Original Article

Heat-Related Mortality in Germany From 1992 to 2021

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Summary

Background: 2018–2020 were unusually warm years in Germany, and the summer of 2018 was the second warmest summer since record-keeping began in 1881. Higher temperatures regularly lead to increased mortality, particularly among the elderly.

Methods: We used weekly data on all-cause mortality and mean temperature from the period 1992–2021 and estimated the number of heat-related deaths in all of Germany, and in the northern, central, and southern regions of Germany, employing a generalized additive model (GAM). To characterize long-term trends, we compared the effect of heat on mortality over the decades.

Results: Our estimate reveals that the unusually high summer temperatures in Germany between 2018 and 2020 led to a statistically significant number of deaths in all three years. There were approximately 8700 heat-related deaths in 2018, 6900 in 2019, and 3700 in 2020. There was no statistically significant heat-related increase in deaths in 2021. A comparison of the past three decades reveals a slight overall decline in the effect of high temperatures on mortality.

Conclusion: Although evidence suggests that there has been some adaptation to heat over the years, the data from 2018–2020 in particular show that heat events remain a significant threat to human health in Germany.

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Extreme heat and prolonged periods of heat are important risk factors for human health. Numerous studies have not only shown that high temperatures result in an increased burden on the health care system (1, 2), but also provided evidence of a systematic correlation between heat events and increased mortality (3–6). For Germany, the effect of heat on mortality has been quantified both for individual federal states (7–12) and nationwide (3, 13–16).

High ambient temperatures have a variety of effects on the human body, for example reduced blood viscosity due to increased fluid loss, which exerts considerable strain on the cardiovascular system, or the challenge to maintain a constant body temperature (17, 18). In particular, preexisting conditions, such as diseases of the respiratory system, may be aggravated (19, 20). Since heat is rarely identified as a direct cause of death, statistical methods have to be used to estimate the number of heat-related deaths. This article builds on the modeling approaches applied in studies on heat-related mortality between 1992 and 2017 as well as between 2001 and 2015 and estimates the number of heat-related deaths between 1992 and 2021, using a generalized additive model (GAM) (21).

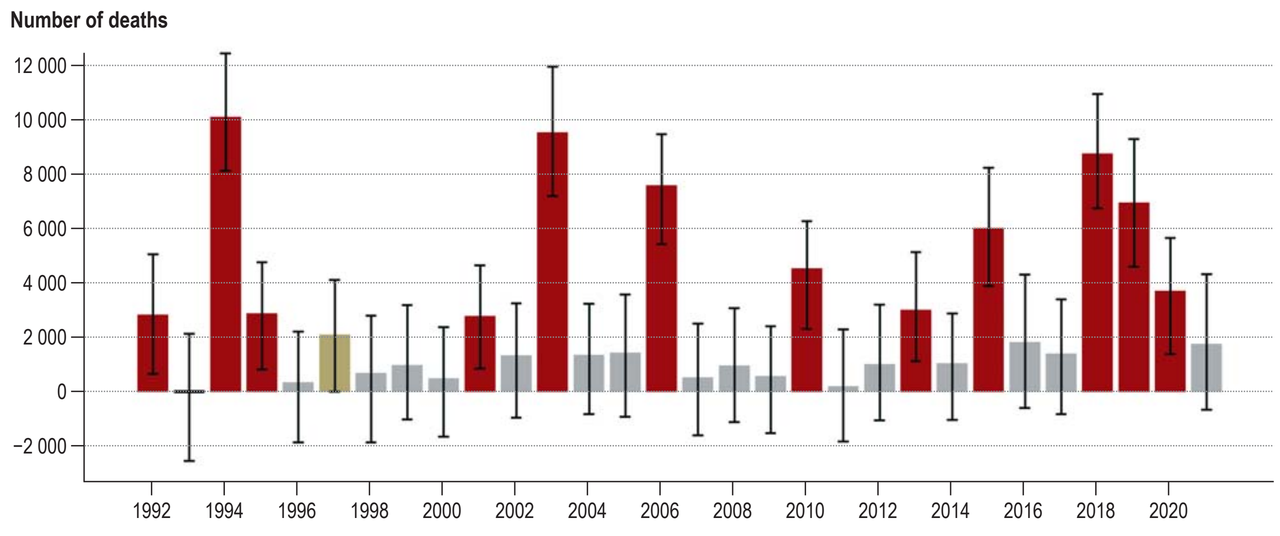
Methods

Data

As in the 1992–2017 study (3), we used all-cause mortality data of the German Federal Statistical Office (StBA, Statistisches Bundesamt) per calendar week in the period from 1992 to 2021 (22). These data are aggregated by four age groups (<65, 65–74, 75–84, and 85+ years of age) and by federal state. In addition, we made use of the StBA's official population statistics as well as the results of the population projection for the year 2021 (scenario G2-L2-W2, assuming moderate developments in birth rate, life expectancy and net migration) (23).

For the temperature data, we used hourly air temperature measurements of 52 stations of the surface observation network of the German Weather Service (Deutscher Wetterdienst, DWD). These data were first averaged over the 24 hours of the day and then over

FIGURE 1



Estimated number of heat-related deaths in Germany in the period 1992–2021. Years with significant numbers of heat-related deaths (5% significance level) are highlighted in red. Years with marginally significant numbers of heat-related deaths (10% significance level) are highlighted in beige. In addition, the estimated numbers of heat-related deaths with 95% confidence intervals are listed in the *Table* and *eTable*.

calendar week and federal state. We also considered the previously analyzed period 1992–2017, on the one hand, to ensure stable adaption of the seasonal pattern due to the longer observation period, and, on the other hand, to allow for comparability with previous estimates. As before, we analyzed only the summer half-year (calendar weeks 15–40) and distinguished the following three decades: 1992–2001, 2002–2011 and 2012–2021. Furthermore, we grouped the federal states into three major regions: "North" (Bremen, Hamburg, Mecklenburg-Western Pomerania, Lower Saxony, Schleswig-Holstein), "Central" (Berlin, Brandenburg, North Rhine-Westphalia, Rhineland-Palatinate, Saarland, Hesse, Saxony, Saxony-Anhalt, Thuringia) and "South" (Baden-Wuerttemberg, Bavaria). This approach allowed us to take specific regional features of the effect of high temperatures on mortality into account.

Model

We used a generalized additive model (GAM) (21) and the R statistical software (version 4.0.5, package "mgcv" [24]) to model the curve of all-cause mortality observed during the study period. For each region and age group, the modelled all-cause mortality curve is composed of a long-term trend, a seasonally recurring pattern and exposure-response curves which quantify the relative effect of mean temperature on mortality of the same week and the following three weeks.

Based on the exposure-response curves, we identified temperature thresholds for each age group, region and decade above which temperature has a relevant effect on mortality. We refer to a calendar week during which the mean temperature is above the threshold as a "heat week" and to contiguous periods of heat weeks as "heat periods". Since the thresholds are close to 20 °C, we occasionally use this temperature value as an indicator of a heat week.

We refer to the mortality to be expected if the weekly mean temperature always remained below the threshold as "background mortality". The difference between the modeled mortality curve and the background mortality yields the "heat-related mortality". If the 95% confidence interval of the estimated heat-related mortality is entirely above zero, we speak of a significant number of deaths. For a detailed description of the modelling used and the sensitivity analyses conducted refer to the "Methods" *eSupplement* and (3).

Results

Heat-related deaths

Figure 1 shows the estimated number of heat-related deaths in Germany in the period 1992–2021. Between 2018 and 2020, heat-related deaths occurred in significant numbers for three consecutive years for the first time during the study period. The year 2018, in particular, is with an estimated number of about 8700 heat-related deaths similar in magnitude to the historical heat years 1994 and 2003 (each about 10 000 deaths). For the years 2019 and 2020, the model estimates approximately 6900 and 3700 deaths, respectively. The numbers of deaths are comparable to those in the years 2006, 2010 and 2015. For 2021, no significant heat-related increase in (all-cause) mortality was found. The estimated numbers of deaths and confidence intervals for the decade 2012–2021 are also summarized in the *Table;* the results for the entire period since 1992 are presented in the *eTable*.

Figure 2 shows the development of mortality over time (deaths per 100 000 population) in the period 2018–2021. Between 2018 and 2020, in particular, both the modelled and the observed all-cause mortality was significantly higher than the modelled background mortality.

The *eFigures* 1 and 2 show a more detailed breakdown of mortality rates over time by the three regions (North, Central, South) and a comparison of heat-related mortality by region and age group. In line with previous findings (3, 9, 15), there is a clear indication that the group aged 85 years and over is the most affected in all regions. The heat periods in the years 2018 and 2020 were shorter in the northern region, but still associated with a high number of heat-related deaths.

Figure 3 shows the shapes of the exposure-response curves of the current week and the previous week for the age group over 85 years in the three regions (North, Central and South) in the period 2012–2012. It can be seen here that the temperature threshold at which the effect of heat on mortality can be considered relevant is somewhat lower in the northern region (19.7 °C) compared to the central region (20.2 °C) and southern region (20.8 °C). Moreover, in the northern region the exposure-response curves of the current week and the previous week show a considerably steeper rise for temperatures above the threshold. Thus, an effect of heat on mortality, which increases from the southern to the northern regions, is noted. Consequently, the expected number of heat-related deaths (per 100 000 population of the same age group) for a specific weekly mean temperature is somewhat higher in the northern region and somewhat lower in the southern region compared to the center of Germany.

Changes in the estimation of the exposure-response curves

Figure 4 shows the exposure-response curves for the age group 85 years by geographical region and decade. Overall, a significant increase in mortality is observed for weekly mean temperatures above 20 °C. Over the decades, a slight flattening of the curves can be observed, especially in the central region, i.e. in the period 2012–2021 the same weekly mean temperature resulted in a weaker increase in mortality compared to, for example, the period 1992–2001. A summary of the exposure-response curves for the various regions and age groups is provided in the "Analysis" *eSupplement*.

