the full extent of heat-related mortality in Germany, particularly in the extreme summer of 2022. The monitoring of heat-related mortality should be systematic and as comprehensive as possible if it is to enable the development of effective heat-health action plans.

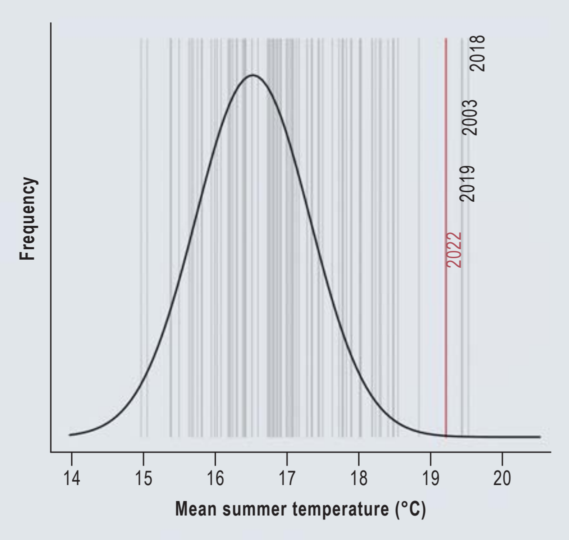
Cite this as
Huber V, Breitner-Busch S, He C, Matthies-Wiesler F, Peters A, Schneider A: Heat-related mortality in the extreme summer of 2022—an analysis based on daily data. Dtsch Arztebl Int 2024; 121: 79–85. DOI: 10.3238/arztebl.m2023.0254

The increasing number of episodes of extreme heat represents one of the most significant health risks posed by climate change worldwide and in Germany (1, 2). The association between high outdoor temperatures and excess mortality is well documented for German cities (3, 4), regions (5), and Germany as a whole (6, 7). The risk of heat-related mortality is particularly high among the elderly (7, 8). In the majority of cases, heat causes an acute deterioration in pre-existing cardiovascular and respiratory diseases (3). Estimates suggest that almost a third of heat-related deaths in German cities are attributable to anthropogenic climate change that has already taken place (9).

Due to decentralized structures in data collection and for reasons of data protection, mortality data is usually more readily available on a weekly basis, particularly if the data are to be used within a narrow time frame and the age and sex of the deceased are also to be taken into account. This is one of the main reasons why previous statistical estimates of heat-related mortality in Germany (7) as well as at the European level (10) are based on weekly data.

The documentation of heat-related deaths during periods of extreme heat in the recent past can serve as a basis on which to assess Germany's current vulnerability to climate change. According to an analysis by the German Weather Service (*Deutscher Wetterdienst*), the summer of 2022 was one of the four warmest summers since records began (11). Analyses conducted by the Robert Koch Institute based on weekly data estimated the number of heat-related deaths in Germany in the summer of 2022 to be 4500 [2100; 7000] (12, 13). A recent study evaluating data from all over Europe based on weekly mortality records puts the heat-related mortality for Germany in the summer of 2022 at the rounded-up figure of 8200 [5400; 11 000] deaths (14).

Figure 1



Mean temperature in Germany during the summer months of June, July, and August (gray) in the period 1940–2023 compared to the estimated frequency distribution (black) in the climatological reference period (1961–1990). The four warmest years are marked. Red is used to highlight 2022. See *eFigure 2* for data on the individual federal states.

The large discrepancy between the estimates available for summer 2022 based on weekly data (12–14) can be explained by the different methods used to calculate excess mortality and by uncertainties regarding the definition of a threshold temperature. The thermal optimum that is usually used as a threshold value to define heat-related mortality can often be determined only imprecisely as the minimum of the temperature–mortality curve (15). Moreover, in addition to the thermal optimum, other criteria for the determination of a temperature threshold are also used in the literature (16, 17).

At the same time, there is good evidence that high temperatures can have an acute effect on the risk of mortality within only a matter of days (18). Therefore, it is our hypothesis that heat waves lasting only a few days, as was frequently the case in 2022, are underestimated in their effect on heat-related mortality in analyses based on weekly mortality records, irrespective of the temperature threshold and the precise statistical modeling method used to calculate excess mortality.

To investigate this hypothesis, the present study estimates the number of heat-related deaths (and death rates per 100 000 inhabitants) in the extreme summer of 2022 and all years since 2000 in the German federal states and nationwide on the basis of daily temperature data and daily death counts. We used established epidemiological modeling approaches (18) and accounted for a possible adaptation to the increasing number of periods of extreme heat over the last two decades. In sensitivity analyses, we also took into account the reported COVID-19 deaths and reflected the uncertainty in determining a temperature threshold to define heat-related mortality.

Methods

Data

Data on total daily deaths in the years 2000–2023 (up to and including September 17, 2023) in the 16 German federal states are taken from two special publications issued by the German Federal Statistical Office (*Statistisches Bundesamt*) (19, 20). These include all deaths registered by German registry offices, which are assigned to the federal states by the officially registered municipalities of residence of the deceased. COVID-19 deaths reported on a daily basis in the federal states were made available by the Robert Koch Institute (up to and including 16 July 2023). The annual data on the total population in the federal states for the period 2000–2022 came from the Genesis database of the German Federal Statistical Office (21). These statistics take into account all individuals subject to registration in Germany. Since the data on population status in 2023 were not yet available at the time of the analysis, the population status for 2022 was assumed for that year. Daily mean temperatures in the federal states and in Germany as a whole in the period from 1940 to 2023 (up to and including 30 September 2023) were determined as area-averaged values from hourly 2-m temperatures in the freely available ERA5 re-analysis data (22). We defined that an extreme summer occurred if the mean summer temperature (June–August) was more than three standard deviations above the mean of the climatological reference period of 1961–1990.

Statistical analysis

Temperature–mortality associations were estimated in a two-stage approach, according to Gasparrini et al. (18) *(eSupplement, eFigures 1 a + b)*. In the first stage, quasi-Poisson regression models were calculated on the basis of daily mortality and temperature time series in the individual federal states. Here, we modeled the temperature–mortality associations with a non-linear function that accounted for lag effects of up to 21 days. In the second stage, federal state-specific model coefficients were combined in meta-regression models.

We then determined the number of daily heat-related deaths in the federal states based on the model coefficients from the second stage of the analysis, daily mean temperatures, and deaths registered, according to Gasparrini and Leone (23) (equation in the *eSupplement*). In this calculation, we took into account only those days on which the observed daily mean temperature was above the excess risk temperature (ERT). We defined the ERT as the daily mean temperature above which there was a consistently and significantly increased relative risk of mortality (lower bound of the 95% confidence interval > 1) (24).

In order to account for possible adaptation processes, we calculated the temperature–mortality associations in two subperiods (2000–2010 and 2011–2022). The estimates for 2023 were based on the temperature–mortality associations for the more recent time period (2011–2022) and the provisionally registered mortality data. We restricted the calculation of heat-related deaths to the period May–September in order to achieve the highest possible degree of comparability with the existing studies based on weekly data (12–14).

Table 1

Estimated number of heat-related deaths in Germany, based on temperature–mortality associations in the periods 2000–2010 and 2011–2022 for the standard model and the sensitivity analyses conducted, including 95% confidence intervals [95% CI]

Year	Standard model T > ERT; including COVID-19 deaths	Additional temperature threshold		Without COVID-19 deaths*2
		"Moderate" heat: ERT < T ≤ T95	"Intense" heat T > T95	
2000	2200 [2000; 2400]	700 [500; 900]	1500 [1400; 1700]	–
2001	4000 [3600; 4400]	1200 [900; 1500]	2800 [2500; 3100]	–
2002	3400 [3100; 3800]	900 [700; 1200]	2500 [2200; 2800]	–
2003	11 600 [10,500; 12,700]	1400 [1000; 1900]	10 200 [8900; 11,400]	–
2004	2600 [2300; 2900]	1100 [800; 1400]	1500 [1400; 1600]	–
2005	3600 [3200; 4000]	1500 [1100; 1900]	2100 [1900; 2400]	–
2006	9000 [8200; 9800]	1900 [1500; 2400]	7100 [6300; 7700]	–
2007	2800 [2500; 3100]	1000 [700; 1300]	1800 [1600; 2000]	–
2008	3000 [2600; 3300]	1200 [900; 1500]	1800 [1600; 1900]	–
2009	2200 [1800; 2600]	1300 [1000; 1700]	900 [800; 1000]	–
2010	7600 [6900; 8200]	1200 [900; 1600]	6300 [5500; 7000]	–
2011	1500 [1200; 1800]	600 [500; 800]	800 [700; 1000]	1500 [1100; 1800]
2012	2900 [2400; 3500]	1000 [800; 1200]	2000 [1500; 2300]	2900 [2300; 3500]
2013	5100 [4000; 6000]	1200 [1000; 1500]	3800 [3000; 4600]	4900 [3900; 5900]
2014	3000 [2300; 3600]	1200 [900; 1500]	1800 [1400; 2200]	2900 [2300; 3600]
2015	9100 [7200; 10,900]	1600 [1200; 2000]	7500 [5900; 9000]	8800 [6900; 10,500]
2016	3900 [3100; 4600]	1200 [900; 1600]	2600 [2200; 3000]	3800 [3100; 4600]
2017	2700 [2200; 3300]	1600 [1300; 2000]	1100 [900; 1300]	2700 [2100; 3400]
2018	10 700 [8600; 12,600]	2500 [1900; 3100]	8200 [6500; 9800]	10 500 [8300; 12,400]
2019	9400 [7500; 11,000]	1700 [1300; 2200]	7600 [6200; 8900]	9100 [7200; 10,700]
2020	6100 [5000; 7200]	1300 [1000; 1600]	4900 [3900; 5800]	6000 [4800; 7200]
2021	2800 [2200; 3400]	800 [600; 1000]	2000 [1500; 2400]	2700 [2100; 3300]
2022	9100 [7300; 10,700]	2200 [1700; 2700]	6900 [5500; 8100]	8600 [6800; 10,200]
2023*1	4500 [3500; 5500]	1900 [1400; 2300]	2700 [2000; 3200]	–

*1 Preliminary estimate based on temperature–mortality associations for 2011–2022 and registered deaths up to and including 17 September 2023; estimates excluding registered COVID-19 deaths are unfeasible as yet due to incomplete data at the time of the analysis.
*2 Since excluding registered COVID-19 deaths could affect temperature–mortality associations over the entire second period of the analysis (2011–2022), results of this sensitivity analysis are listed starting from 2011 already, rather than from 2020, the year of the pandemic, onwards.
ERT, excess risk temperature; T95, 95th percentile of temperatures

As sensitivity analyses, we carried out the calculations firstly on the basis of daily all-cause mortality minus reported COVID-19 deaths. Secondly, we determined the 95% percentile of daily mean temperatures from May to September (T95) and defined "moderate" heat as ERT < daily mean temperature ≤ T95 and "intense" heat as daily mean temperature > T95, in order to reflect uncertainties in the definition of a heat threshold.

