Impact of Climate and Population Change on Temperature-Related Mortality Burden in Bavaria, Germany

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ABSTRACT

Background: Recent studies on temperature-related mortality burden generally found higher cold-related deaths than heat-related deaths. It is anticipated that global warming will on one hand result in larger heat-related mortality but on the other hand lead to less cold-related mortality. Thus, it remains unclear whether the net change in temperature-related mortality burden will increase in the future under climate change.

Objectives: We aimed to quantify the impact of climate change on heat-, cold-, and the total temperature-related (net change) mortality burden across five administrative areas in Bavaria by the end of the 21st century.

Methods: We applied location-specific, overall all ages and age-specific exposure-response functions to project the net change in temperature-related mortality burden during the future period 2083-2099 as compared to the baseline period 1990-2006 under four climate scenarios (Representative Concentration Pathway [RCP] 2.6, 4.5, 6.0, and 8.5) and six population projection scenarios (assuming a constant population, Shared Socio-economic Pathway [SSP] 1, SSP2, SSP3, SSP4, and SSP5). We further calculated changes in the age-specific temperature-related mortality burden during the future period.

Results: When considering the exposure-response function for all ages for mortality projection, the net temperature-related mortality was found to remain similar under SSP1 and SSP2, decrease significantly for SSP3 and SSP4 (under three RCPs -2.6, 4.5 and 6.0) and increase significantly only under SSP5. The highest decline was found for the scenarios of SSP3 and RCP 2.6 where deaths during the future period decreased by 41%, i.e. [-15,382 (95% empirical confidence interval, eCI: -21,364; -8,487)]. However, when considering the age-specific exposure-response functions for mortality projection, the net temperature-related mortality burden was found to increase significantly under all SSPs and RCPs. In consequence, even under the previous highest decrement scenario of SSP3 and RCP 2.6, deaths in the future period were two times larger [33,407 (95% eCI: 24,979; 66,173)]

Conclusion: The elderly population, highly vulnerable to both heat and cold, is projected to be about four folds the younger population in the future. Thus, the combined effect of global warming and population aging results in an increase in both the heat-related deaths and the cold-related deaths. Mitigation and age-specific adaptation strategies might greatly reduce the temperature-related mortality burden in the future.

KEYWORDS: Climate Change, Population Change, Temperature, Aging, Mortality Burden, Bavaria

1. INTRODUCTION

The association between ambient temperature and mortality outcomes has been studied extensively (1-4). There is agreement that there exists a temperature of minimum mortality (MMT) at which the Relative Risk (RR) of temperature-related mortality is one (5-8). Exposure-response functions (ERFs) between temperature and mortality are found to be U-, J- or V-shaped deviating from this MMT (6, 8) and are location-specific depending upon climatic, geographic and demographic characteristics (5, 7, 8). However, it makes, of course, a difference, if the deaths can be attributed to cold or to heat. A multi-country study conducted in 13 nations estimated 7.29% of the total mortality attributable to cold and only 0.42% to heat (9). Thus, low ambient temperature seems to contribute more temperature-related mortality than high ambient temperature.

Under a changing climate, the surface temperature of the earth is projected to increase in the future (10). There exists evidence that a warming climate would result in higher future heat-related mortality (11-14). Several studies also show an increasing impact of climate change on heat-related cause-specific mortality burden, such as cardiovascular and respiratory causes (15, 16). However, with increasing temperatures, cold-related mortality burden will decrease in the future (8, 17-20). Thus, heat-related mortality might be outnumbered by the reduction in cold-related mortality, resulting in a decrease of the net temperature-related mortality (8). Given a certain geographic location, the direction of the net change depends on the ERF, the projected temperature, and the population changes of that specific location.

A number of international studies have projected the impact of climate change on the total, i.e. both heat and cold-related mortality burden in different locations of the world (3, 8, 18, 20, 21). Most studies so far have incorporated only climate-change scenarios (3, 21) while some have also taken into account the changes in future population for mortality projection (8, 20). But only a limited number of these studies have incorporated age-specific exposure-response curves for future mortality projection (3, 20). A study projecting cold-related mortality for population ≥ 85 years of age under a constant population scenario, found decrement by 29% and 30% in the United Kingdom and Australia respectively (20). Under the same scenario, another study found 25% reduction in cold-related deaths by 2050s; however, this reduction when considering the future population changes would be 2-3% (3). These finding suggest us the need for considering the age-specific exposure-response association together with future demographic condition when projecting future temperature-related mortality. Moreover, these studies were based on the older climate projection scenarios (3, 20). Thus, there still exists a gap in estimating future temperature-related mortality under recent climate models considering both climate change and the effect of age. Our study, based on new climate projection scenarios, attempts to address this gap.

In this study, we aim to assess the impact of climate change on heat, cold and the net temperature-related mortality burden in five administrative areas of Bavaria under different scenarios of climate and population projection. We incorporated both the overall ERF for all ages and the age-specific ERF to project and compare the total temperature-related mortality burden.