Special features of the years 2018–2020 and the effect of heat period duration

Figure 2 and *eFigure 1* show that the model can generally provide a good representation of mortality over time. However, mortality during the heat periods 2018 and 2020 is slightly underestimated, while it is slightly overestimated in 2019. This may be explained by differences in the character of the heat waves in these three years.

In all three regions, the year 2018 was characterized by an unusually long heat period (up to nine weeks in the southern region and up to five weeks in the northern and central regions). In addition, remarkably high weekly mean temperatures were measured (up to 26.6 °C in the central and southern regions; up to 25.1 °C in the northern region). Although very high temperatures were also measured in 2019 (maximum weekly mean temperatures of 25.8 °C in the central region, 25.7 °C in the southern region and 25 °C in the northern region), these heat periods were repeatedly interrupted by weeks with lower temperatures. Finally, in the year 2020 again a prolonged period of heat (up to five weeks in the central and southern regions, up to three weeks in the northern region) was observed; however, the maximum weekly mean temperature was significantly lower compared to the year 2018 (maximum weekly mean temperature of 24.9 °C).

The effect of explicitly including heat period duration in the model was assessed; however, taking this parameter into account did not result in a relevant improvement of the description of the observed data. A detailed summary of key temperature figures during the study period is provided in the "Data" *eSupplement*.

TABLE

The estimated numbers of heat-related deaths with 95% confidence intervals for the period 2012–2021**

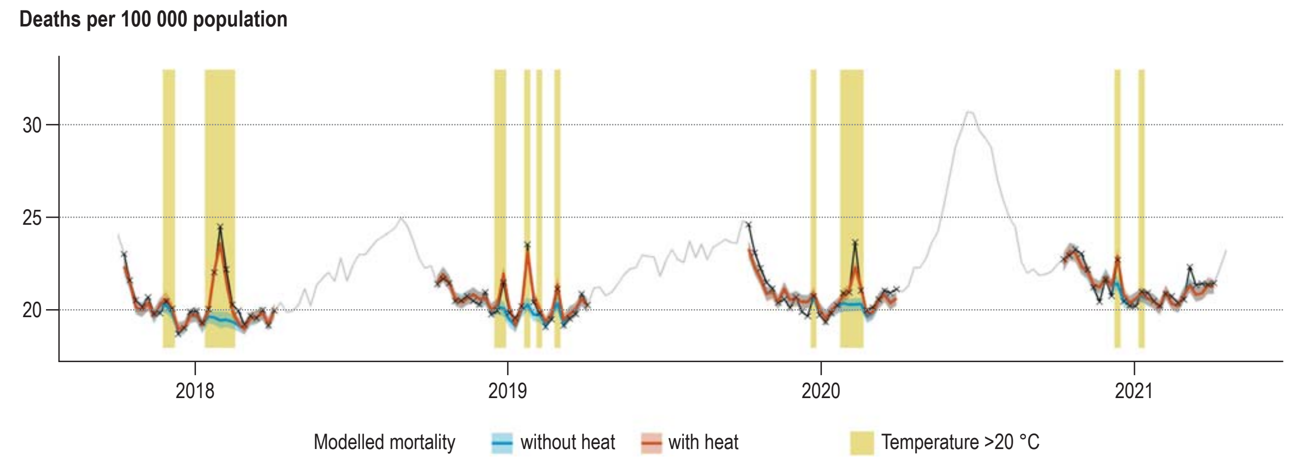
Year	Estimated number of heat-related deaths [95% confidence interval]
2012	1000 [–1100; 3200]
2013	**3000 [1100; 5100]**
2014	1000 [–1100; 2900]
2015	**6000 [3900; 8200]**
2016	1800 [–600; 4 300]
2017	1400 [–800; 3400]
2018	**8700 [6700; 10 900]**
2019	**6900 [4600; 9300]**
2020	**3700 [1 400; 5600]**
2021	1700 [–700; 4300]

*Values in bold are statistically significant.

Discussion

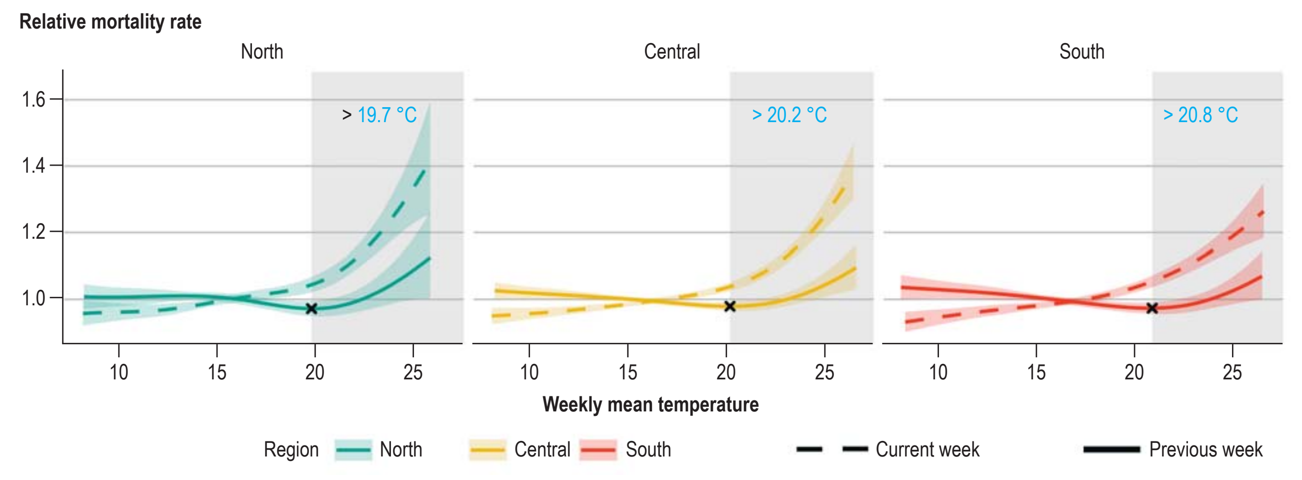
In each of the years from 2018 to 2020, the number of heat weeks was higher compared to the numbers in the other years of the 2012–2021 decade. The year 2018 particularly stands out, as not only did above-average periods of prolonged heat occur, but, in addition, exceptionally high temperatures were measured.

FIGURE 2



Mortality over time (deaths per 100 000 population) in the period 2018–2021. The gray line shows the reported all-cause mortality, the red line shows the mortality estimated by the model (only in the summer half-year) and the blue line shows the estimated background mortality (expected mortality without heat). Weeks with weekly mean temperatures (averaged across all federal states) above 20 °C are highlighted in yellow. The slightly increased all-cause mortality in spring 2020 and the significantly increased all-cause mortality in winter 2020/21 are explained by the first and second wave of the COVID-19 pandemic. A regional breakdown of the time series can be found in *eFigure 1*.

FIGURE 3



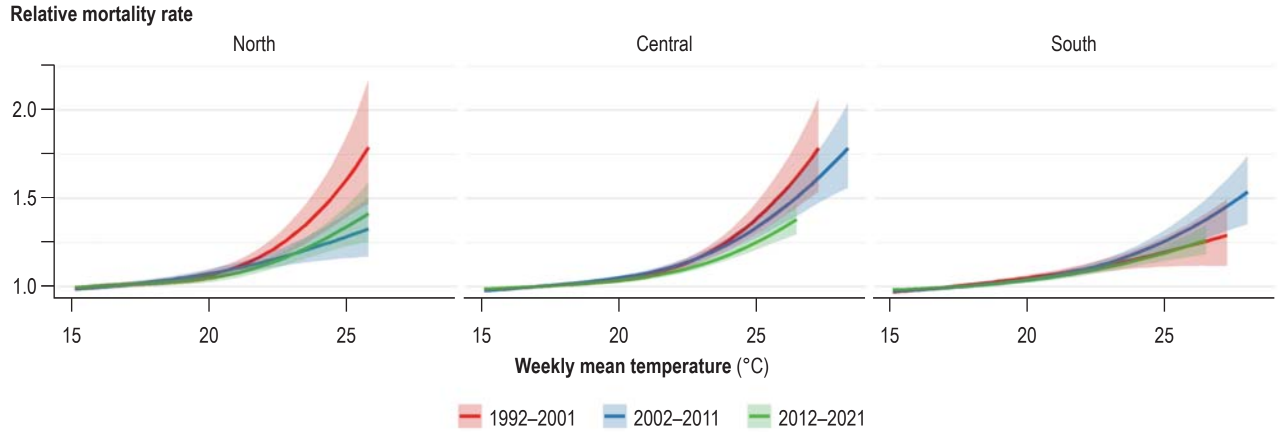
Exposure-response curves of the current week (dotted line) and the previous week (solid line) for the 85+ age group in the period 2012–2012, stratified by the three regions "North", "Central" and "South". In each case, the minimum of the exposure-response curve of the previous week is highlighted with a black "x" and marks the temperature threshold above which both the temperature of the previous week and the temperature of the current week result in an increase in mortality. Temperature ranges above the threshold are highlighted in gray. The temperature threshold increases from north to south.

However, significant differences in the duration and number of heat periods are observed between the regions (see also the "Data" *eSupplement*). In the period 2018–2020, heat-related mortality was also found to be considerably above the rates of the other years of the decade. In the year 2018, the estimated number of heat-related deaths was comparable to those in the historical heat years 1994 and 2003. However, a direct comparison of mortality rates in the various weeks shows that despite comparable temperatures fewer deaths occurred in 2018 compared to 1994 and 2003 ("Analysis" *eSupplement*). In 2021, only sporadic heat weeks were observed which did not result in a significant increase in all-cause mortality.