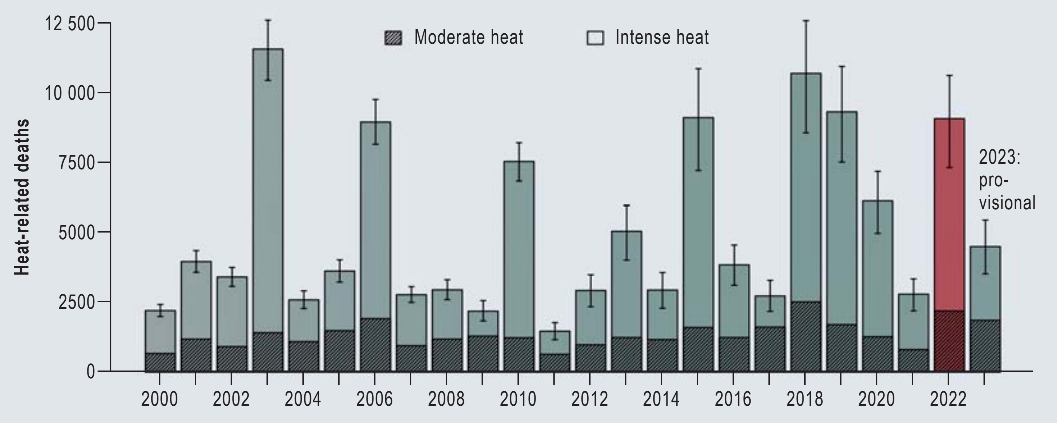
Data analysis was performed with R (version 4.3.1) using the *dlnm* and *mixmeta* packages. The programing code is available upon request from the first author.

Results

According to the available temperature data, the summer of 2022 was the fourth warmest summer across Germany since 1940, surpassed only by the summers of 2003, 2018, and 2019 *(Figure 1)*. The mean summer temperature in Germany was almost 3° C (or more than three standard deviations) above the temperature of the 1961–1990 climatological reference period. In the federal states of Baden-Württemberg, Bavaria, Rheinland-Palatinate, Saarland, and Thuringia, the only years in which mean summer temperatures were higher than in 2022 were 2003 and 2018 *(eFigure 2)*. In the summer of 2022, a considerable excess mortality was seen in Germany *(eFigure 3)*.

The estimated temperature–mortality associations in the German federal states showed a significant rise in relative risk of mortality above a daily mean temperature of between 19° C and 22° C *(eFigure 4)*. On average, these temperatures correspond to daily maximum temperatures

Figure 2



Estimated number of heat-related deaths in Germany per year, based on temperature–mortality associations in the periods 2000–2010 and 2011–2022 *(eFigure 4)*. The error bars show the 95% confidence intervals. Red is used to highlight 2022. The shaded area shows the separation into "moderate" and "intense" heat according to the two temperature thresholds (ERT and T95). The numbers for 2023 are a provisional estimate. ERT, excess risk temperature; T95, 95th percentile of temperatures

of roughly 24–27° C *(eFigure 5)*. Only in eight federal states (Berlin, Bremen, Hamburg, Hesse, Lower Saxony, North Rhine-Westphalia, Rheinland-Palatinate, and Saarland), we observed a certain reduction in the risk of heat-related mortality in recent years *(eFigure 4)*.

Based on these associations, we calculated 9100 [7300; 10 700] heat-related deaths in Germany for the summer of 2022 *(Table 1, Figure 2)*. That is roughly the same number of heat-related deaths as we estimated for the summers of 2006, 2015, and 2019. Only in the historic record-breaking summer of 2003 and the extreme summer of 2018 were the estimates of heat-related deaths, at 11 600 [10 500; 12 700] and 10 700 [8600; 12 600], respectively, considerably higher than the number for 2022. In comparison, the median across all years was only 3800 [3300; 4200] heat-related deaths, and for 2023 we (provisionally) estimated 4500 [3500; 5500] heat-related deaths *(Table 1, Figure 2)*. In all federal states, our estimates of heat-related deaths for the summer of 2022 were comparable to the estimates for previous years with extreme summers *(Table 2, eFigure 6)*. The relative classification of 2022 based on heat-related mortality rates per 100,000 inhabitants, which account for the population trend, differs only marginally from the results based on the absolute mortality figures *(eFigure 7, eFigure 8)*.

In the extreme summer of 2022, the highest number of estimated heat-related deaths per day was 1030 [800; 1220] at the national level, attributable to the extremely high temperatures recorded across large parts of Germany on 20 July, 2022 *(Figure 3)*. The number of COVID-19 deaths reported in the summer of 2022 was < 173 cases per day, and thus far smaller than the number of deaths attributable to individual hot days *(eFigure 3)*. The individual federal states showed a similar picture *(eFigures 9 a+b)*.

In the sensitivity analysis, we found that an evaluation based on all-cause mortality minus the reported COVID-19 deaths did not yield significantly different results *(Table 1)*: Our estimate of heat-related deaths for 2022 was 8600 [6800; 10 200] instead of 9100 [7300; 10 700], based on our standard approach. We estimated 6900 [5500; 8100] heat-related deaths across Germany in the summer of 2022 that were attributable to "intense" heat *(Table 1, Figure 2)*, defined as daily mean temperatures above the 95th percentile of the distribution in summer *(eFigure 4)* .

Discussion

This analysis is the first to use a dataset of daily death counts and daily mean temperatures across all federal states to estimate heat-related mortality in Germany since 2000. Our results show that significant excess mortality in the order of between 9000 and 10000 heat-related deaths occurred in Germany in summers with periods of extreme heat over the last decade (2015, 2018, 2019, and most recently 2022). For the summer of 2022, our estimation was 9100 [7300; 10,700] heat-related deaths nationwide. More than a tenth of these are attributable to extremely high temperatures recorded on a single day in Germany (20 July 2022).

Our estimation of temperature–mortality associations in two time periods pointed to a certain level of adaptation to higher temperatures in some federal states. However, the identified differences in mortality risk at the same temperature were small and showed overlapping 95% confidence intervals *(eFigure 4)*. These results are in concordance with the results of previous studies, in which no clear evidence was found that an adaptation to more frequent and intense periods of heat had taken place across all regions of Germany (7). In a recently published study by Rai et al. (25), the estimated temperature-mortality associations in 15 German cities in the period 1994–2016 even suggested an increase in the relative risk of heat-related mortality from respiratory causes of death in the age groups < 75 years. Future research must elucidate where and under which conditions the German population has adapted to the warming experienced in recent decades. As part of this, and to the extent possible, adaptation factors such as the introduction and improvement of heat early warning systems (26) and heat-health action plans (27), as well the distribution of airconditioning systems (28), should be taken into consideration in the analysis of changes over time in heat-related mortality risk.

Another important factor is the demographic trend, which could not be taken into account here due the lack of age group-specific mortality data at a daily resolution. In fact, neglected trends in an aging population potentially make adaptation processes appear weaker than they actually are. On average across all federal states, the percentage of the total population in the 65–74, 75–84, and ≥ 85-year age groups rose over the study period by 2.1%, 2.8%, and 1.4%, respectively *(eFigure 10)*. Thus, one would generally expect to see a rise in the risk of heat-related mortality for the overall population, had adaptation processes not obscured this.

In our standard approach, the estimation of heat-related deaths is based on all-cause mortality data, regardless of reported COVID-19 deaths. Previous studies indicate a weak temperature effect in the spread of SARS-CoV-2 and COVID-19 incidence, with partial evidence of less transmission and lower incidence when outdoor temperatures are high (29, 30). At the same time, there is evidence of an immunosuppressive effect of heat exposure (31), and the generally greater vulnerability of the population during episodes of extreme heat could ultimately also increase COVID-19-related mortality in the case of an existing wave of infection. Due to these uncertainties, we deem a consideration of all-cause mortality to be a robust analytical approach that does not treat COVID-19 differently to any other cause of death (not further identified here) underlying overall mortality figures. Additional analyses also showed that our estimation of heat-related deaths since 2020 is relatively robust compared to when reported COVID-19 deaths are excluded *(Table 1)*. This is consistent with the observation that, even in 2022, reported COVID-19 deaths represent only a small proportion of overall mortality in the May–September period (approximately 3% nationwide) *(eTable)*.

We attribute at least some of the differences between previous studies conducted by the Robert Koch Institute (12, 13) and the present analysis to the fact that the weekly averages used in those studies can reflect only a portion of the daily temperature–mortality associations. The variability in daily mean temperatures compared to the weekly mean in summer 2022 was unusually high, especially in the northern and eastern federal states *(eFigure 11)*. Therefore, there is a clear difference, particularly for 2022, between the results of the present analysis and the estimates from the Robert Koch Institute based on weekly data *(eFigure 12)*. In contrast, temperature variability, for example in the most recent summer of 2023, was comparatively low across all federal states *(eFigure 11)*. As a result, the differences between our analyses based on daily data and the estimates from the Robert Koch Institute based on weekly data (13) for 2023 are comparatively small *(eFigure 12)*.

Table 2

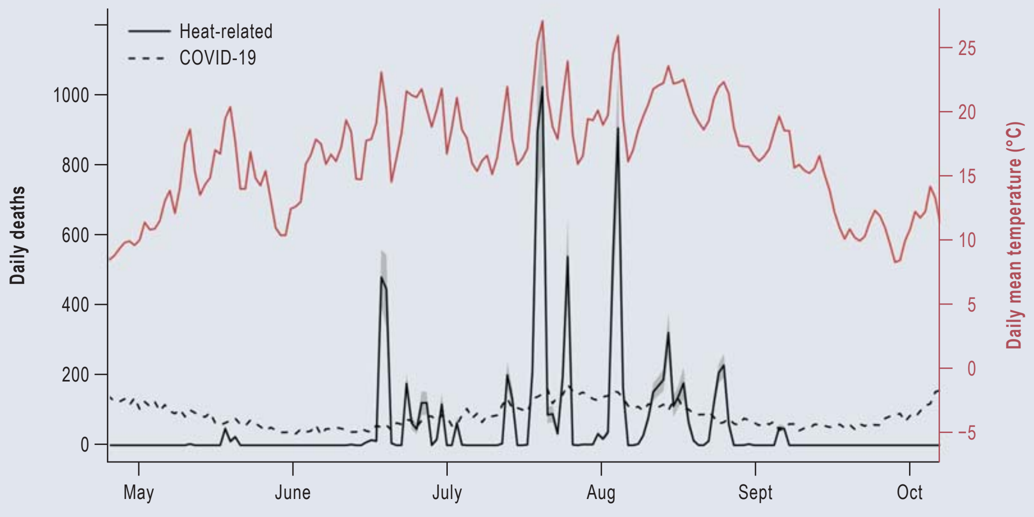
Estimated number of heat-related deaths in the German federal states in summer (May–September) 2022, including 95% confidence interval

Federal state	Mean estimate [95% confidence interval]
Baden-Württemberg	1270 [1070; 1460]
Bavaria	1040 [670; 1370]
Berlin	400 [270; 520]
Brandenburg	410 [310; 500]
Bremen	60 [40; 80]
Hamburg	160 [110; 210]
Hesse	570 [450; 700]
Mecklenburg-West Pomerania	190 [120; 250]
Lower Saxony	770 [600; 940]
North Rhine-Westphalia	2300 [1980; 2620]
Rheinland-Palatinate	510 [410; 600]
Saarland	160 [110; 200]
Saxony	480 [340; 610]
Saxony-Anhaltt	350 [260; 420]
Schleswig-Holstein	220 [90; 330]
Thuringia	240 [130; 340]

In addition to the temporal data resolution, the definition of a threshold temperature has a crucial effect on the calculation of heat-related mortality. Based on our standard model (using ERT as the threshold temperature), we systematically identify more deaths attributable to heat in all years compared to studies available to date from the Robert Koch Institute *(eFigure 12)*. If one considers a higher threshold temperature (T95), the differences between our analysis and those studies tend to be smaller *(eFigure 12)*. Under this setup, discrepancies directly attributable to the differing temporal resolutions of the data (particularly in 2010, 2015, and 2022) become more clearly visible (*eFigure 12*).