2. METHODS

2.1. Overview

We conducted this study in five locations within the state of Bavaria, Germany. Bavaria, the largest state in Germany is located in the south-eastern part and had a population of 13 million in 2017 (22). The five locations included in this analysis were Augsburg, Fürstenfeldbruck, Munich, Nuremberg, and Rosenheim. These five locations encompass a wide range of socio-economic and demographic variations (23) (see Table 1 for location-specific information). This analysis was carried out in two parts, each with three stages. For the first part of the analysis, we first derived an ERF for all ages for the association between mean daily temperature and mortality in each of the five locations during the baseline-period (1990-2006; 17 years). Then the location-specific ERFs were applied to project temperature-related mortality in the future-period (2083-2099; 17 years) under four Representative Concentration Pathways (RCPs) and five Shared Socioeconomic Pathways (SSPs). The future-period was specifically chosen, in order to keep it consistent with the 17-year baseline period and to include the year 2099, the end-year of the 21st century. Finally, we calculated the difference in the net attributable number of deaths (ΔAN), defined as the sum of total heat and cold-related deaths, between the future-period and the baseline-period under each RCP and SSP. The attributable fraction (AF) was reported as the ratio of temperature-related deaths and total deaths. For the second part of the study, we carried out the same steps, however now considering the age-specific ERFs for each of the five locations, thus considering differences in vulnerability between age groups and the impact of population age-structure changes.

2.2. Data sources

Baseline temperature and mortality

We obtained daily mean temperature for the baseline-period from the German Weather Service and the Bavarian Environment Agency. Daily total death counts and age-specific death counts were obtained from the Bavarian State Office for Statistics and Data Processing. International Classification of Diseases 9th Revision (ICD-9) codes for the period 1990–1997 and International Statistical Classification of Diseases and Related Health Problems 10th Revision (ICD-10) codes for the period 1998–2006 were used for classifying the causes of death. All non-accidental deaths were included as total number of deaths for our analysis. This dataset was also used in our two previous publications (23, 24).

Temperature projections

The daily mean temperature for the future-period was obtained from the Inter-Sectoral Impact Model Intercomparison Project phase 2b (ISIMIP2b) dataset. The ISIMIP2b models were developed for the Intergovernmental Panel on Climate Change Special Report (IPCC SR15) (25). This spatial dataset includes downscaled daily climate projections on a horizontal grid with 0.5° × 0.5° resolution from four global climate models (GCMs) (i.e., GFDL-ESM2M, HadGEM2-ES, IPSL-CM5A-LR, and MIROC5) (26). We obtained daily temperature simulations for all of the four GCMs under four climate change scenarios, i.e. under RCP 2.6, RCP4.5, RCP6.0, and RCP8.5 for each location. We then constructed modelled daily mean temperature series averaging the four GCMs under each RCP for each location by extracting the temperature projections from the corresponding grid cell covering the centroid of the location similar to previous studies (21, 27). This resulted in 16 temperature projections per location and a total of 80 temperature projections. These temperature simulations have been corrected for bias based on the EartH2Observe, WFDEI and ERA-Interim data Merged and Bias-corrected for ISIMIP (EWEMBI) dataset (28).

Population projections

In order to analyze the climate-only effect on temperature-related mortality, our first analysis was under constant population scenario i.e. assuming that the population structure in the future-period will remain the same as in the baseline-period. For this, we applied a previously proposed method (29) and computed future annual series of total mortality counts as the average for each day of the year from the baseline daily mortality data in order to control for the seasonal trends of the observed mortality series. We also obtained population projections for each of the five locations under the five SSPs with the year 2090 (as reference for the future-period) from a high-resolution global spatial population projection downscaled from 1/8 degree to 1km grid cell from the National Centre for Atmospheric Research (NCAR) (30). The assumption for the population projection for Germany under different SSPs are medium fertility, low mortality, medium migration and high education for SSP1; medium fertility, medium mortality, medium migration and medium education for SSP2; low fertility, high mortality, low migration and low education for SSP3; low fertility, medium mortality, medium migration and polarised education for SSP4; and high fertility, low mortality, high migration and high education for SSP5 (31). Location-specific population projections were calculated by taking the sum of the populations of each grid cell covering the area of the location, a method used previously (16). Additionally, we corrected the obtained projected population for bias by extracting the population for the year 2010 from the NCAR dataset and comparing it with the observation from the German census authority (22) in order to find the location-specific correction factor. We then calculated a population change factor for each location under each of the five SSPs, which is defined as the ratio of the population in the future period to the population of the baseline period. The year 2010 (the NCAR-SSP dataset starts at this year) and 2090 were taken as a reference for the baseline and future period, respectively. The formerly computed location-specific annual series of total mortality counts were then multiplied by the location-specific and SSP-specific population change factor to obtain the SSP-specific annual total mortality count series. We thus obtained six sets of population scenarios for each location and 30 population scenarios in total. Similarly, the age-specific population projection for each location under each SSP was obtained from the International Institute for Applied System Analysis (IIASA) (32). The projected and bias-corrected age-specific annual series of total mortality counts for all population scenarios for each location were obtained with the same procedure as described above.

2.3. Statistical analysis

Exposure-response function (ERF)

We applied distributed lag non-linear models with a quasi-Poisson distribution extending the lag period to 21 days to establish the location-specific baseline temperature-mortality relationship. We used quadratic B-splines centered around the location-specific MMT with three internal knots placed at 10th, 75th and 90th percentiles of the location-specific mean temperature. The regression also included an indicator for the day of the week and 7 degrees of freedom per calendar year to control the seasonal and long term trends. We modelled the lag-response curve for temperature with a natural cubic B-spline with three knots placed at equally spaced values on the log scale. The association was then reduced to the overall temperature-mortality association, cumulating the risk during the lag period. The location-specific overall cumulative exposure-response association was then pooled using a multi-variate meta-analytical model from which we obtained the best linear unbiased prediction (BLUP) of each location-specific temperature-mortality association. This approach has been previously described and applied by a large international study (33). The same approach as above was applied to derive the age-specific ERFs for each location. The two age categories were age<75 years and age≥75 years.