Impact of the period 2018–2020 on the total decade

Since the exposure-response curves are estimated per decade, the inclusion of the comparably hot years 2018–2020 necessitated a re-estimation of the exposure-response curves for the decade 2012–2021,

FIGURE 4



The trend of the exposure-response curves for the three regions "North", "Central" and "South" over the decades. The results for the 85+ age group are depicted because the strongest effects are observed in this age group. The three decades 1992 to 2001 (red), 2002 to 2011 (blue) and 2012 to 2021 (green) show a slightly declining trend which is particularly evident in the central region. Since in the northern region weekly mean temperatures above 25 °C occur significantly less frequently, the estimates in this area are associated with greater uncertainty, a fact that is reflected in the wider confidence intervals.

which showed a steeper rise compared to the model based on the data up to 2017 (3). This implies that the estimated number of heat-related deaths for this decade also needs to be revised slightly upward. The updated estimates are within the 95% confidence intervals of the previous estimation (see "Analysis" *eSupplement*).

Duration of heat periods

By taking the duration of heat periods into account, only minor improvements in model fit were obtained and no significant changes in the estimates of heat-related deaths were noted. A possible explanation could be that calendar weeks as a unit are not fine enough to fully capture the time course of a prolonged heat period. In particular, an alternation between hot and cooler days within a week and the magnitude of cooling at night cannot be clearly differentiated based on weekly figures; for example, with the use of weekly data the duration of a heat period tends to be overestimated ("Data" *eSupplement*). The analysis of daily mortality data could help to identify an optimum time unit.

Finally, phenomena other than temperature could also play a role, such as the occurrence and concentration of air pollutants, humidity and the position of a heat period in the calendar year (25). For example, in (26) it was shown that mortality during the first days of the heat waves in 2003 and 2015 differed significantly despite comparable temperature curves. These differences may be explained by the considerably higher humidity during the 2015 heat wave.

Comparison with other models

Some federal states, such as Hesse (10), Baden-Wuerttemberg (11), Berlin, and Brandenburg (27), publish estimates of the number of heat-related deaths on a regular basis. In these models, background mortality is calculated using the mean mortality rates of the previous years excluding periods with known heat events. The advantage of these models over the modelling approach used in our study is their ease of use, as they do not require any specialized statistical software. However, the challenge with these models is that, with extreme heat events occurring in increasing frequency, increasingly longer periods of time must be excluded, thereby potentially confounding the estimated background mortality. Furthermore, the exposure-response relationship cannot be directly quantified, so temperature thresholds and adjustment processes must be described in some other way.

In addition, the topic of heat-related mortality is increasingly becoming the focus of international studies. In 2020, for example, the indicator "heat-related mortality" was included in the Lancet Countdown on Health and Climate Change. An estimated 296 000 heat deaths occurred worldwide in 2018, of which 20 000 were estimated to have occurred. in Germany alone (6). However, this estimate is based on the assumption of a globally uniform exposure-response curve, and seasonal fluctuations in mortality were only broadly taken into account. While this simplified approach allows to estimate heat-related mortality on a global scale, it may lead to considerable overestimation or underestimation in some countries (with regard to the significance of regional differences, see also [28]).

Adaption to heat periods in Germany

The development of the exposure-response curves over the decades, as shown in *Figure 4,* reveals that in general the effects of the same weekly mean temperatures on mortality were weaker in the decade 2012–2021 compared to, for example, the decade 1992–2001. This may be interpreted as an indication that some adjustment to recurrent heat periods has taken place in the population.

The data analyzed by us do not allow to draw conclusions about what caused this limited adjustment. Possible explanations include individual behavioral changes due to greater awareness, such as wearing light clothing, adequate hydration and moving to shaded or air-conditioned areas (29). For example, information about heat events is also made available by the Heat Health Warning System (HHWS) of the German Weather Service (30).

Since the elderly and those with preexisting conditions are affected most, the topic of heat prevention continues to be a focus in the health and care sectors, based on initial implementation experiences (2). When initiating adaptation strategies at the community level, coordination and interdisciplinary interaction is essential (31, 32). To this end, the 2020 Conference of Health Ministers emphasized the need for heat-health action plans ("Hitzeaktionsplan") in its relevant resolution, noting that these should be prepared by 2025 (33).

Outlook

Numerous studies suggest that the frequency of extreme heat events with, at times, dramatic effects on human health is likely to increase in Germany as a result of climate change (4, 20, 34–38). The study of heat-related mortality makes a significant contribution to the evaluation of health risks. Our updated analysis reveals for the first time significant numbers of heat-related death in three consecutive years, highlighting the fact that heat events continue to be a serious threat to the health of the population in Germany. There is still an ongoing need and challenge to significantly improve the handling of heat periods in Germany and to adequately protect vulnerable groups of the population.

Funding

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Conflict of interest

The authors declare no conflict of interest.

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► **Supplementary material**

eTables, eFigures, eSupplement:
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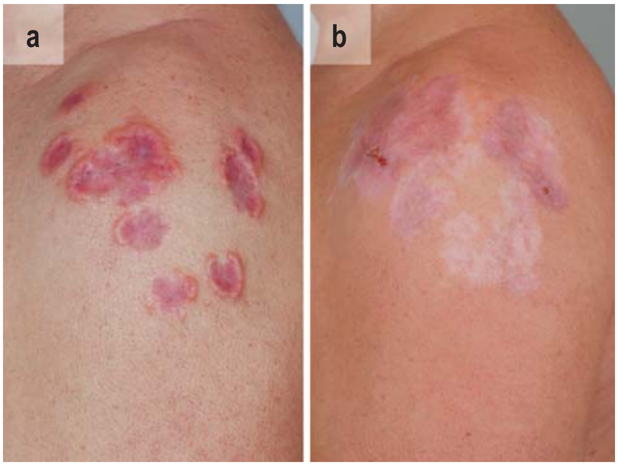
CLINICAL SNAPSHOT



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Gummatous Cutaneous Syphilis

A 54-year-old man presented with persistent annular plaques located exclusively on his upper arms. Each of the foci had a raised indurated margin with central atrophy (*Figure a*, 03/2018). Examination of biopsy tissue showed numerous macrophages, multinuclear giant cells, lymphocytes, and plasma cells, indicating an infectious process. Serology demonstrated syphilis (with positive *Treponema pallidum* particle agglutination test and Western blot). The patient received intramuscular injections of 2.4 million units of tardicillin on days 1, 8, and 15. The gummas healed, leaving large hypopigmented scars (*Figure b*, 02/2019).The serum titer of cardiolipin antibodies (VDRL test) was much lower 6 weeks later. The diagnosis of tertiary syphilis with cutaneous gummas should be followed by immediate exclusion of involvement of any other organs (cardiovascular system, nervous system, eyes, liver, bones, joints). The incidence in Germany has increased to over nine registrations per 100 000 inhabitants. If left untreated, the mortality is up to 50–60%. Contact tracing is advised, particularly with regard to congenital infection with syphilis.

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Supplementary material to:

Heat-Related Mortality in Germany From 1992 to 2021

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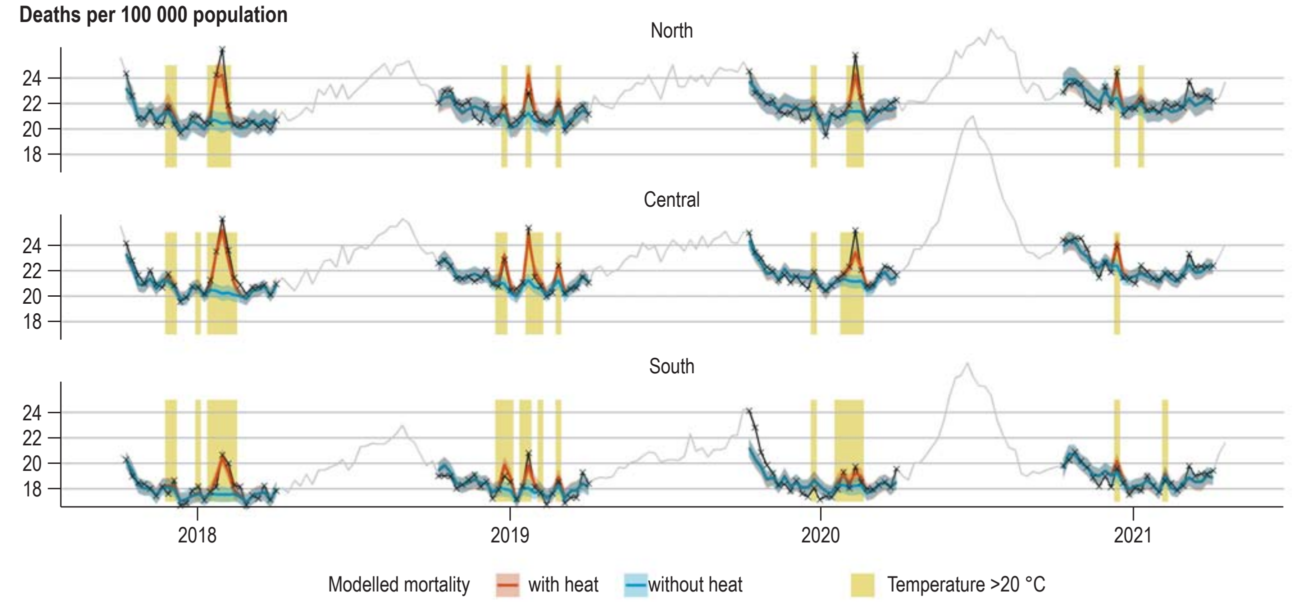
eTABLE