If one compares our results for summer 2022 with the estimates in the most recent Europe-wide study (14), one sees an underestimation by around 10% in heat-related mortality based on weekly mortality records compared to daily records. When considering the model-based results from the Robert Koch Institute, the underestimation is between 35% and 50% *(eFigure 12)*. This is due in particular to the fact that the European study (14) defined temperature thresholds using a methodology that more closely resembles our study than do the calculations of the Robert Koch Institute (12, 13). Other epidemiological studies that include a stratification by age, sex, and cause of death, together with physiological investigations into heat stress, are required in order to further narrow down the threshold temperature above which one can assume a causal relationship between heat exposure and mortality risk.

Figure 3



Estimated number of daily heat-related deaths (solid black line, with gray 95% confidence band), reported COVID-19 deaths (dashed black line), and daily mean temperatures (red) in Germany in the summer of 2022. The estimation of heat-related deaths per day takes into account the cumulative mortality risk and the average of observed deaths during the subsequent 21 days.

We conclude that heat poses a serious health risk in Germany, as our results highlight in a striking manner. A summer such as 2022 will be considered a cool summer in decades to come as climate change progresses (32). If no efforts are made to expand and improve existing heat-health action plans and to protect particularly vulnerable groups of the population (33, 34), heat-related mortality in Germany could rise sharply (4). Against this background, the monitoring of heat-related mortality is an important component of comprehensive health care. However, analyses based on weekly data could substantialla underestimate heat-related mortality, at least in individual years, compared to daily evaluations.

Conflict of interest statement
The authors declare that no conflict of interests exists.

Manuscript received on 23 June 2023, revised version accepted on 16 November 2023.

Translated from the original German by Christine Rye.

References

1. Romanello M, Di Napoli C, Drummond P, et al.: The 2022 report of the Lancet Countdown on health and climate change: health at the mercy of fossil fuels. Lancet 2022; 400: 1619–54.
2. Matthies-Wiesler F, Herrmann M, Schulz C, et al.: The Lancet Countdown on Health and Climate Change Policy—Policy Brief für Deutschland 2021. www.klimawandel-gesundheit.de/wp-content/uploads/2021/10/20211020_Lancet-Countdown-Policy-Germany-2021_Document_v2.pdf (last accessed on 3 May 2023).
3. Breitner S, Wolf K, Devlin RB, Diaz-sanchez D, Peters A, Schneider A: Short-term effects of air temperature on mortality and effect modification by air pollution in three cities of Bavaria, Germany: a time-series analysis. Sci Total Environ 2014; 486: 49–61.
4. Huber V, Krummenauer L, Peña-Ortiz C, et al.: Temperature-related excess mortality in German cities at 2 °C and higher degrees of global warming. Environ Res 2020; 186: 109447.
5. Muthers S, Laschewski G, Matzarakis A: The Summers 2003 and 2015 in South-West Germany: heat waves and heat-related mortality in the context of climate change. Atmosphere 2017, 8: 224.
6. Karlsson M, Ziebarth NR: Population health effects and health-related costs of extreme temperatures: comprehensive evidence from Germany. J Environ Econ Manage 2018; 91: 93–117.
7. Winklmayr C, Muthers S, Niemann H, Mücke HG, an der Heiden M: Heat-related mortality in Germany from 1992 to 2021. Dtsch Arztebl Int 2022; 119: 451–7.
8. Rai M, Breitner S, Wolf K, Peters A, Schneider A, Chen K: Impact of climate and population change on temperature-related mortality burden in Bavaria, Germany. Environ Res Lett 2019; 14: 124080.
9. Vicedo-Cabrera AM, Scovronick N, Sera F, et al.: The burden of heat-related mortality attributable to recent human-induced climate change. Nat Clim Chang 2021; 11: 492–500.
10. van Daalen KR, Romanello M, Rocklöv J, et al.: The 2022 Europe report of the Lancet Countdown on health and climate change: towards a climate resilient future. Lancet Public Health 2022; 7: e942–65.
11. Deutscher Wetterdienst: Deutschlandwetter im Sommer 2022. www.dwd.de/DE/presse/pressemitteilungen/DE/2022/20220830_deutschlandwetter_sommer2022_news.html (last accessed on 25 March 2023).
12. Winklmayr C, an der Heiden M: Hitzebedingte Mortalität in Deutschland 2022. Epid Bull 2022; 42: 3–9.
13. an der Heiden M, Winklmayr C, Buchien S, Schranz M, RKI-Geschäftsstelle für Klimawandel & Gesundheit, Diercke M, Bremer V: Wochenbericht zur hitzebedingten Mortalität KW 38/2023 vom 05.10.2023; Robert Koch-Institut; DOI: 10.25646/11720.
14. Ballester J, Quijal-Zamorano M, Méndez Turrubiates RB, et al.: Heat-related mortality in Europe during the summer of 2022. Nat Med 2023; 29: 1857–66.
15. Tobías A, Armstrong B, Gasparrini A: Investigating uncertainty in the minimum mortality temperature—methods and application to 52 Spanish cities. Epidemiology 2017; 28: 72–6.
16. Siebert H, Uphoff H, Grewe HA: [Monitoring heat-related mortality in Hesse]. Bundesgesundheitsblatt Gesundheitsforschung Gesundheitsschutz 2019; 62: 580–8.
17. an der Heiden M, Muthers S, Niemann H, Buchholz U, Grabenhenrich L, Matzarakis A: Heat-related mortality—an analysis of the impact of heatwaves in Germany between 1992 and 2017. Dtsch Arztebl Int 2020; 117: 603–9.
18. Gasparrini A, Guo Y, Hashizume M, et al.: Mortality risk attributable to high and low ambient temperature: a multicountry observational study. Lancet 2015; 386: 369–75.

19. Destatis: Sterbefälle, Fallzahlen nach Tagen, Wochen, Monaten, Altersgruppen, Geschlecht und Bundesländern für Deutschland, 2016–2023. www.destatis.de/DE/Themen/Gesellschaft-Umwelt/Bevoelkerung/Sterbefaelle-Lebenserwartung/Tabellen/sonderauswertung-sterbefaelle.html (last accessed on 17 October 2023).
20. Destatis: Sterbefälle, Fallzahlen nach Tagen, Wochen, Monaten, Altersgruppen, Geschlecht und Bundesländern für Deutschland, 2000–2015. www.destatis.de/DE/Themen/Gesellschaft-Umwelt/Bevoelkerung/Sterbefaelle-Lebenserwartung/Tabellen/sonderauswertung-sterbefaelle-endgueltige-daten.html?nn=209016 (last accessed on 27 January 2023).
21. Destatis: Fortschreibung des Bevölkerungsstandes. www-genesis.destatis.de/ (last accessed on 4 October 2023).
22. Hersbach H, Bell B, Berrisford P, et al.: ERA5 hourly data on single levels from 1940 to present. Copernicus Climate Change Service (C3S) Climate Data Store (CDS): www.cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-single-levels?tab=overview (last accessed on 4 October 2023).
23. Gasparrini A, Leone M: Attributable risk from distributed lag models. BMC Med Res Methodol 2014; 14: 55.
24. Petitti DB, Hondula DM, Yang S, Harlan SL, Chowell G: Multiple trigger points for quantifying heat-health impacts: new evidence from a hot climate. Environ Health Perspect 2016; 124: 176–83.
25. Rai M, Breitner S, Huber V, Zhang S, Peters A, Schneider A: Temporal variation in the association between temperature and cause-specific mortality in 15 German cities. Environ Res 2023; 229: 115668.
26. Matzarakis A, Laschewski D, Muthers S: The heat health warning system in Germany—application and warnings for 2005 to 2019. Atmosphere 2020; 11: 170.
27. Blättner B, Grewe HA, Janson D, et al.: Arbeitshilfe zur Entwicklung und Implementierung eines Hitzeaktionsplans für Kommunen. www.hs-fulda.de/fileadmin/user_upload/FB_Pflege_und_Gesundheit/Forschung___Entwicklung/Klimawandel_Gesundheit/Arbeitshilfe_zur_Entwicklung_und_Implementierung_eines_Hitzeaktionsplans_fuer_Kommunen_21.03_final.pdf (last accessed on 28 March 2023).
28. Sera F, Hashizume M, Honda Y, et al.: Air conditioning and heat-related mortality—a multi-country longitudinal study. Epidemiology 2020; 31: 779–87.
29. Nottmeyer L, Armstrong B, Lowe R, et al.: The association of COVID-19 incidence with temperature, humidity, and UV radiation—a global multi-city analysis. Sci Total Environ 2023: 854: 158636.
30. Sera F, Armstrong B, Abbott S, et al.: A cross-sectional analysis of meteorological factors and SARS-CoV-2 transmission in 409 cities across 26 countries. Nat Commun 2021; 12: 1–11.
31. Presbitero A, Melnikov VR, Krzhizhanovskaya VV, Sloot PMA: A unifying model to estimate the effect of heat stress in the human innate immunity during physical activities. Sci Rep 2021; 11: 1–18.
32. Freychet N, Hegerl GC, Lord NS, Lo YET, Mitchell D, Collins M: Robust increase in population exposure to heat stress with increasing global warming. Environ Res Lett 2022; 17: 064049.
33. Bund/Länder Ad-hoc Arbeitsgruppe: Handlungsempfehlungen für die Erstellung von Hitzeaktionsplänen zum Schutz der menschlichen Gesundheit. Bundesgesundheitsblatt Gesundheitsforschung Gesundheitsschutz 2017; 60: 662–72.
34. Kaiser T, Kind C, Dudda L, Sander K: Klimawandel, Hitze und Gesundheit: Stand der gesundheitlichen Hitzevorsorge in Deutschland und Unterstützungsbedarf der Bundesländer und Kommunen. UMID: Umwelt und Mensch – Informationsdienst, 2021, 1: 27–37; www.adelphi.de/en/publication/klimawandel-hitze-und-gesundheit (last accessed on 3 May 2023).

Corresponding author
Dr. rer. nat. Veronika Huber
IBE-Lehrstuhl für Epidemiologie am Helmholtz Zentrum München
Ludwig-Maximilians-Universität (LMU)
Ingolstädter Landstraße 1
85764 Neuherberg, Germany
veronika.huber@ibe.med.uni-muenchen.de

Cite this as:
Huber V, Breitner-Busch S, He C, Matthies-Wiesler F, Peters A, Schneider A: Heat-related mortality in the extreme summer of 2022—an analysis based on daily data. Dtsch Arztebl Int 2024; 121: 79–85.
DOI: 10.3238/arztebl.m2023.0254

Supplementary material
eMethods Section, eTables, eFigures:
www.aerzteblatt-international.de/m2023.0254

eSupplement

Heat-Related Mortality in the Extreme Summer of 2022—An Analysis Based on Daily Data

Veronika Huber et al.

veronika.huber@ibe.med.uni-muenchen.de

eMethods

Step 1: Modeling the temperature–mortality associations in the individual German federal states

On the basis of the federal state-specific time series of daily deaths and daily mean temperatures in the periods 2000–2010 and 2011–2022 (total, n = 8401 per federal state), we calculated quasi-Poisson regression models according to Gasparrini et al. (18). Here, we modeled the temperature–mortality associations using a distributed-lag non-linear model (DLNM), which incorporates the delayed effect of temperature exposure on mortality risk. The DLNM consisted of a quadratic B-spline with three knots at the 10th, 75th, and 90th percentiles of the federal state-specific temperature distribution and a further natural cubic spline to model the time lag of up to 21 days. Considering up to 21-days lag is a usual assumption when modeling temperature-related mortality (18), which, with regard to heat, accounts for short-term mortality displacements (often referred to as "harvesting") (23). We controlled for day of the week as a categorical variable and possible seasonal and long-term trends via a natural cubic spline with 8 degrees of freedom per year.