Impact assessment on temperature-related mortality burden

We estimated the mortality counts attributable to heat and cold. The net temperature-related mortality was then calculated as the sum of heat and cold-related mortality for the baseline and the future periods according to a previously established approach (34). To estimate the future temperature-related mortality, we applied the previously estimated ERFs and the modelled daily series of temperature and mortality to calculate the daily temperature-attributable deaths. We calculated the total attributable number by summing the contributions from all the days of the series. Finally, the differences between the temperature-related future and baseline mortality were computed and reported as ΔAN for each projection scenario.

To account for uncertainty in both ERF and the projections of future climate and population models, we used Monte Carlo simulations to obtain empirical confidence intervals (eCI). We obtained the eCI from the empirical distribution across 5,000 samples of random parameter sets describing the ERF in the distributed lag nonlinear model under each climate and population projection scenario for each location (21, 34). We then applied the same analytical approach with age-specific ERF and age-specific population projection for each location.

Our results are segregated into location-specific change in heat-related and cold-related mortality rate, defined as the deaths due to temperatures above and below the location-specific MMT respectively (34). Both of the changes are summed to report the net change in temperature-related mortality. The results are presented for both stages, i.e. without and with consideration of the effect of age.

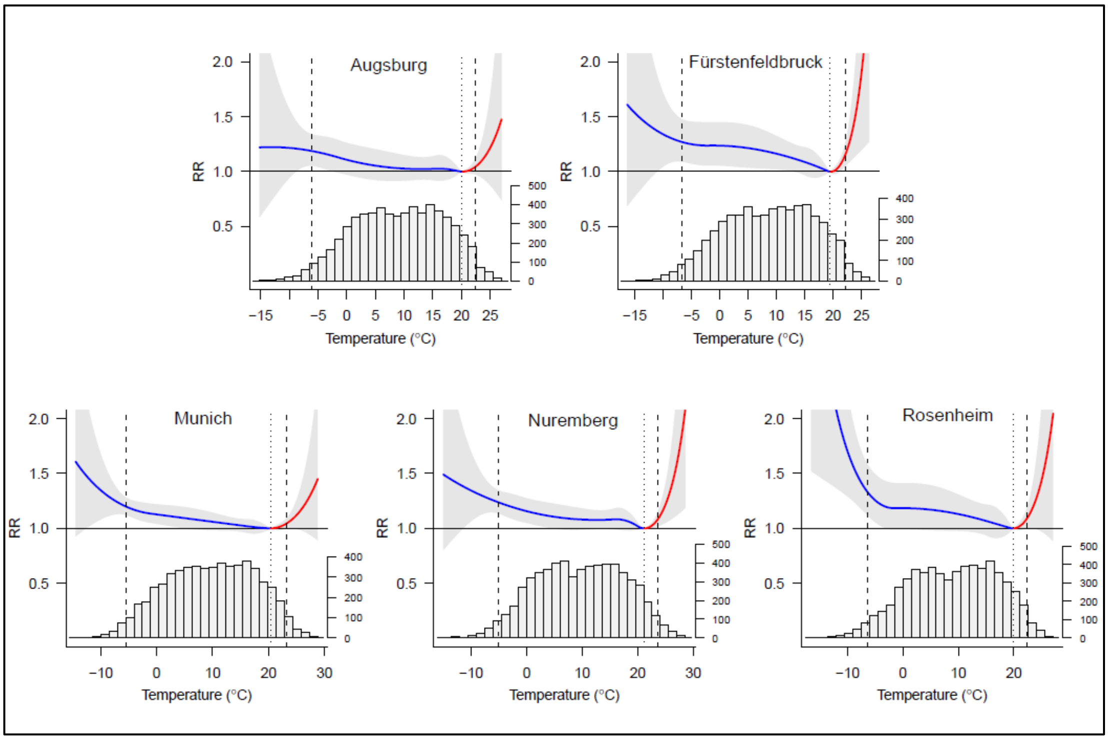
We performed all analyses in R version 3.4.3 (35) using the packages ‘dlnm’ (36) and ‘mvmeta’ (37) .

3. RESULTS

3.1. Baseline temperature-mortality association

Depending upon the location, we found U- or J-shaped associations between mean daily temperature and mortality during the baseline period (Fig.1). The MMTs ranged from 19.4°C to 21.1°C (Table 1). When considering the age-specific ERFs, the RR for the older age category was found to be higher for both cold and heat effects than the lower age category with CIs overlapping in certain locations. Tables 1 presents heat, cold and net temperature-attributable mortality number during the baseline period. For all five locations, the cold-attributable mortality count was found to be higher than the heat-attributable mortality count. (Supplement Table. S1 and S2 for AF).