The estimated numbers of heat-related deaths with 95% confidence intervals for the period 1992–2021*

Year	Estimated number of heat-related deaths [95% confidence interval]
1992	**2800 [600; 5000]**
1993	0 [–2600; 2 100]
1994	**10 100 [8 100; 12 400]**
1995	**2800 [800; 4700]**
1996	300 [–1900; 2200]
1997	2100 [0; 4100]
1998	600 [–1900; 2800]
1999	900 [–1000; 3200]
2000	400 [–1700; 2400]
2001	**2700 [800; 4600]**
2002	1300 [–1000; 3200]
2003	**9500 [7200; 12 000]**
2004	1300 [–800; 3200]
2005	1400 [–900; 3600]
2006	**7500 [5400; 9500]**
2007	500 [–1600; 2500]
2008	900 [–1100; 3100]
2009	500 [–1600; 2400]
2010	**4500 [2300; 6300]**
2011	100 [–1900; 2300]
2012	1000 [–1100; 3200]
2013	**3000 [1100; 5100]**
2014	1000 [–1100; 2900]
2015	**6000 [3900; 8200]**
2016	1800 [–600; 4300]
2017	1400 [–800; 3400]
2018	**8700 [6700; 10 900]**
2019	**6900 [4600; 9300]**
2020	**3700 [1400; 5600]**
2021	1700 [–700; 4300]

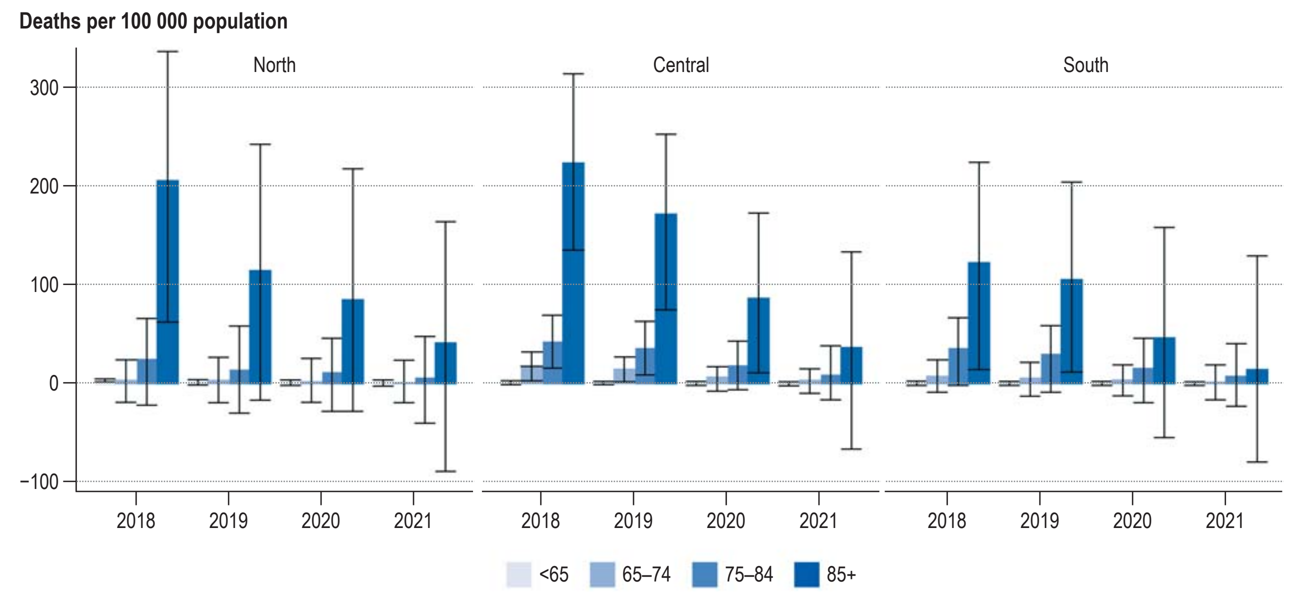
*Values in bold are statistically significant.

eFIGURE 1



The time series of mortality (death per 100 000 population) for the period 2018–2021, stratified by the northern, central and southern regions. The gray line shows the reported all-cause mortality, the red line shows the mortality estimated by the model (only in the summer half-year) and the blue line shows the estimated background mortality. Weeks with weekly mean temperatures (averaged across all federal states) above 20°C are highlighted in yellow. In the years 2018 to 2020, a shorter duration of the heat periods is noted in the northern region. The increased mortality in spring 2020 in the southern region is explained by the first wave of the COVID-19 pandemic. The high mortality rates due to the second wave of the COVID-19 pandemic in the 2020/2021 winter were drawn beyond the limits of the y-axis to avoid distorting the depiction of the summer mortality.

eFIGURE 2



The heat-related mortality (deaths per 100 000 population) in the period 2018–2021, stratified by region and age group. Despite the shorter duration of the heat periods (*eFigure 1*) in the northern region, the heat-related mortality in the oldest age group in this region is comparable to the central and southern region mortality rates.

1 Methods

In the following, we explain the different steps involved in the modeling of heat-related deaths. In particular, we look at: (1) the modeling of observed weekly all-cause mortality rates using a generalized additive model, (2) the determination of the temperature threshold, (3) the modeling of background mortality under the assumption of a “capped” temperature curve, and (4) the calculation of heat-related mortality as the difference between modeled and background mortality. This approach was already used in [1], where it is described too.

1.1 Modelling of mortality over time

First, the goal is to model the development of weekly deaths during the summer half-year (CW15 to CW40). Here, we assume three key components:

1. a long-term trend, reflecting population growth or rising life expectancy;
2. a seasonal pattern, reflecting seasonal changes in mortality as a function of the calendar week;
3. exposure-response curves, quantifying the effect of temperature on mortality.

We use a generalized additive model (GAM) [5] that allows us to estimate these components from the data without making specific assumptions about their shape. Since the target variable (weekly number of deaths) is integer, we assume a logarithmic link function and a random disturbance with a negative binomial distribution (with the over-dispersion parameter θ). The model equation is then calculated as:

$$s_{t,a} \sim \mathrm{NegBin}\left(E(s_{t,a}), \theta\right)$$

$$E(s_{t,a}) = b_{t,a} \exp\left(\beta_a + f_a^{\mathrm{Trend}}(t) + f_a^{\mathrm{Season}}(w_t) + \sum_{i=0}^{3} f_{a,a_t}^{\mathrm{Heat},i}(m_t)\right).$$

Here, the expected number of deaths $E(s_{t,a})$ in week t and age group a is a function of the corresponding population size $b_{t,a}$, the long-term trend $f_a^{Trend}(t)$, the seasonal pattern as a function of the calendar week wt, $f_a^{Season}(w_t)$, and the exposure-response curves $f_{a,dt}^{Heat,\,i}(m_t)$ as a function of the weekly temperature m_t. The exposure-response curves are estimated separately for each age group a and decade d_t.

The superscript indices i of the exposure-response curves $f^{Heat,i}$ indicate that not only the mean temperature of the current week, but also the temperatures of three previous weeks are considered. The reason for considering the weekly mean temperature of the first preceding week is that high temperatures at the end of a calendar week can also influence the mortality in the following week. On the other hand, taking the second and third previous week into account allows to describe “harvesting” or “short time mortality displacement” (see e.g. [3], [2]). This refers to the fact that some of the deaths observed during heat periods are persons already very weakened by pre-existing conditions who would have died within a few days or weeks even without the exposure to heat. Looking at all-cause mortality, such shifts at the end of significant heat periods may show up as “below-average mortality”: The number of observed deaths is then slightly below the expected background mortality rate. The corresponding exposure-response curves show a negative correlation with the mortality rate.

The smooth functions f^{Trend}, f^{Season} and $f^{heat,i}$ are chosen as penalized B-splines (or P-splines). The allowed maximum degrees of freedom (DoF) were chosen such that, on the one hand, the seasonal pattern can be flexibly adjusted and, on the other hand, excessive fluctuations in the trend are prevented (1 DoF per 2 years). For each of the exposure-response curves, 8 DoF were allowed. With higher numbers of degrees of freedom, the model does not better explain the data; in fact, the number of degrees of freedoms actually used is significantly below the allowed maximum number, both for the seasonal pattern and for the exposure-response curves. The model coefficients and functions were calculated using the R statistical software (version 4.0.5, package mgcv [4]).

Modeling is performed separately for each of the three regions so that the strength of the random disturbance can be determined on a regional basis. In earlier studies, this approach has already proven to be superior to a regionally uniform model [1].