Step 2: Multivariate meta-regression of the federal state-specific reduced model coefficients

We pooled the reduced model coefficients of the federal states reflecting the cumulative mortality risk added up over all time lags considered (lags 1–21) in a multivariate meta-regression model. In addition to an intercept, the model also included the average annual temperature and the temperature range in the federal states as meta-predictors. The federal states were all equally weighted. From this model, we calculated so-called best-linear unbiased predictors (BLUPs) as a compromise between the partially unstable estimates of the model coefficients from the first stage and the pooled estimators from the meta-regression. Figures S1a and S1b show that the first-stage estimates of the temperature–mortality associations in our analysis diverge from the BLUP-based estimates in only a small number of federal states.

Step 3: Calculating heat-related excess mortality

To express the temperature–mortality associations as relative risk (RR) and calculate heat-related excess mortality, the next step is to determine a reference temperature at which, by definition, there is no risk of heat-related mortality. We calculated this temperature of minimum mortality (T_{mm}) according to standard methods (18) as the minimum of the curve derived from the BLUPs, considering the 1^{st}-99^{th} percentiles of the temperature distribution. The RR then describes the probability of death at a particular temperature T compared to the probability of death at T_{mm}. The number of heat-related deaths S on day t with temperature T is derived, based on the "forward method" of Gasparrini and Leone (23), as

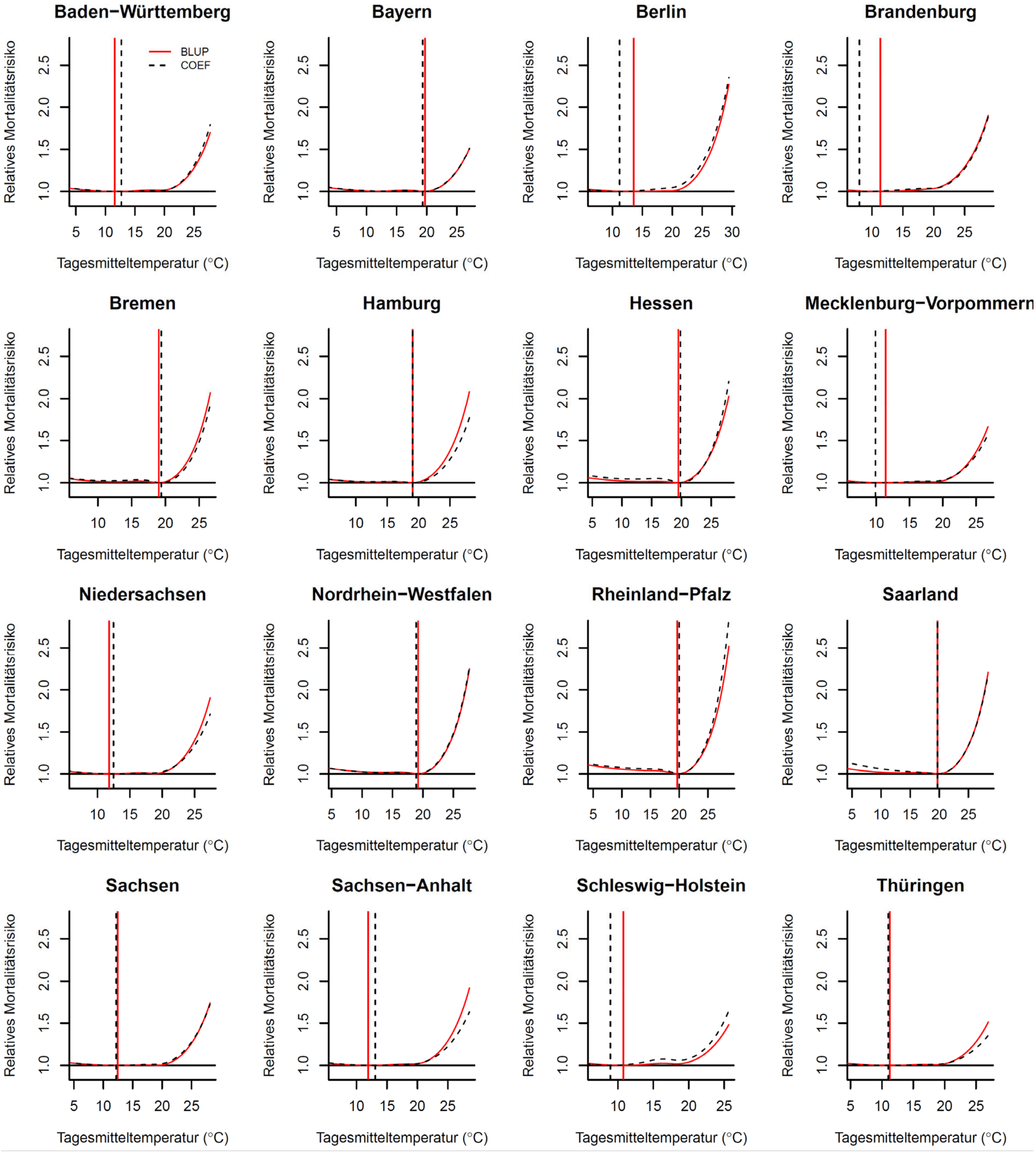
$$S_{T,t} = \begin{cases} \left(1 - e^{-(f(T_t,\theta) - f(T_{mm},\theta))}\right)\left(\sum_{l=0}^{L} \frac{G_{t+l}}{L+1}\right), \ if\ T_t > ERT \\ 0,\ if\ T_t \leq ERT \end{cases} \qquad \text{(Eq. 1)}$$

where f and θ describe the temperature–mortality association that is obtained from the BLUPs in the second analytical step. G represents the registered total mortality, L describes the maximum lag number (here, 21 days), and ERT refers to the excess risk temperature (see the *Methods Section* in the main text). In our sensitivity analysis, we replaced ERT in Eq. 1 with the 95^{th} percentile of daily mean temperatures (T95). The 95% empirical confidence intervals (CI) were calculated using a bootstrap procedure, drawing 1000 times from a multivariate normal distribution of the reduced model parameters (BLUPs), following the procedure in Gasparrini et al. (18).

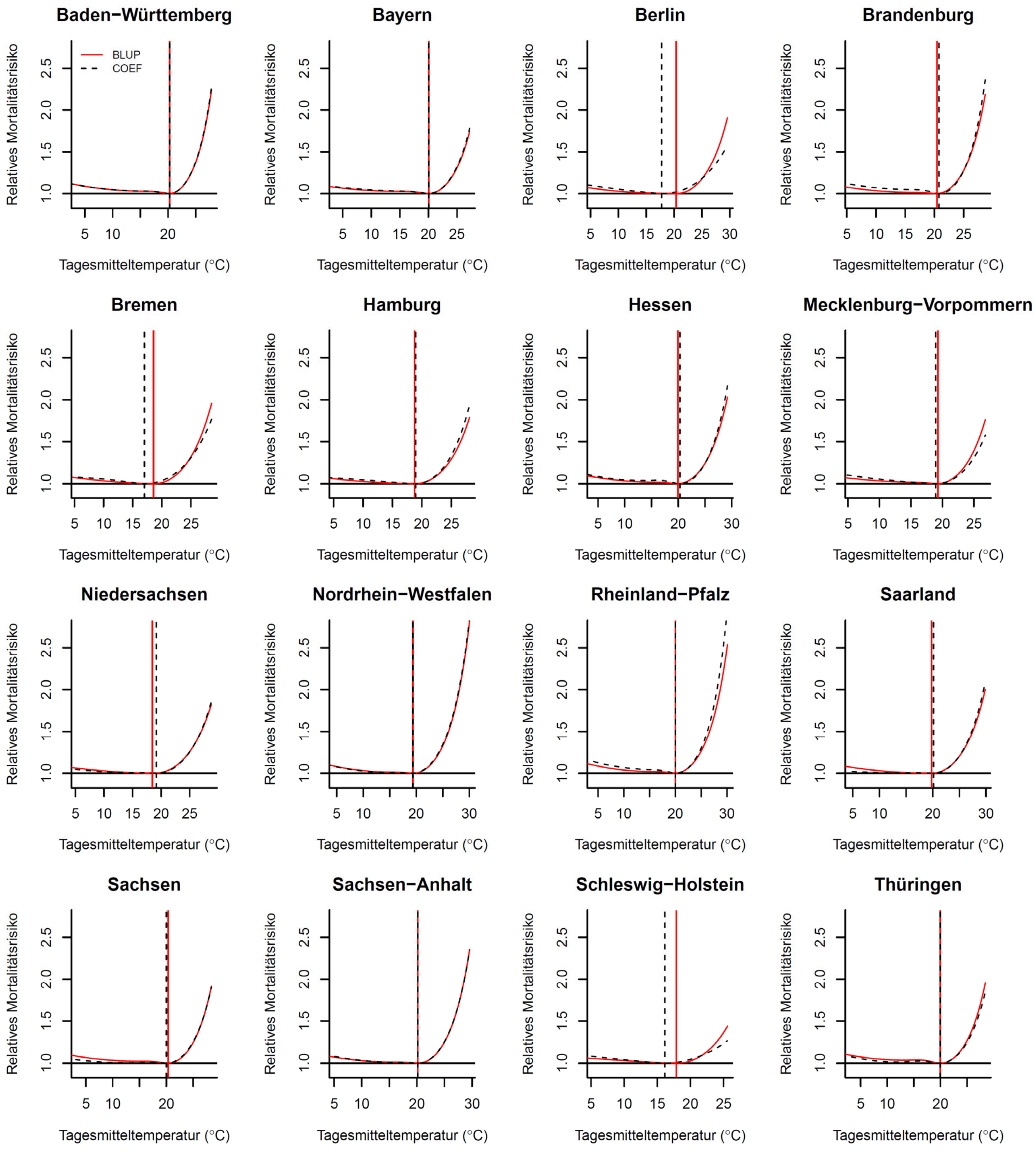
Since we considered all-cause mortality, our analysis also included accidental deaths that were possibly indirectly related to heat (e.g., motorbike or swimming accidents). However, we cannot make any statements on the share of these causes of death in the total heat-related mortality, since we do not have access to the cause-of-death data.

eTabelle Prozentualer Anzahl der gemeldeten COVID-19-Todefälle an der Gesamtmortalität im Zeitraum Mai-September in den Jahre 2020-2022, für alle Bundesländer und deutschlandweit.