(A) All ages



(B) Age-specific

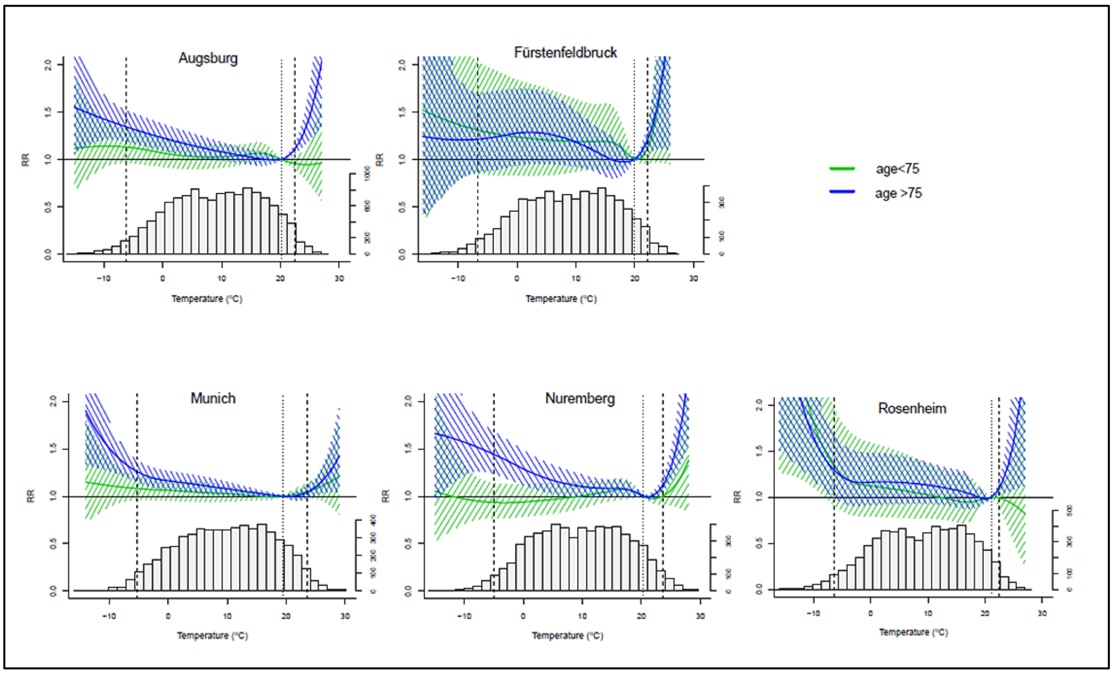


Fig 1: Location-specific exposure-response associations

Overall cumulative exposure-response associations in five locations for all ages (A); Age-specific cumulative exposure-response association in five locations (B). Exposure-response associations are presented as best linear unbiased prediction with 95% eCI (shaded) and temperature distributions during the baseline period. Dotted lines represent the minimum mortality temperature and the dashed lines the 2.5th and 97.5th percentiles. RR=Relative Risk.

Table 1: Baseline overall (all age) and age-specific temperature-attributable mortality number (1990-2006; 17 years)

Administrative areas (MMT)	**Age categories**	**Total deaths during baseline period**	**Attributable Number of Deaths**		
			Total (CI)	**Cold (CI)**	**Heat (CI)**
Augsburg (20.13°C)	All age	98,201	5,309 (-3,448, 2,979)	4,973 (-3,276, 11,004)	336 (-189, 642)
	Age<75	36,466	550 (-2011,4372)	711 (-1747,4345)	-160 (-330,157)
	Age≥75	61,735	4499 (2008,12159)	4080 (1784,11603)	418 (355,1058)
Fürstenfeldbruck (19.97°C)	All age	24,741	3,513 (1,012, 5,688)	3,268 (915, 5,386)	245 (101, 361)
	Age<75	9448	1139 (-367,2318)	1096 (-290,2236)	42 (-66,111)
	Age≥75	15,293	1545 (242,3398)	1409 (123,3272)	135 (230,685)
Munich (19.41°C)	All age	232,117	15,575 (2,414, 27,158)	14,832 (2,530, 27,158)	743 (23, 1,369)
	Age<75	86,870	2154 (-8072,10380)	1903 (-7405,9753)	251 (-568,997)
	Age≥75	145,247	11982 (5320,18014)	11581 (5184,17687)	401 (-193,960)
Nuremberg (20.32°C)	All age	95,249	8,858 (2,467, 14,887)	8,315 (1,762, 14,040)	543 (162, 886)
	Age<75	36,309	13 (-3547,3434)	-27 (-3665,3245)	40 (-204,275)
	Age≥75	58,940	7331 (4022,10505)	6937 (3459,10054)	394 (207,549)
Rosenheim (21.1°C)	All age	37,253	4,430 (-19, 8,181)	4,210 (-7, 7,849)	220 (4, 387)
	Age<75	12,332	633 (-1781,2907)	642 (-1745,2835)	-9 (-115,99)
	Age≥75	24,921	3069 (-446,5975)	2809 (-396,5786)	179 (71,264)
Total	**All age**	**487,561**	**37,685 (18,961, 52,071)**	**35,598 (17,970, 50,232)**	**2,087 (990, 2,877)**
	Age<75	**175,303**	**5022 (-6199,18199)**	**4820 (-5459,17460)**	**201 (-811,1138)**
	Age≥75	**312,258**	**29,402 (26123,48722)**	**27,818 (24870,46871)**	**1,584 (1095,2563)**

Location-specific attributable number summed up for total attributable number for Bavaria. CI=Confidence Interval (95%); MMT=Minimum Mortality Temperature; Total = results from all five cities summed up;

3.2. Climate and population projections

Under all RCPs, the mean temperature was projected to increase in the future period. The annual mean increases in temperature in Bavaria under different RCPs during the future period 2083-2099 were: 1.1ºC for RCP 2.6; 2.1ºC for RCP 4.5; 2.5ºC for RCP 6.0 and 4.6ºC for RCP 8.5. Fig. 2 shows the distribution of temperature during the baseline period and the future period under different RCPs. (Supplement Fig. S1. for location-wise temperature distribution). For the population projections under different SSPs, we found the highest increment factor under SSP5 and the lowest under SSP3. Under all SSPs, the increment factor for population of age≥75 years is on an average 4 folds times than that of age<75 years (Fig. 3).