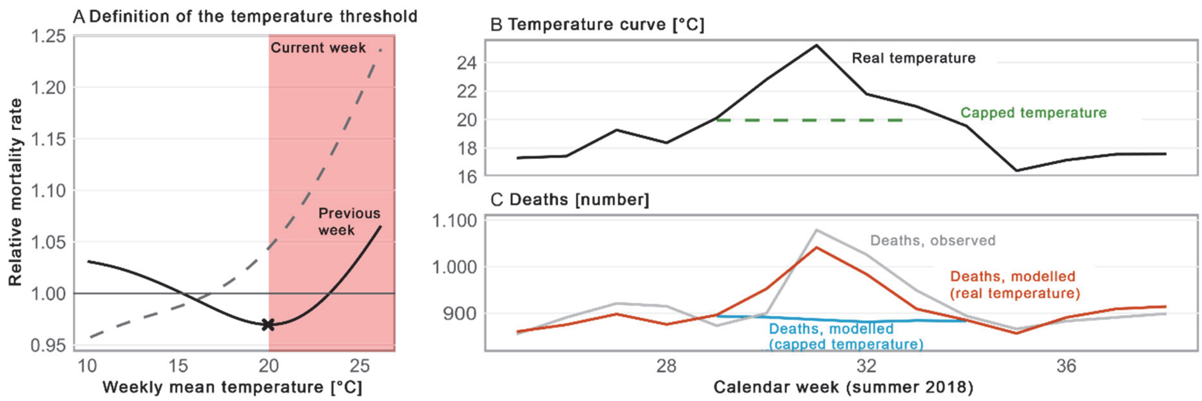


Figure 1: **A** Exposure-response curves of the current week (gray, dashed) und the immediately preceding week (black, solid). While the curve of the current week increases monotonously over the entire temperature range studied, the curve of the previous week shows a clear minimum at 20°C. The red shaded area shows the monotonic increase of both exposure-response curves at temperatures above the threshold. **B** Real (black) and capped (green) temperature curve with regard to the threshold value from A. **C** Curve of the weekly numbers of deaths (gray), modelled curve based on real temperature conditions (red) and background mortality under the assumption of a "capped" temperature curve (≤ 20°C). All subfigures refer to data for the 85+ age groups in Bavaria in 2018.

1.2 Estimation of the temperature threshold

In order to define heat periods and to quantify the number of heat-related deaths on the basis of weekly data, we use the exposure-response curves to define a temperature threshold above which a week is referred to as a "heat week" and has a relevant effect on mortality. This threshold value is defined as the mean temperature above which the exposure-response curve of both the current week and the previous week show increasing mortality rates. In our case, the threshold value corresponds to the minimum of the exposure-response curve of the previous week (see *Figure 1 A*).

1.3 Background mortality

To define background mortality, we consider a "capped" temperature curve that corresponds to the real curve but remains on threshold value for values above the threshold (see *Figure 1* ***B***). Entering this hypothetical temperature curve into the model equation yields a hypothetical curve of mortality that would be expected within our model for the capped temperature (see *Figure 1* ***C***).

1.4 Heat-related mortality

Finally, heat-related mortality can be calculated by taking the difference between the modeled mortality for the real temperature curve and the background mortality. The total number of heat-related deaths is the sum over all calendar weeks of the summer half-year (CW 15 to CW 40).

2 Data

2.1 Temperature data

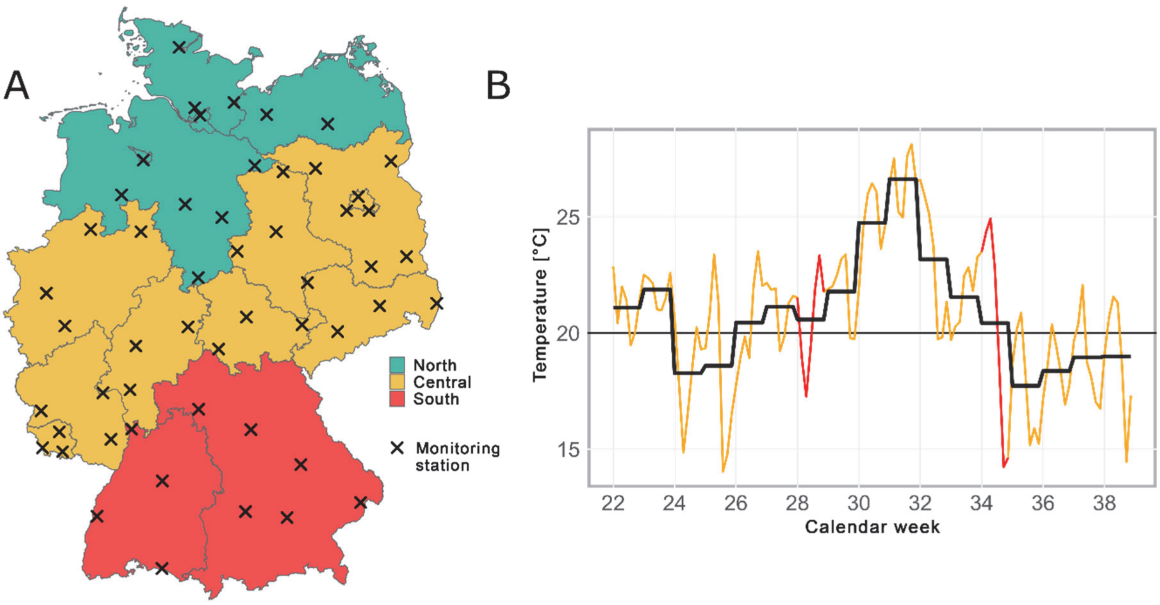


Figure 2: **A** Geographical distribution of the temperature monitoring stations. The breakdown into regions is marked in color. **B** Example comparison of the daily mean temperature (yellow) and the weekly mean temperature (black) in Baden-Württemberg in the summer of 2018. Weeks with high fluctuations in daily mean temperatures are highlighted in red.

The temperature data used are based on hourly measurements obtained at 52 stations of the German Meteorological Service (DWD). The geographical distribution of the stations is shown in the Figure 2 **A.** For each station, daily means (over 24 hours) are first calculated and then aggregated over all stations in a German federal state. Finally, the weekly means are calculated from the daily means, separately for each state. The values for a specific federal state are directly included in the modeling and are only aggregated to regions in the analysis. Given the large number of values per data point (24h × 7 days × at least 3 stations per federal state), individual missing values can be safely ignored. The stations were pre-selected so that no extended downtime would occur over the study period. Figure 2 **B** shows the difference between daily and weekly mean temperatures, using Baden-Württemberg in the summer of 2018 as an example.

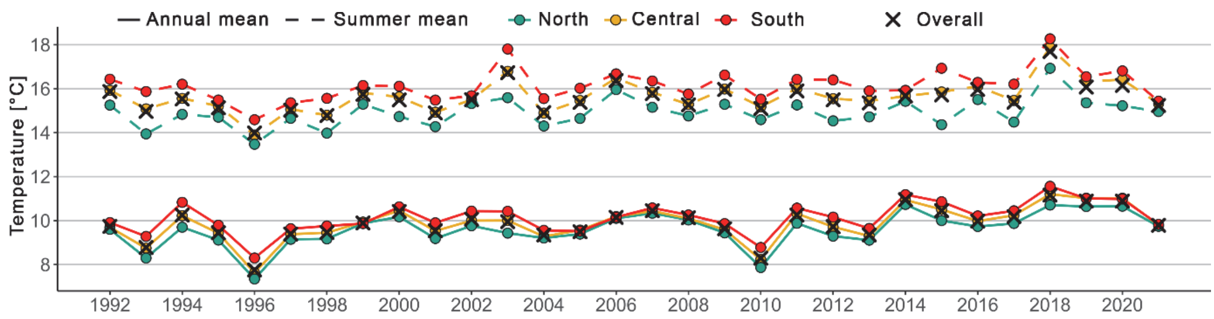


Figure 3: Curve of the annual mean temperature (solid) and the mean summer temperature (dashed) in the period 1992-2021. Color coding corresponds to the breakdown into regions.

Figure 3 shows the development of the annual mean temperatures and the mean summer temperatures during the period 1992-2021 in the three regions studied as well as in all of Germany. Especially the mean summer temperatures show clear differences between the regions. The nationwide mean temperature closely matches the values in the Central region.

Figure 4 **A** shows the maximum weekly temperatures for Germany and the three regions in the period 1992–2021. It reveals that in 2003, for example, there were strong temperature differences between the regions, while temperatures in 2018 were very similar in magnitude.
4 **B** shows the number of heat weeks in Germany overall und for each of the three regions.

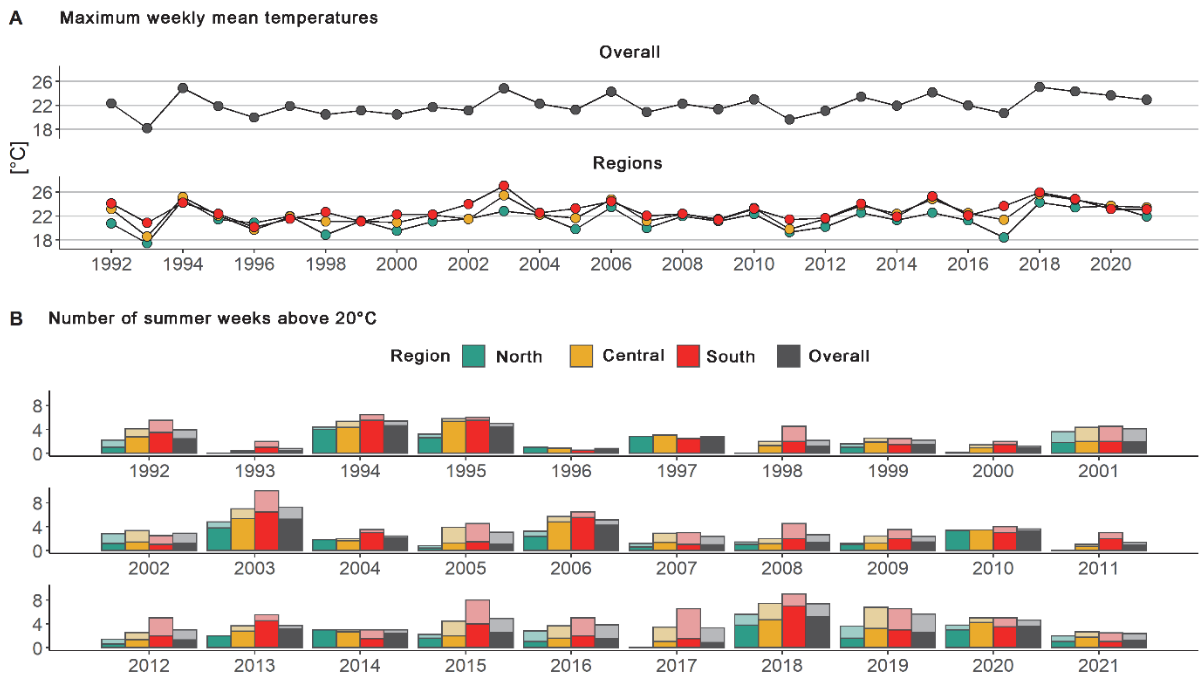


Figure 4: Key temperature figures for the period 1992-2021. **A** Maximum weekly mean temperature per year averaged over all federal states (above) and over the three regions (below). **B** Mean number of hot weeks (with temperatures >20°C) per year and region (colors as above) as well the entire country (gray). The bright areas mark the proportions of the longest continuous hot periods in the total number of hot weeks (contiguous periods were calculated per federal state and then averaged).