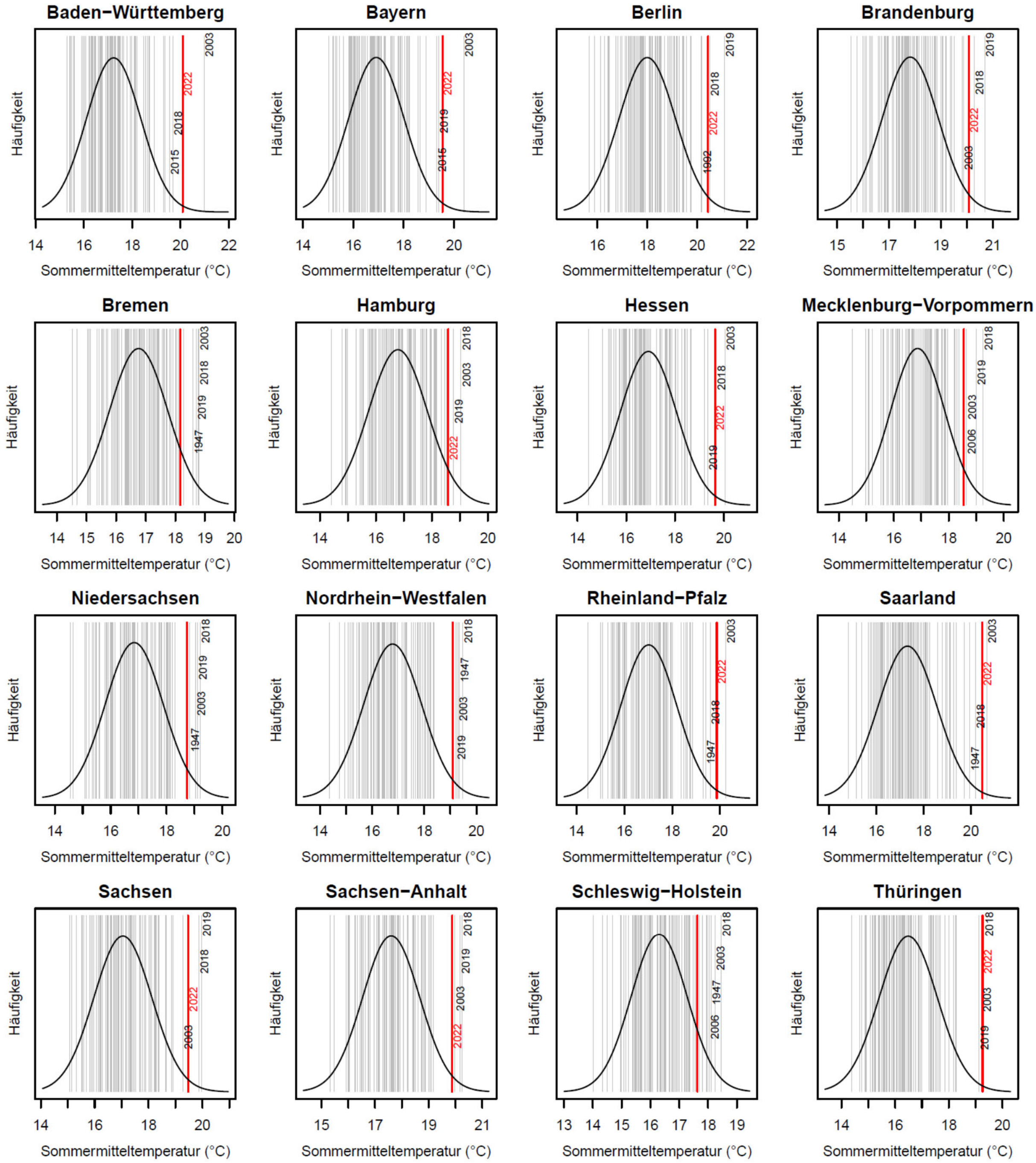
	2020	**2021**	**2022**
Baden-Württemberg	0,9	2,3	2,6
Bayern	1,0	2,2	3,4
Berlin	0,5	1,3	1,9
Brandenburg	0,2	1,4	2,1
Bremen	0,9	1,4	2,4
Hamburg	0,9	2,6	5,8
Hessen	0,7	2,6	3,3
Mecklenburg-Vorpommern	0,0	1,4	3,1
Niedersachsen	0,5	1,4	4,3
Nordrhein-Westfalen	0,7	2,3	2,7
Rheinland-Pfalz	0,4	1,6	2,6
Saarland	0,8	1,4	3,1
Sachsen	0,3	3,6	2,7
Sachsen-Anhalt	0,2	2,1	2,6
Schleswig-Holstein	0,3	1,0	2,5
Thüringen	0,9	3,1	3,1
Deutschland	0,6	2,1	3,0



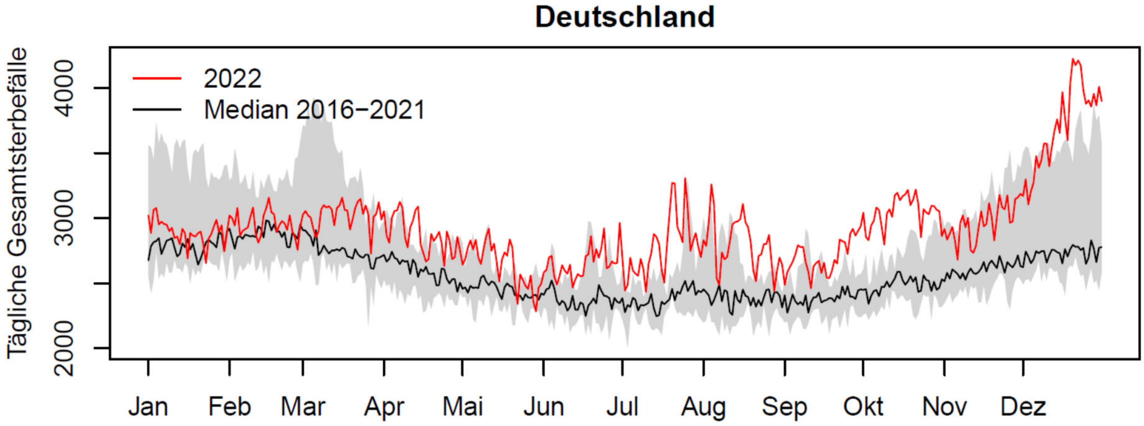
eGrafik 1a Temperatur-Mortalitäts-Zusammenhänge auf Basis der geschätzten Modellkoeffizienten aus dem ersten (COEF, schwarz) und zweiten Analyseschritt (BLUP, rot) für den Zeitraum 2000-2010 (siehe eMethoden). Die vertikalen Linien zeigen die Temperatur des minimalen Mortalitätsrisikos (T_{mm}).



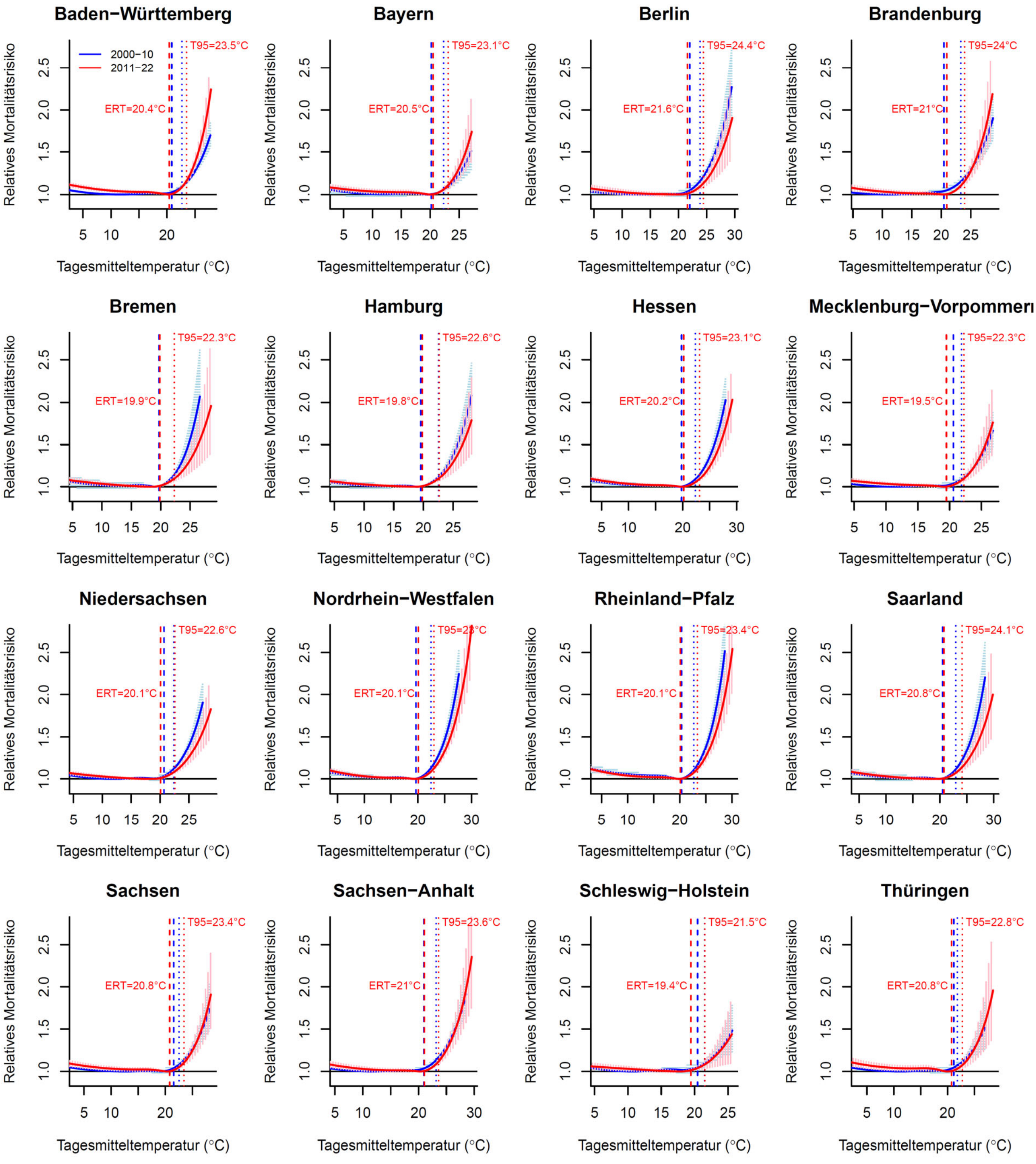
eGrafik 1b Wie eGrafik 1a, aber für den Zeitraum 2011-2022.