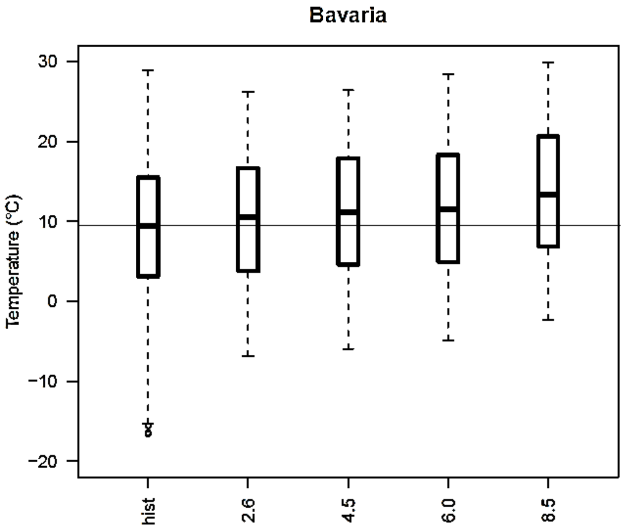


Fig 2: Baseline and projected annual mean temperature of Bavaria for the baseline period (hist) and the different RCPs.

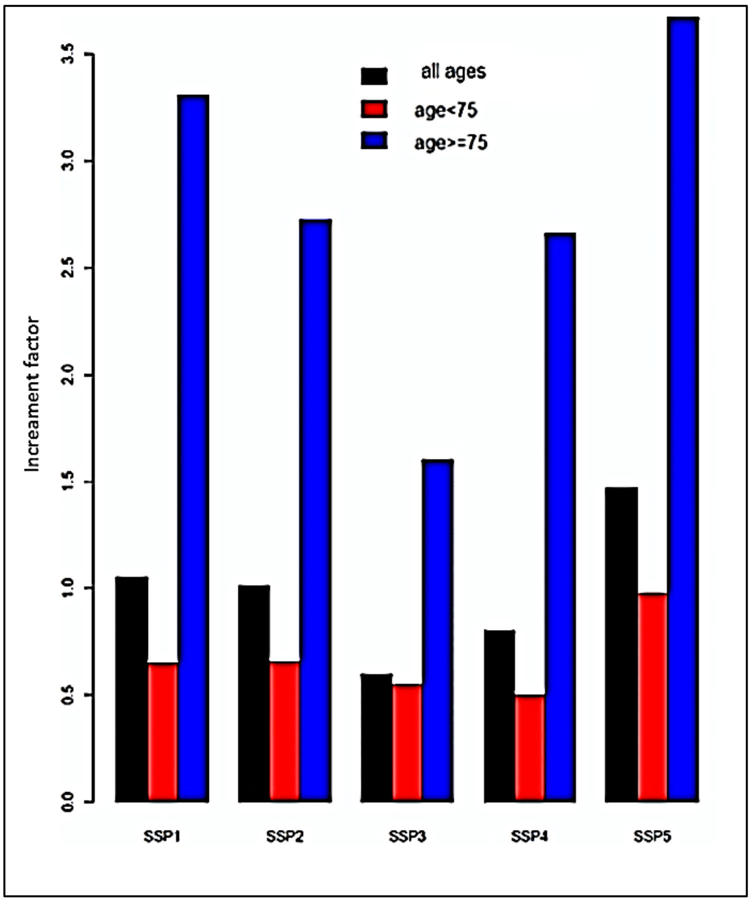


Fig 3: Projected population increment factor under different SSPs: ratio of future and baseline population.

3.3. Change in overall temperature attributable mortality

Location-specific changes in overall temperature-attributable mortality count are shown in Fig 4. and Supplement Table. S3. Under a constant population scenario, the ΔAN of deaths in the future period for Bavaria under RCP 2.6 will be -2,181 (-4,100;-512), a significant reduction in net temperature-related mortality (Supplement Table. S3). For the business as usual scenario RCP 8.5, the ΔAN will be 7,658 (-3,639; 33,045). Under the population projection scenarios SSP3 and SSP4, there will be significant decrease of net temperature-related mortality for all RCPs except for RCP 8.5. The ΔAN will increase under SSP1 and 2, however not significantly. Only under SSP5, we found a significant increase in ΔAN for all RCPs. All described results, however, vary among locations (Fig 4). Similarly, the overall cold- and heat-related mortality burden in Bavaria were found to decrease and increase, respectively, for most RCPs and SSPs (Supplement. Table. S4 for ΔAN).