Highlighted bar segements show how many of these weeks occurred in a contiguous hot period. It is striking that the number of hot weeks during the three years 2018, 2019 und 2020 was significantly higher compared to other years in the 2012-2021 decade. Furthermore, the particularly long duration of the heat period in 2018 is notable.

As can be seen from the example in Figure 2 **B**, the duration of heat periods varies considerably in the daily and weekly data. Especially, there is a smoothing effect of the weekly mean values: The particularly long heat period in Baden-Württemberg during the summer of 2018 (9 consecutive weeks with mean temperatures above 20°C) is noticeable in the daily data, but the daily temperature data reveal numerous drops in temperatures lasting for several days. The longest continuous period of days with daily mean temperatures >20°C in the summer of 2018 was 18 days in Baden-Württemberg.

Region	Weeks >20°C	(days/7) >20°C
North	1.8	1.2
Central	2.2	1.4
South	2.9	1.7

Table 1: Mean duration of the longest continuous heat period per region. For better comparability with the weekly data, the number of consecutive days with mean temperatures >20°C is divided by 7.

Table 1 summarizes the mean durations of the longest continuous heat periods in weekly means for the three regions (North, Central and South) and compares them to the mean duration of the longest continuous period with daily mean temperatures >20°C (for better comparability, we use (number of days)/7).

2.2 Population data

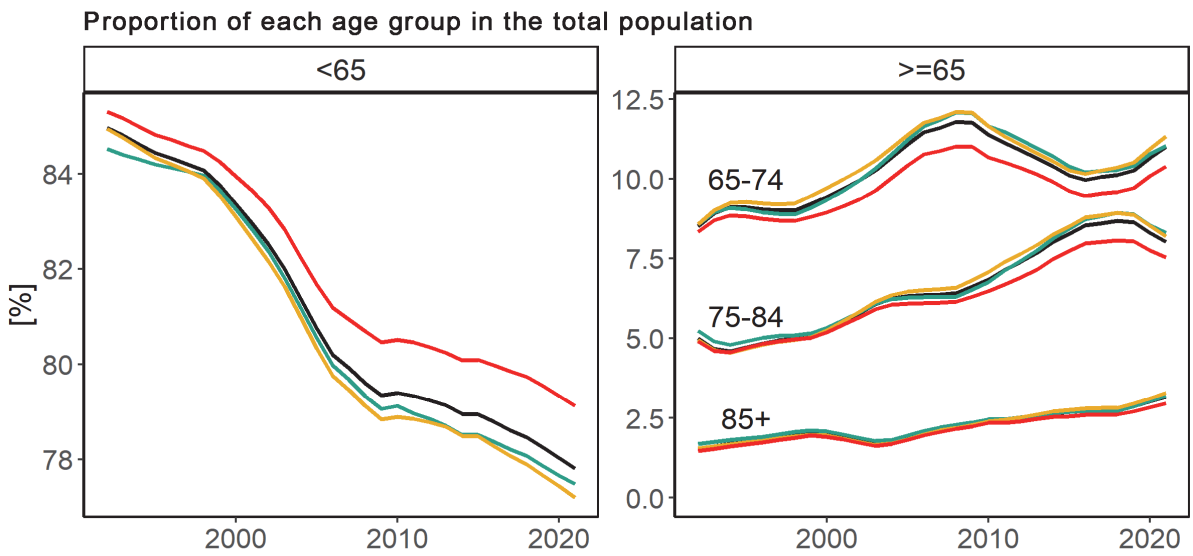


Figure 5: Development of the share of the four age groups in the total population and the populations of the three regions.

Both the number of deaths and mortality (deaths per 100,000 population) are influenced by demographic changes, such as population growth or increases in life expectancy. Between 1992 and 2021, the population of Germany grew from about 81 million to about 83.5 million. At the same time, the proportion of older people has risen considerably: About 3% of the population is now over the age of 85; in 1992, this age group accounted only for 1.5% of the population.

Figure 5 shows the development of the proportions of the various age groups for the three regions and all of Germany during the period 1992 - 2021. When looking at heat-related mortality, these changes are important as older people are particularly affected by the impact of heat. This means that an increase in the proportion of older people can lead to an increase in heat-related deaths even if the susceptibility of the population as a whole decreases.

3 Analyses

In the following, we present in-depth analyses that expand on the research presented in the main text.

3.1 Comparison with excess deaths

The number of excess deaths during heat periods can be used as a reference value for the estimated number of heat-related deaths (see main text). This value is calculated as the difference between observed mortality and background mortality in weeks with mean temperature of above 20°C. Since both heat-related mortality and excess mortality are calculated using the same background mortality, the comparison between the two measures can be used as a quality criterion for the model fit.

Figure 6 shows the estimated number of heat-related deaths as well as the estimated excess deaths during the period 1992-2021. Especially in years with significant heat mortality (e.g., 1994, 2003, 2018), the model slightly underestimates the observed mortality which can be seen from the number of heat-related deaths being lower than the number of excess deaths.

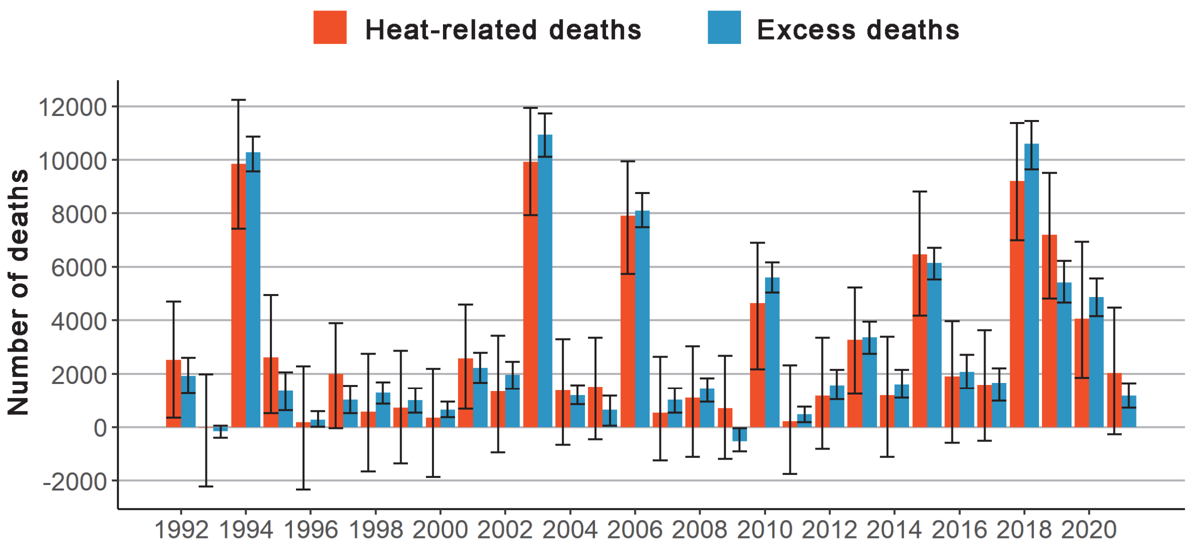


Figure 6: Comparison of the estimated number of heat-related deaths (red) and excess deaths (blue) in Germany for the period 1992- 2021

3.2 Exposure-response curves and threshold values

To better understand the impact of temperature on mortality, all exposure-response curves of the 2012-2021 decade are depicted in Figure 7, stratified by age group, region and week.
Starting from mean weekly temperature values ≤ 20°C, both the current week's temperature and the previous week's temperature show an amplifying effect on the mortality rate. Particularly for the mean temperature of the current week, a clear division of the regions and age groups is noted, with the 85+ age group and the northern region being the most affected. The mean temperatures of the second and third previous week show either an insignificant or a slightly negative impact on mortality rate.

As already described in the Methods section, we choose the minimum of the exposure-response curve of the previous week as the temperature threshold. The resulting values are summarized in Table 2. However, in some casesthe curves do not show a clear minimum and no threshold value can be determined. This limitation of our approach is illustrated in Figure 9 where we show the exposure-response curves of the current week and the previous week for all regions, age groups and decades.