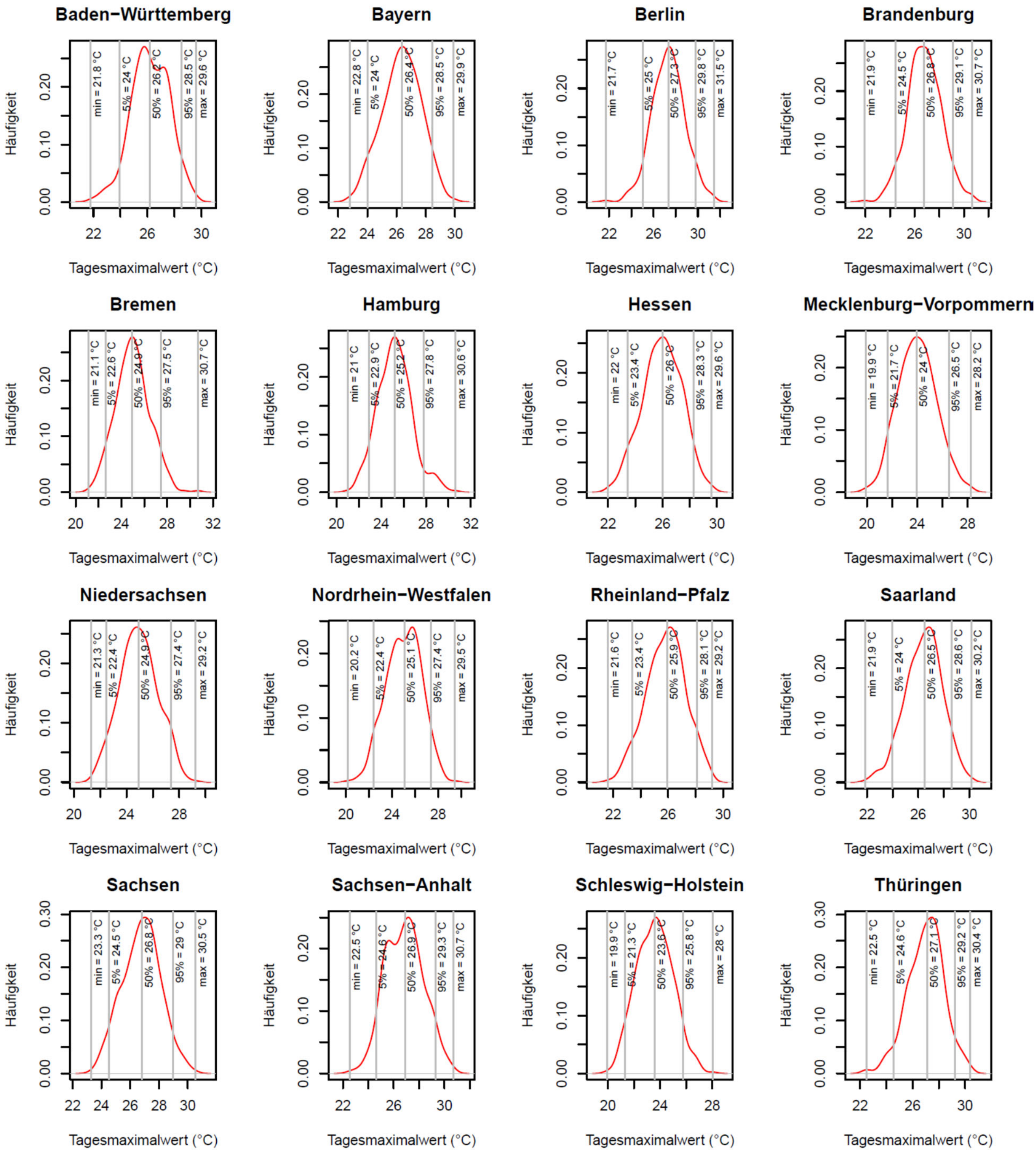
eGrafik 2 Häufigkeitsverteilung (schwarz) der mittleren Temperatur in den 16 Bundesländern während der Sommermonate Juni, Juli, August (grau) im Zeitraum 1940-2023. Die vier wärmsten Jahre sind beschriftet. Das Jahr 2022 ist rot hervorgehoben.



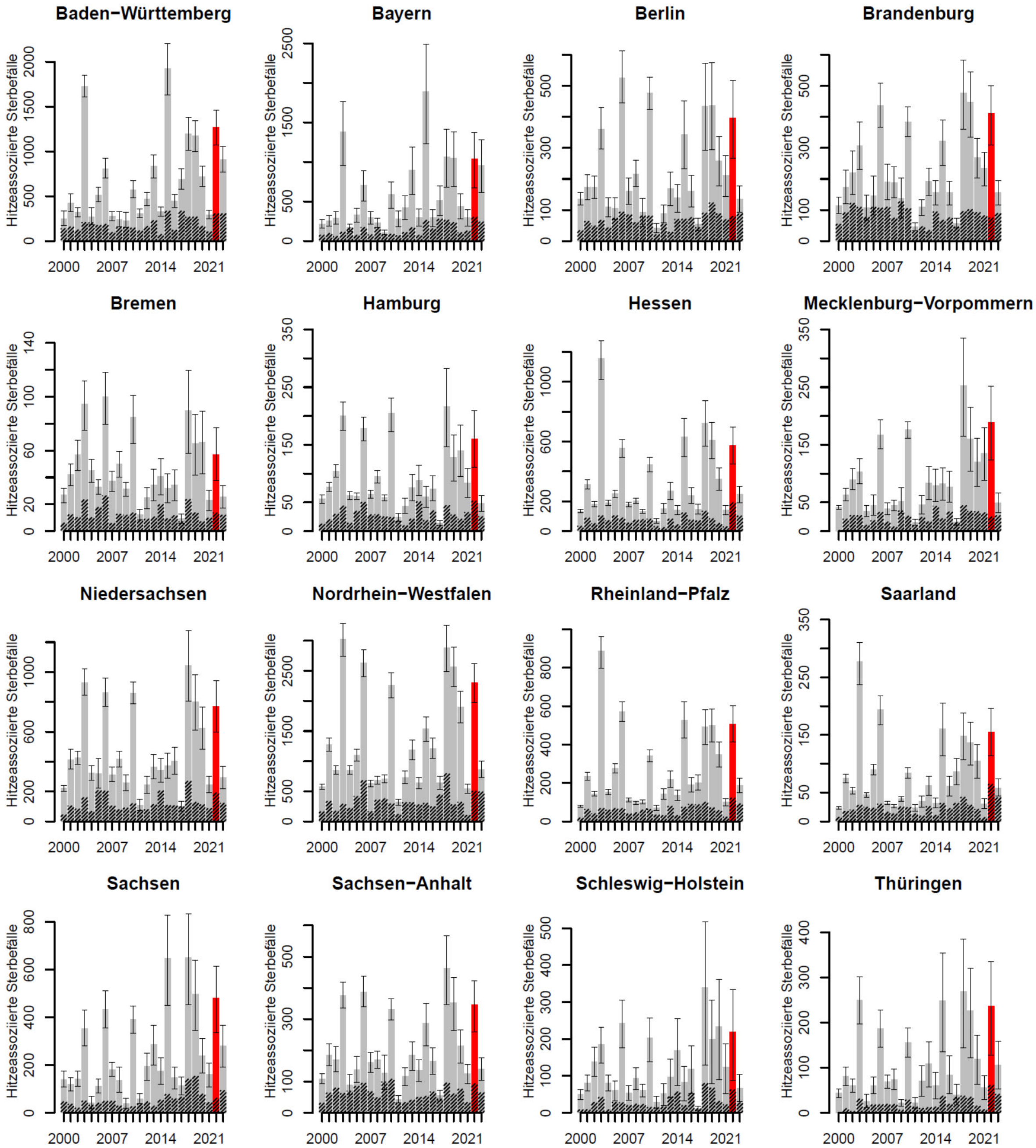
eGrafik 3 Tägliche Gesamtsterbefälle in Deutschland im Jahr 2022 (rot) im Vergleich zum Median der Jahre 2016-2021 (schwarze Linie, Spannweite: grauer Bereich).



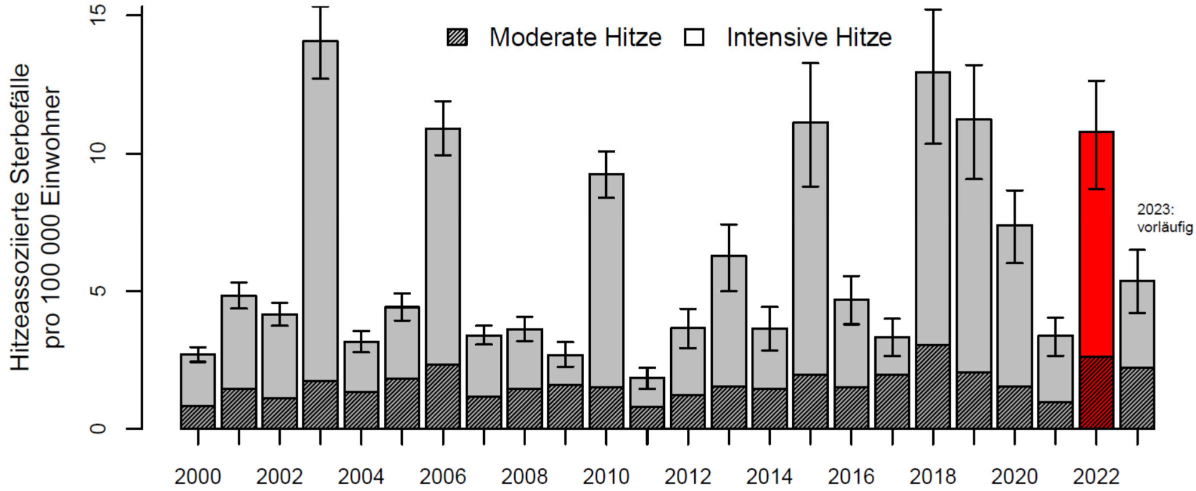
eGrafik 4 Temperatur-Mortalitäts-Zusammenhänge (Mai-September) in den Zeiträumen 2000-2010 (blau) und 2011-2022 (rot) mit 95% Konfidenzbereich (schraffiert) für alle Bundesländer. Die gestrichelten Linien entsprechen den Exzess-Risiko-Temperaturen (ERT), ab denen dem Modell nach im jeweiligen Zeitraum ein signifikantes Mortalitätsrisiko auftritt. Die gepunkteten Linien zeigen die 95-% Temperaturperzentile (T95), die in der Sensitivitätsanalyse zur Definition „moderater“ und „intensiver“ Hitze genutzt werden. ERT und T95 sind für den Zeitraum 2011-2022 beziffert.