3.4. Change in age-specific temperature-attributable mortality

Now, considering the age-specific ERFs for all locations, we found similar projection results for the constant population scenario (Fig. S2, S3 and Table S6). For the age group <75 years, the net ΔAN did not show significant changes for all scenarios of population and climate scenarios (Figure S2). However, for the age group >75, there will be a significant increase in the net ΔAN for all climate and population projection pathways except for the constant population scenario. Considering the heat-only and cold-only effect, there will be no significant changes in mortality burden for the younger age group (Supplement Table.S6.). For the elderly, there will be a decrease in the cold-related deaths under all RCPs under the assumption of constant population. However, for all other population projection scenarios, there will be a significant increase in both cold and heat-related mortality burden for this age group (Supplement Table.S6.)

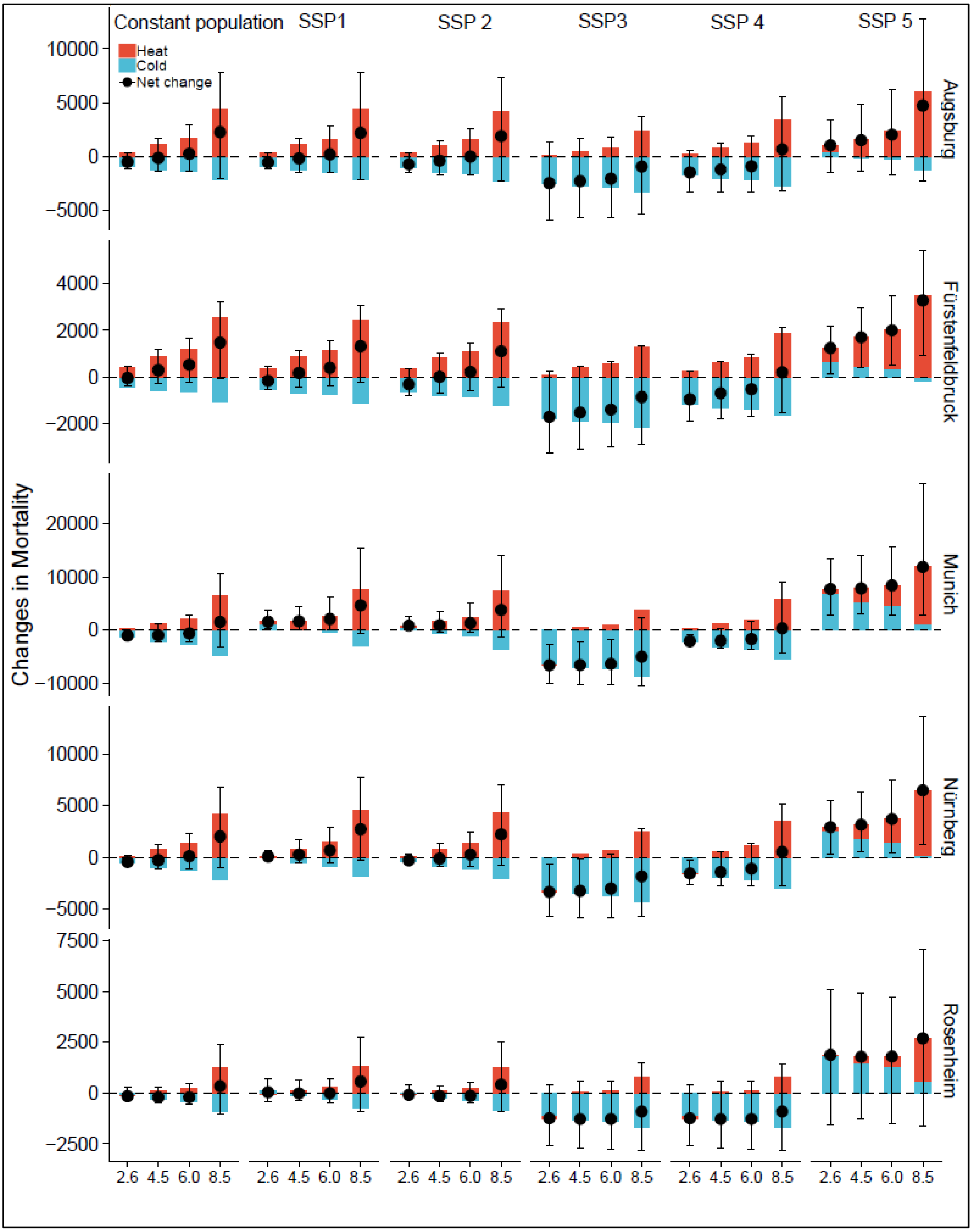


Fig 4: Projected overall location-specific change in heat-related, cold-related and net temperature-related mortality under all RCPs and SSPs during the future period (2083-2099)
Attributable numbers calculated with the location-specific overall exposure-response function for all ages.

3.5. Change in temperature-related mortality burden in Bavaria

The location-specific overall temperature-related mortality during the future period, when summed up, showed that the net mortality burden for Bavaria is projected to decrease significantly under SSP3 and SSP4 under RCP 2.6, 4.5, 6.0 (Fig 5). However, when changes in age structure were considered, we found a significant increase in ΔAN under all climate and population projection pathways (Fig 5).