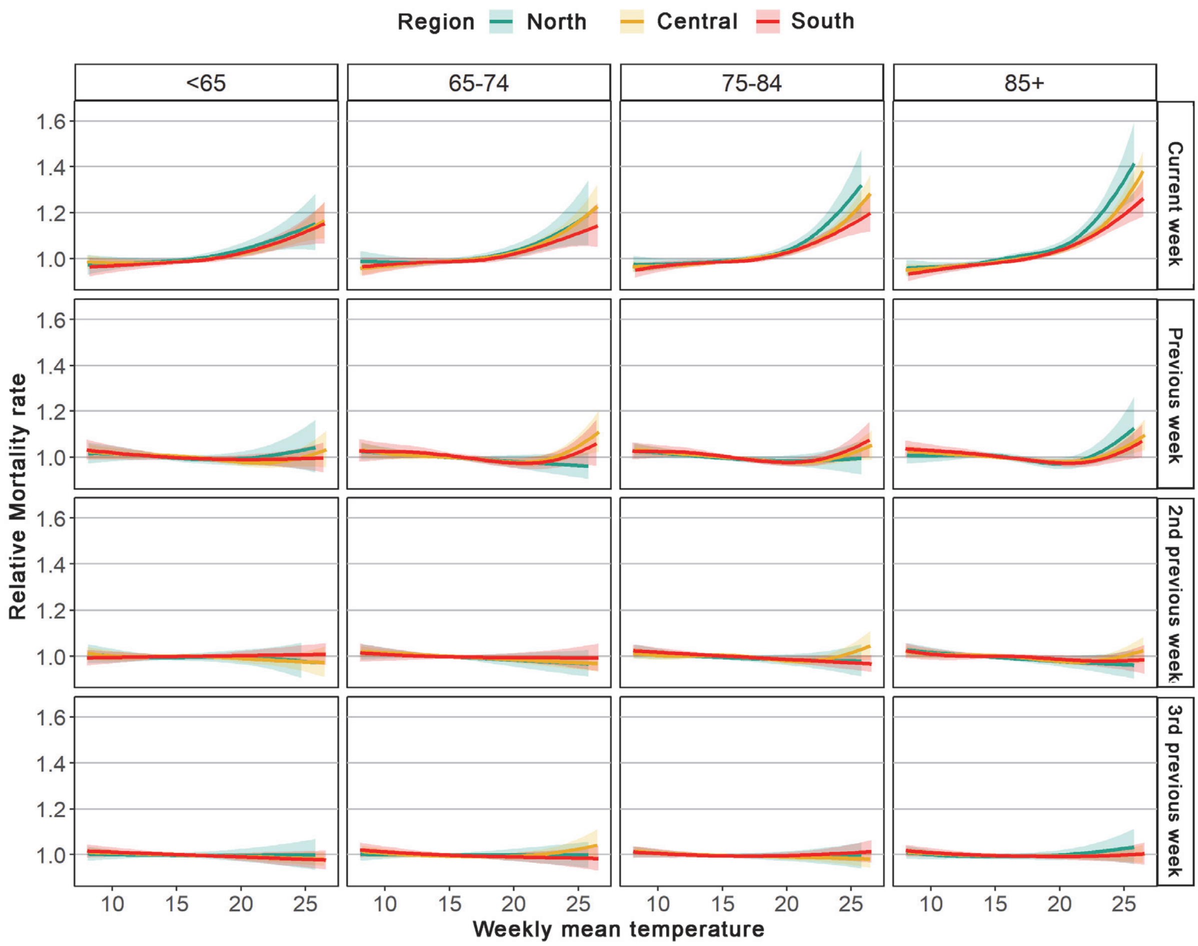


Figure 7: Exposure-response curves of the 2011-2021 decade for all age groups (columns), previous weeks (rows) and regions (colors). The mean temperatures of the current week and the previous week have the strongest positive effect on the relative mortality risk. Particularly for the current week, a clear division of the regions and age groups is noted, with the 85+ age group and the northern region being the most affected.

To the extent that they can be definitively determined, the threshold values range closely around 20°C. Thus, in Figure 8 we compare the estimated number of heat-related deaths on the basis of individual threshold values with the estimated numbers that are obtained if a uniform threshold value of 20°C is used for all regions and age groups.

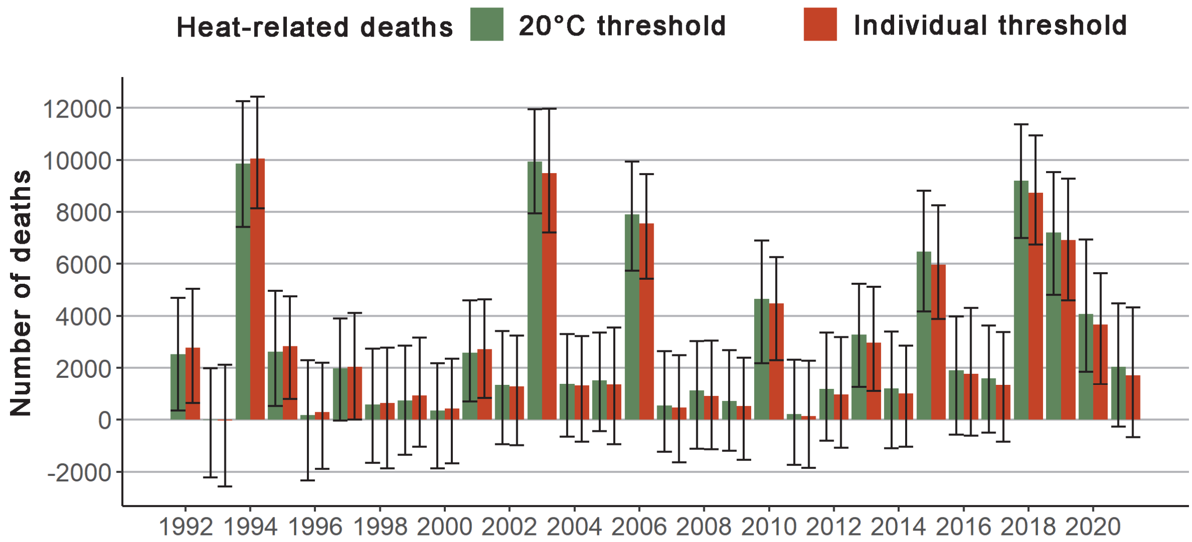


Figure 8: Estimated number of heat-related deaths, if a uniform threshold value of 20°C is assumed (green), in comparison to the number of deaths obtained, if region-specific and age-specific threshold values (red) are assumed, in Germany for the period 1992-2021.

1992-2001

Region	< 65	65 – 74	75 – 84	85+
North	-	-	19.2	18.7
Central	-	20.8	19.9	19.6
South	-	-	20.0	20.0

2002 - 2011

Region	< 65	65 – 74	75 – 84	85+
North	-	-	19.7	19.5
Central	20.8	20.2	20.2	19.9
South	-	20.8	21.1	20.5

2012 - 2021

Region	< 65	65 – 74	75 – 84	85+
North	17.7	-	-	19.7
Central	21.3	20.5	20.8	20.2
South	-	20.8	20.0	20.8

Table 2: Calculated temperature threshold values for all regions and age groups. Missing values are marked with a dash; in this case, the minimum value is located near the edge of the observed temperature range. For the purpose of modelling the background mortality, these values are replaced by values from neighboring regions/age groups.

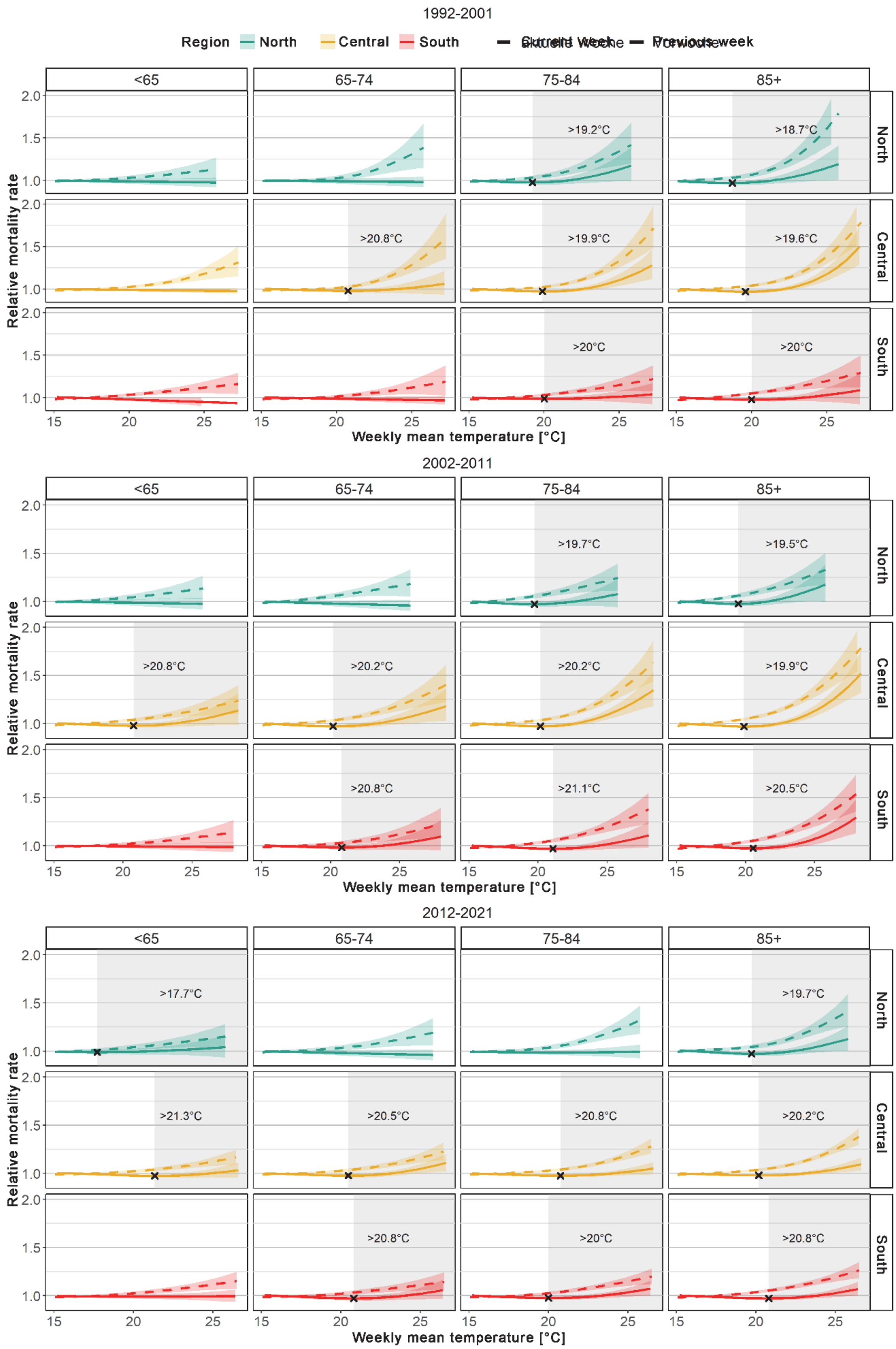


Figure 9: Exposure-response curves of the current week (dashed) and the previous week (solid) for all regions, age groups and decades. Black crosses indicate the threshold value (if identifiable). Temperature ranges above the threshold are highlighted in gray.