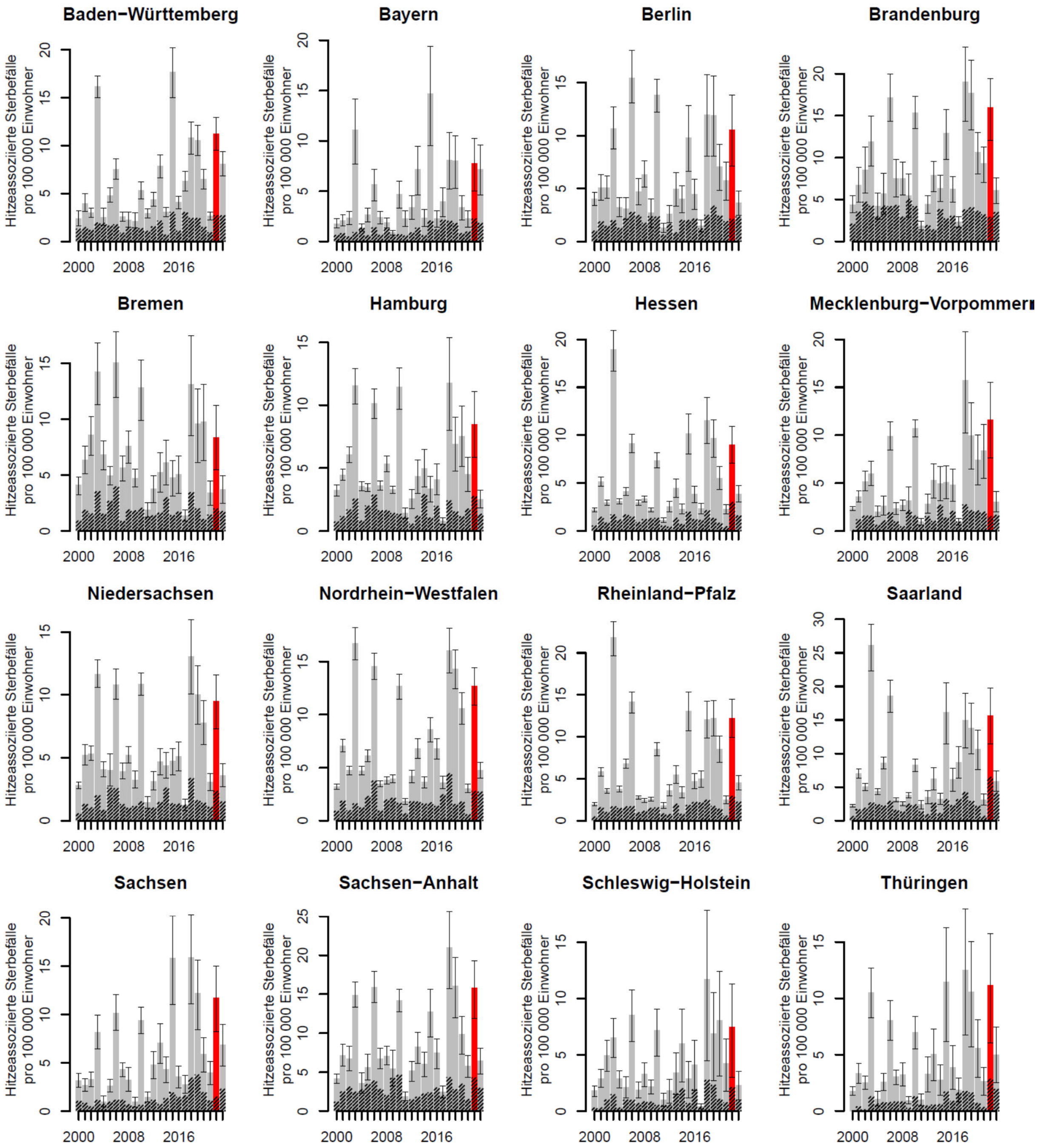
eGrafik 5 Häufigkeitsverteilung der täglichen Temperaturhöchstwerte in den Bundesländern im Intervall der Tagesmitteltemperatur ERT±1. Hier entspricht ERT dem geschätzten Wert der zweiten Analyseperiode 2011-2022 (vgl. Abb. S4).



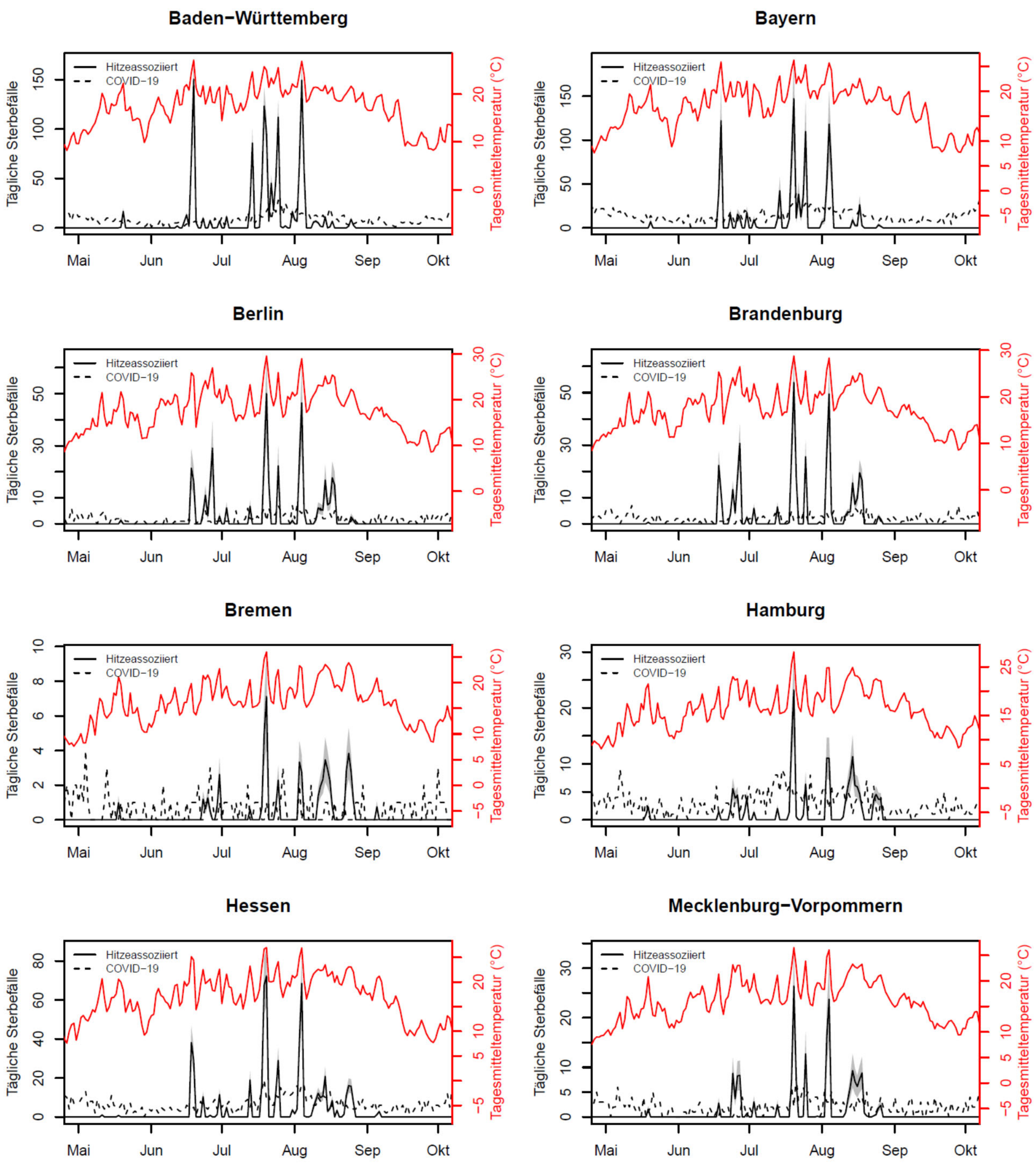
eGrafik 6 Geschätzte Anzahl hitzeassoziierter Sterbefälle pro Jahr in den Bundesländern, basierend auf den Temperatur-Mortalitäts-Zusammenhängen in den Zeiträumen 2000-2010 und 2011-2022 (Abb. S4). Die Unsicherheitsbalken zeigen die 95% Konfidenzintervalle. Schraffiert dargestellt ist der Anteil der Sterbefälle, der auf ‚moderate' in Abgrenzung zu ‚intensiver' Hitze zurückzuführen ist, entsprechend den Temperaturschwellenwerten (ERT und T95) in Abb. S4. Für die Zahlen aus 2022 (rot) siehe auch Tabelle S1. Die Zahlen für 2023 stellen eine vorläufige Schätzung dar.



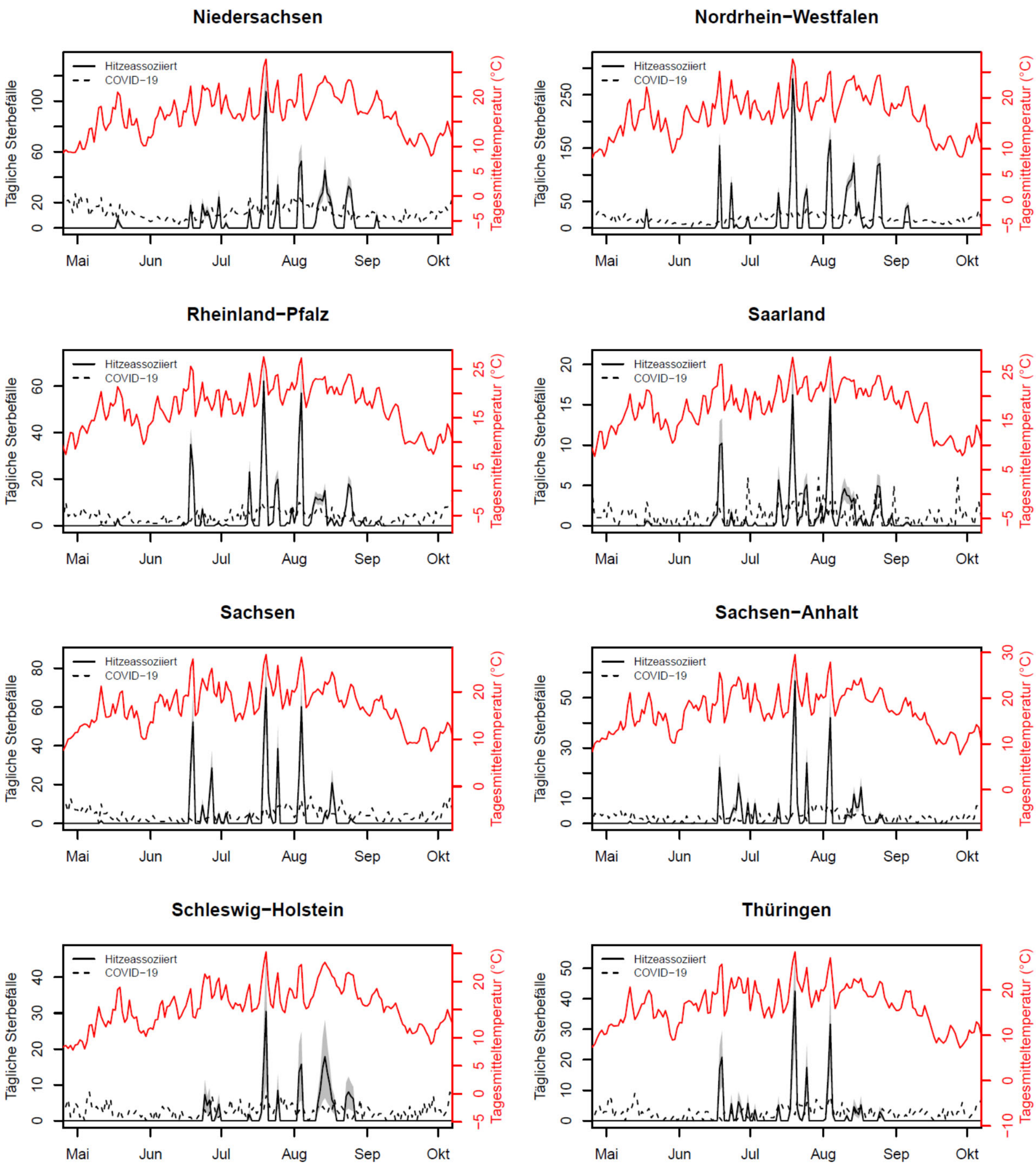
eGrafik 7 Wie Grafik 2, aber für Sterbefallraten pro 100.000 Einwohner.