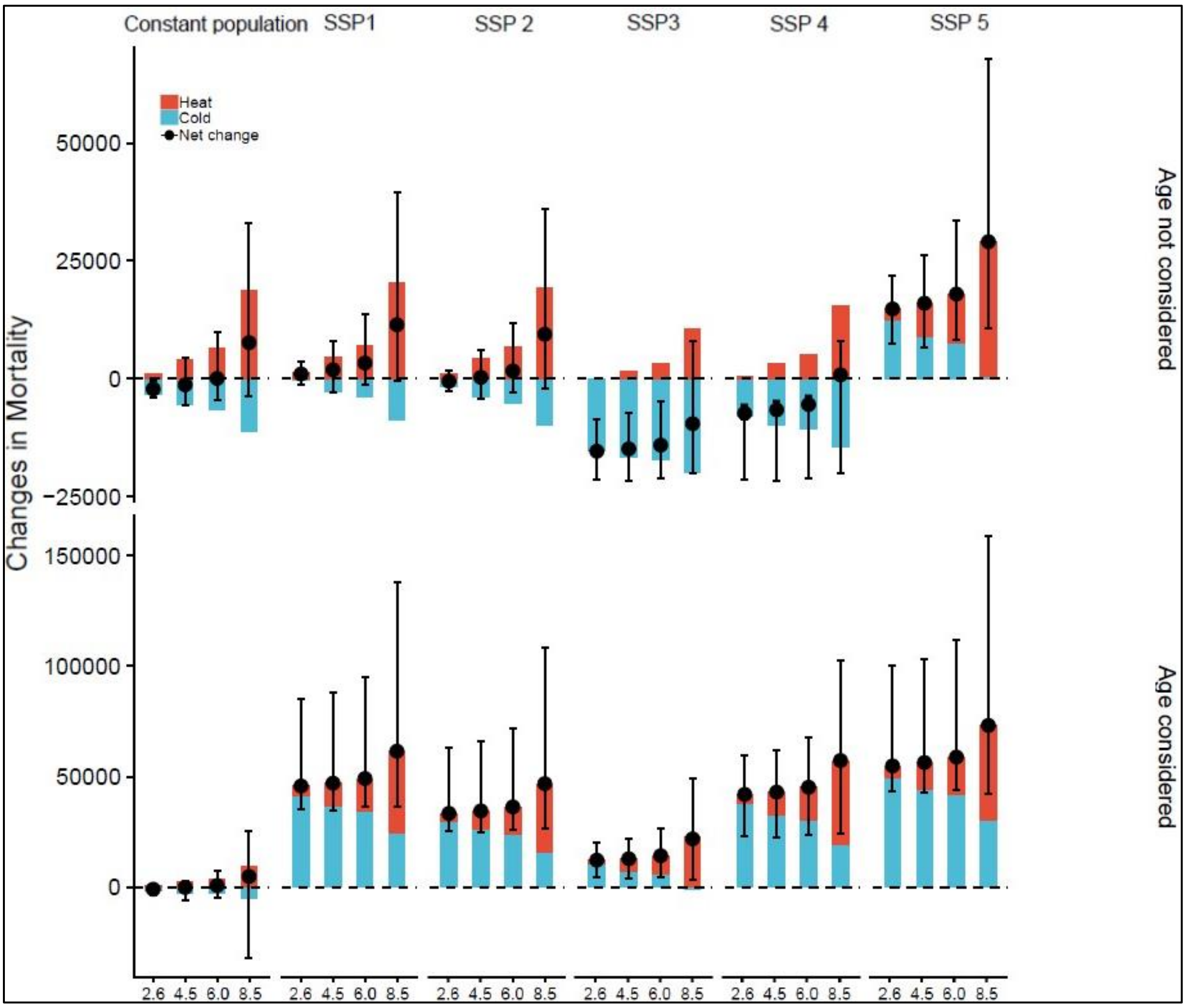


Fig 5: Projected change in the heat-related, cold-related and net temperature-related mortality in Bavaria under all RCPs and SSPs during the future period (2083-2099; 17 years).

Attributable numbers calculated with the overall exposure-response function for all ages (age not considered) and the age-specific exposure-response function (age considered)

4. DISCUSSION

We estimated the change in cold-, heat- and the net temperature-related mortality burden for Bavaria considering five large administrative areas within the state of Bavaria until the end of the 21st century (2083-2099) compared to the baseline period (1990-2006) under different proposed pathways of climate and population projection. When considering ERF for all ages for mortality projection, i.e. considering the entire population within a location reacts similarly to temperature, we found no significant change in the net temperature-related mortality during the future period under all RCPs for constant population, SSP1 and SSP2. Additionally, the net temperature-related ΔAN decreased significantly for SSP3 and SSP4 under three of the RCPs. We observed that the increasing heat-related deaths were compensated by the decreasing cold-related deaths, thus resulting in insignificant or decreasing net temperature-related mortality burden. The highest decreases were found under the scenario of SSP3 and RCP 2.6 where the deaths during the future period decreased by -15,382 (95% eCI:-21,364; -8,487). The net temperature-related ΔAN was found to increase only under SSP5-the highest population increment scenario. However, when considering the age-specific ERFs for mortality projection, the net temperature-related mortality burden increased significantly under all SSPs and RCPs. For the older age group > 75 years, who were based on our age-specific ERFs highly vulnerable to both heat and cold and also expected to have higher population in future , we observed that both heat- and cold-related mortality increased significantly under all RCPs and SSPs, thus resulting in a significant increase in the net future temperature-related ΔAN. When considering the age-specific ERFs, the net ΔAN were insignificant only under the condition of constant population.