3.3 Comparison with previous estimation

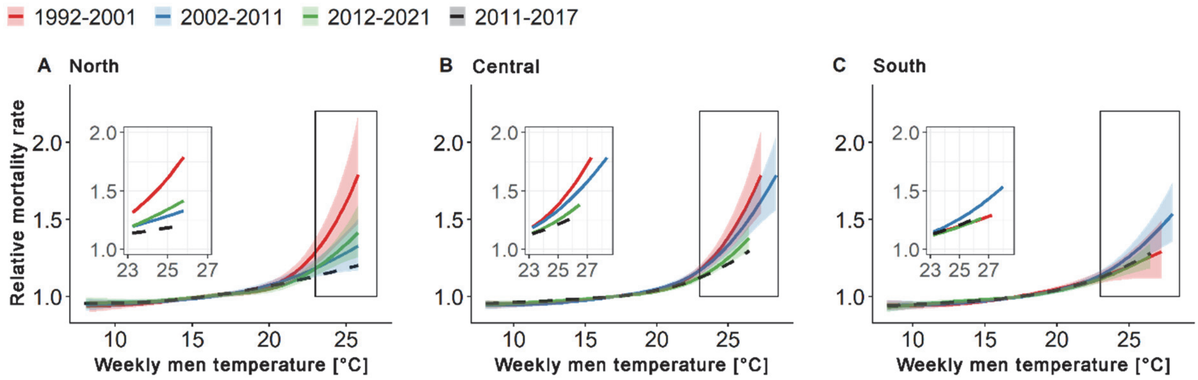


Figure 10: Trend of exposure-response curves for the three regions (North, Central and South).The results for the 85+ age group are depicted because the strongest effects are observed in this age group. The three decades 1992-2001 (red), 2002-2011 (blue) and 2012 to 2021 (green) show a slightly declining trend which is particularly evident in the central region. The estimate for the period 2011-2017 is shown in gray and is slightly below the estimate for 2012-2021 (green).

For the period 1992-2017, heat-related mortality in Germany was already studied in a previous publication [1]. The inclusion of the particularly hot years 2018-2020 leads to a re-estimation of the exposure-response curves of the 2012-2021 decade which shows a steeper rise compared to the model based on the data up to 2017. Figure 10 shows the long-term development of the exposure-response curves, using the 85+ age group as an example, for all three regions. To help put these in context, the exposure-response curves estimated in [1] for the 2011-2017 decade are also presented; in comparison to the updated estimate, these curves have a somewhat less steep slope.

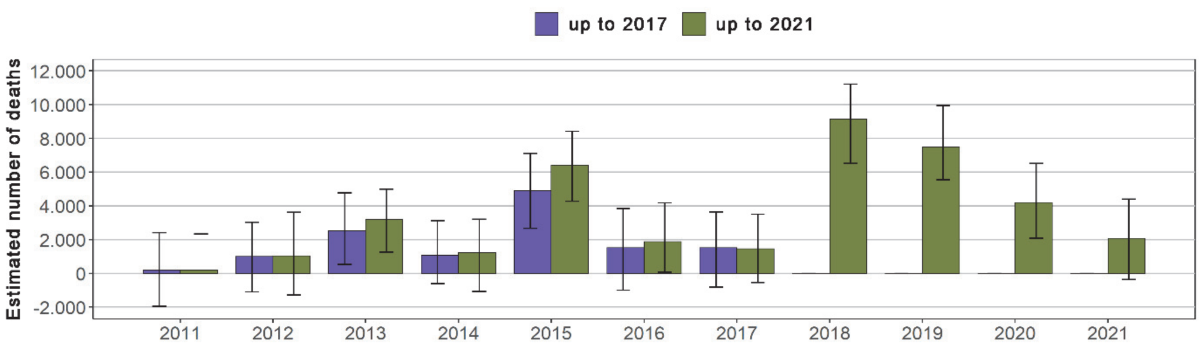


Figure 11: Estimated number of heat-related deaths in the period 2011-2021 on the basis of data up to 2017 (purple) or up to 2021 (green). The steeper slope of the exposure-response curves due to inclusion of the period 2018-2021 leads to a slightly higher estimate of deaths in earlier years. However, these differences are not statistically significant.

The re-estimation of the exposure-response curves for the 2012-2021 decade implies that the estimated number of heat-related deaths for this decade must also be revised slightly upward.

Figure 11 shows the estimate of heat-related deaths from [1] in direct comparison with the updated values. The updated estimates are within the 95% confidence intervals of the previous estimation.

3.4 Comparison of the 2018 heat period with the 1994 and 2003 heat periods

In the entire period 1992-2021, the years 1994, 2003 and 2018 stand out in particular with very high temperatures, long-lasting heat periods (see Data section) and high numbers of heat-related deaths (see main text). Because these years are also in three different decades, it makes sense to directly compare possible changes in the effect of temperature on mortality using these extreme years.

Figure 12 shows heat-related mortality as a function of the temperature observed in the three years 1994, 2003 and 2018, stratified by age group (columns) and region (rows). Despite comparable weekly mean temperatures, the model-estimated heat-related mortality in 2018 is clearly below the 1994 and 2003 values in all age groups. The fact that nevertheless the absolute numbers of deaths in the three years are about comparable can be explained by the high total number of hot weeks as well as the increased proportion of the population belonging to older age groups. Moreover, at times significantly higher weekly mean temperatures were measured in 1994 and 2003 compared to those in 2018.

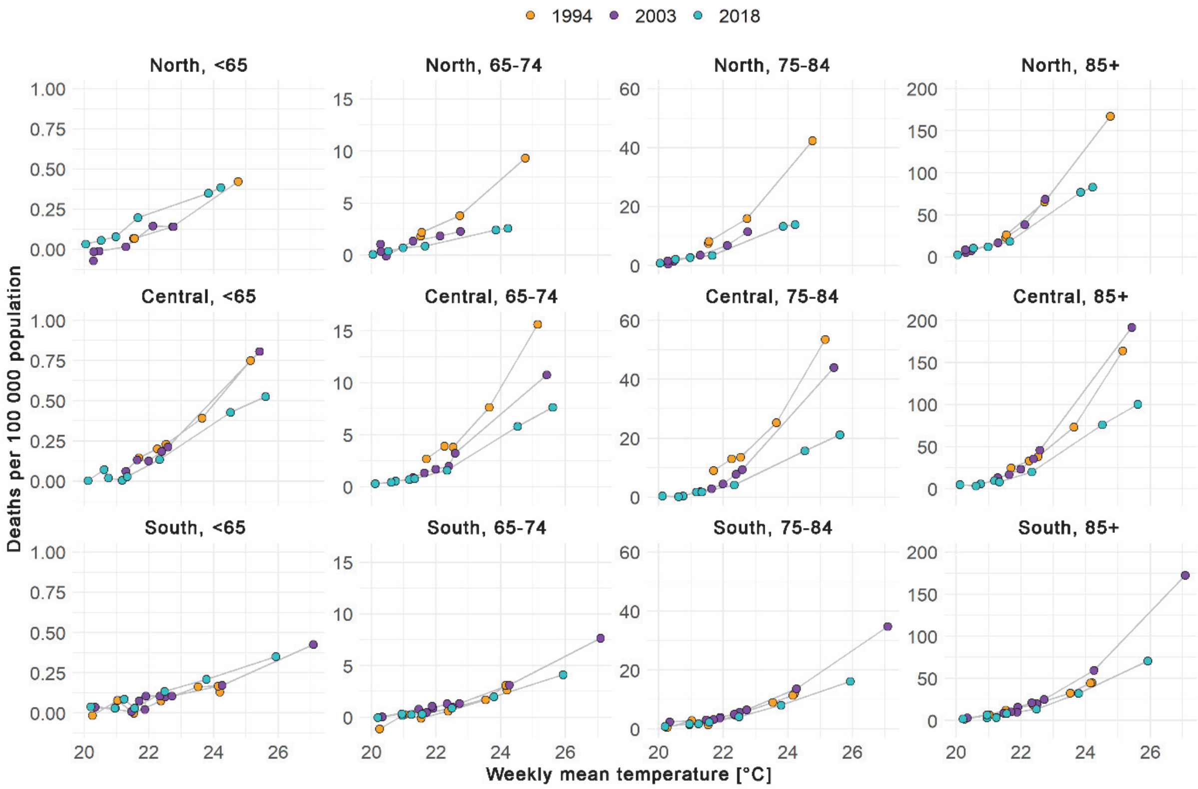


Figure 12: Comparison of the association between heat and mortality for the years 1994, 2003, 2018 in the three regions (North, Central and South). The four age groups are shown in ascending order from left to right. In all age groups, the heat-related mortality estimated by the model is lower in 2018 compared to 1994 and 2003.

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