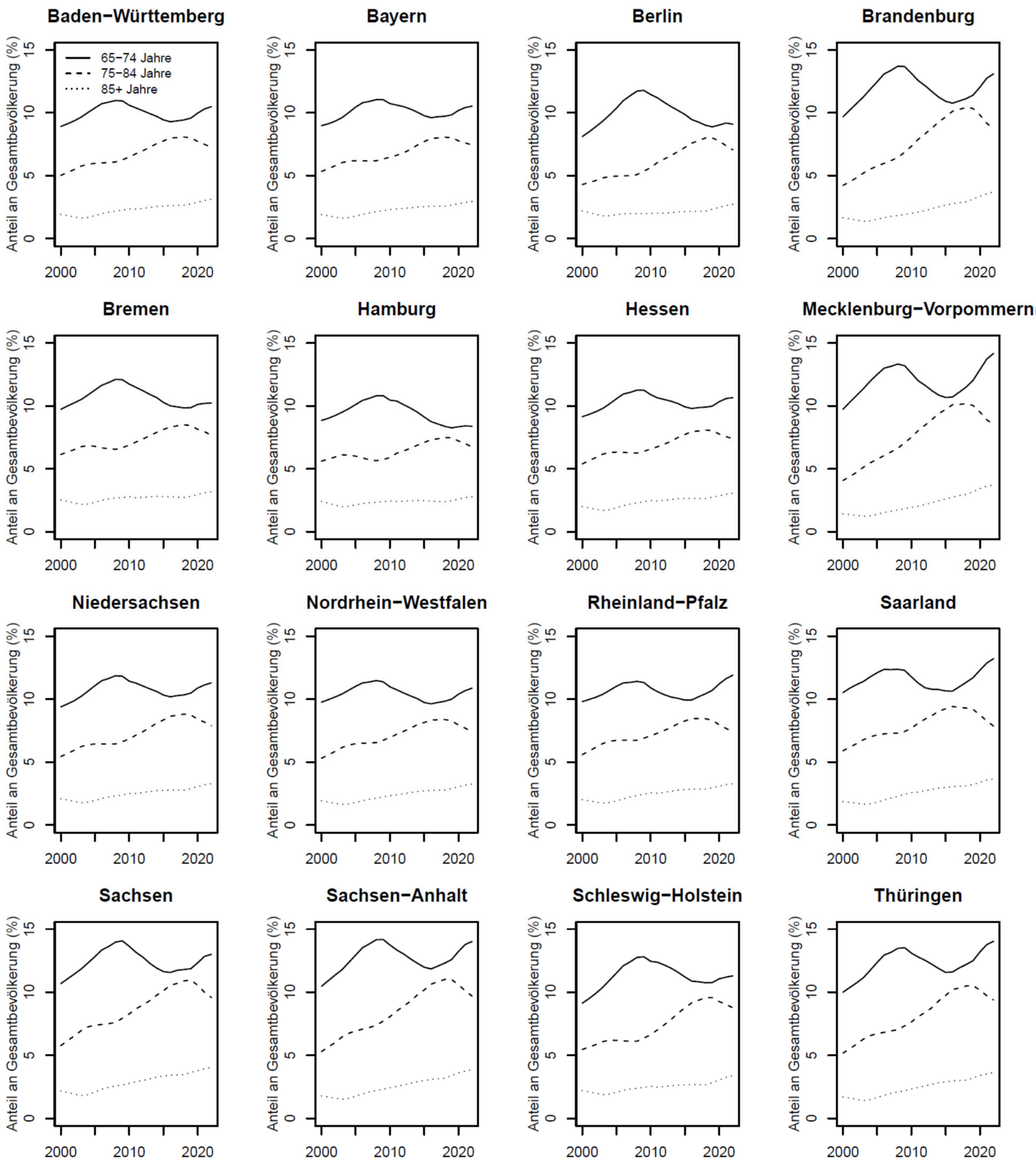
eGrafik 8 Wie eGrafik 6, aber für Sterbefallraten pro 100.000 Einwohner.



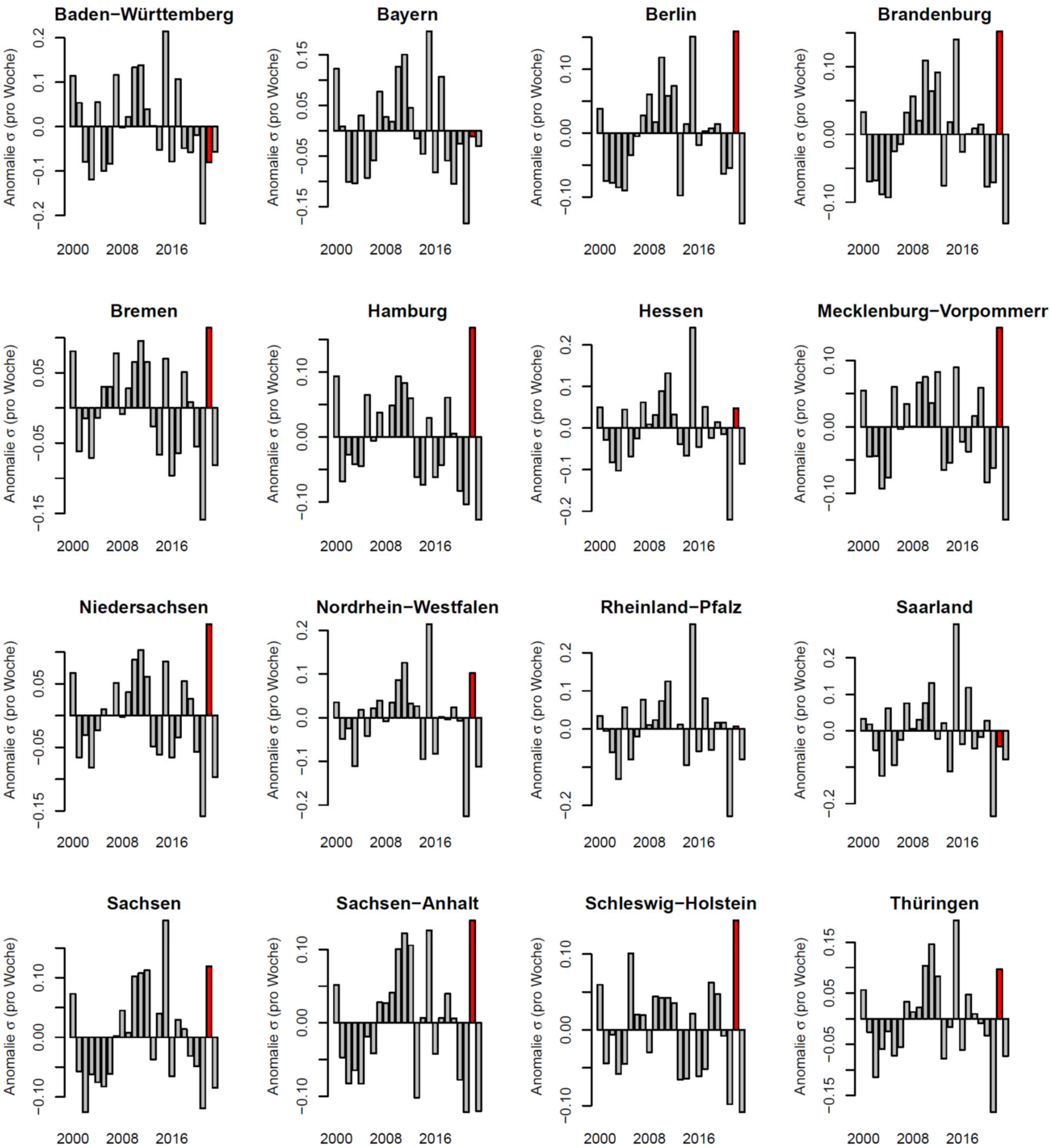
eGrafik 9a Geschätzte Anzahl täglicher hitzeassoziierter Sterbefälle (schwarze durchgezogene Linie, mit grauem 95% Konfidenzbereich), gemeldete COVID-19 Todesfälle (schwarze gestrichelte Linie) und Tagesmitteltemperaturen (rot) in den Bundesländern im Sommer 2022.



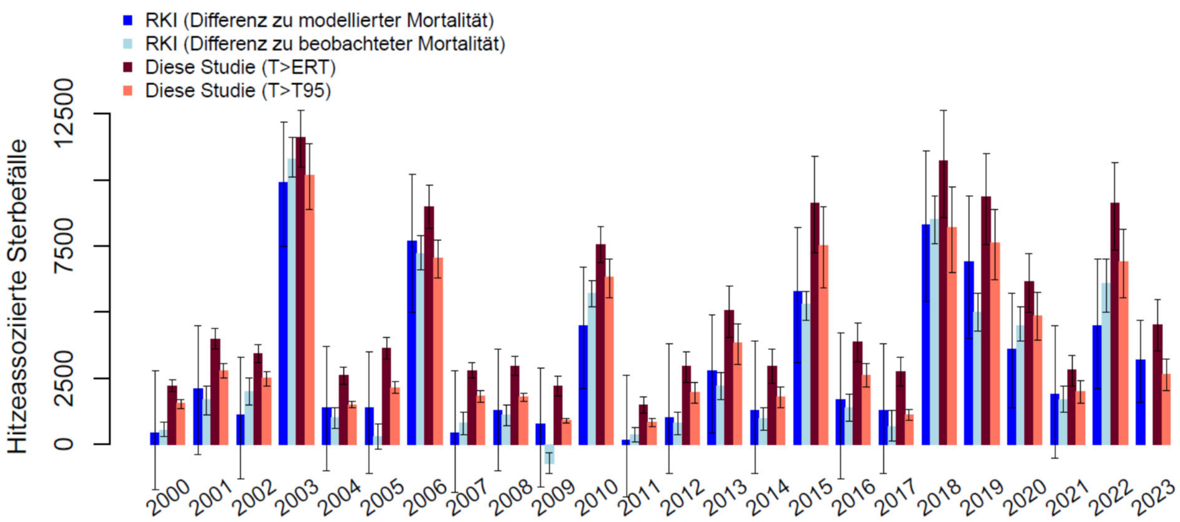
eGrafik 9b Geschätzte Anzahl täglicher hitzeassoziierter Sterbefälle (schwarze durchgezogene Linie, mit grauem 95% Konfidenzbereich), gemeldete COVID-19 Todesfälle (schwarze gestrichelte Linie) und Tagesmitteltemperaturen (rot) in den Bundesländern im Sommer 2022.



eGrafik 10 Prozentualer Anteil der Altersgruppen 65-74, 75-84 und 85+ Jahre an der Gesamtbevölkerung im Zeitraum 2000 bis 2022. Die Daten entstammen der Genesis Datenbank des Statistischen Bundesamtes (21).



eGrafik 11 Durchschnittliche Standardabweichung der Tagesmitteltemperatur pro Woche in den Kalenderwochen 22 bis 35 (ungefähr Juni-August), als Abweichung vom langjährigen Mittel für den Zeitraum 2000-2023 für alle Bundesländer. Der Sommer 2022 ist rot hervorgehoben.



eGrafik 12 Geschätzte Anzahl hitzeassoziierter Sterbefälle in Deutschland im Zeitraum 2000-2023, entsprechend Schätzungen des Robert Koch-Instituts (12, 13) (dunkelblau und hellblau), und geschätzt in dieser Studie basierend auf unterschiedlichen Temperaturschwellenwerten (ERT und T95, siehe eGrafik 4) (dunkelrot und hellrot). Die Unsicherheitsbalken zeigen die 95% Konfidenzintervalle. Zum Zeitpunkt der Analyse stand die Schätzung des Robert Koch Instituts basierend auf der Differenz zur beobachteten Mortalität (hellblau) für das Jahr 2023 noch nicht zur Verfügung.