Previous study in the same locations has also shown an increased vulnerability of the older population to temperature extremes (24). Exposure to either heat or cold stress increases mostly the cardiorespiratory morbidity and mortality. The effects of heat stress like sweating, dehydration, salt depletion, increased blood circulation and cardiac work, hemoconcentration are the causes of myocardial infarction, heart failure and stroke (24, 38). Similarly, cold stress is seen to cause increase in heart rate and blood pressure, fibrinogen and factor VII in blood, and changes in blood markers leading to higher risk of ischemic heart diseases (38).

When computing the temperature-related mortality burden during the baseline period, we found similar results with a previous multi-country observational study that found the cold-related mortality burden (7.29%) to be much higher than the heat-related mortality burden (0.42%) (9).

The total cold-attributable mortality fraction for Bavaria during the baseline period was 7.3% (3.81, 10.65) and that attributable to heat was 0.43% (0.21, 0.61). The observations were consistent for all locations included in our study and also similar when considering the age-specific ERF for each location.

With the projected increase in the average surface temperature of the earth, we expected to see a decrease in overall cold-related mortality when not considering population aging. A number of previous studies have already shown a decrease in future cold-related mortality (8, 17-20). One of the study found the cold-related mortality to decrease by 8.9% by 2050s at a scenario of constant population. (18) In the same population scenario, our study found the cold-related mortality to decrease by around 37.6% until 2099. Our study also found a significant reduction in the cold-related deaths during the future period for most RCPs and SSPs for all ages, thus confirming the hypothesis. A significant reduction was seen under all RCPs under the assumption of no-population change, meaning that if the present day population of Bavaria was exposed to the future climate change scenarios, there will be a significant reduction in cold-related mortality under all RCPs. Similarly, also under the lowest population scenario SSP3, there was a significant reduction in cold-related mortality under all RCPs. For a comparatively medium population scenario (SSP1, 2 and 4), cold-related deaths decreased significantly only under the higher emission scenarios, i.e. RCP 6.0 and RCP 8.5. Thus, the reduction in deaths attributable to cold in the future is under the assumption of constant population, very low increase in population or high emission scenarios.

The increasing surface temperature would result in higher future heat-related mortality. For all scenarios of population projection, our analysis shows a consistent and significant increase in future heat-related mortalities under all RCPs except under the low-emission scenario RCP 2.6. But for SSP5, the highest population projection scenario, the mortality burden of heat increases significantly also under RCP 2.6. A number of previous studies in different international locations have found an increase in heat-related deaths during future periods (11-15). Few studies have also shown an increase in cause-specific and total death counts due to an increase in the mean temperature of the earth in the future (16). However, all these studies have mostly incorporated the medium emission pathway 4.5 and the high emission pathway 8.5. Similarly, only a few studies have incorporated all five SSPs to project the future heat-attributable mortality burden (16). In this regard, our study analyses the change in future mortality burden under all scenarios of climate and population projections giving a full coverage of all plausible future climate and population change. The low emission scenario RCP 2.6 did not show a contribution to the significant increase in heat-related mortality. But if the population increases rapidly until the end of the century (SSP5), there will be a significant increase in heat-related mortality burden even under RCP 2.6. Hence, this result shows the need for immediate mitigation actions to combat climate change.

An important factor to be considered when estimating temperature-related mortality burden is the effect of age, an approach recently proposed (29). The consideration of age is important, first because different age groups react differently on temperature. The older population is found to be more vulnerable to both heat and cold effects (3, 20) which was confirmed by the all ages and the age-specific ERFs in our analysis. Another reason for considering age for the projection of temperature-related mortality burden is that the population of the older age category is estimated to increase much more in the future than the younger population (32), thus increasing the population at risk. Only a few studies to date have incorporated the age-specific ERFs for the estimation of temperature-related mortality burden (3, 20). In our analysis, we attempted to compute the future temperature-related age-specific mortality burden also under all RCPs and SSPs. For the age group <75 years, both future heat- and cold-related mortality did not change considerably. For the age group ≥75 years, under the assumption of constant population, cold-related deaths were found to decrease and heat-related deaths to increase significantly under all RCPs. This result was consistent with former results when considering ERFs for all ages. But when population change was taken into consideration, both cold- and heat-related deaths increased significantly under all climate and temperature projection scenarios.

The five population projection pathways also incorporate scenarios under different challenges to adaptation and mitigation. Four of the pathways (SSP1, SSP3, SSP4 and SSP5) include various combinations of high or low challenges. SSP1 would be the sustainability pathway, also called taking-the-green-road. Whereas, the SSP2 pathway, also called middle-of-the-road pathway, represents the future population under moderate challenges to adaptation and mitigation, i.e. the world would follow a path in which social, economic, and technological trends do not shift markedly from historical pattern (39). The results of our study reflect, even under the ideal SSP1 or the usual SSP2 pathway, there will be a significant increase in the net temperature-related mortality under all RCPs by the end of the 21st century (Fig 5).

To our best knowledge, this the first study which uses the most recent RCP and SSP scenarios and also incorporates the effect of aging for future temperature-related mortality projection. We observed that the projection of future mortality based on the ERF for all ages would lead to an underestimation of temperature-related deaths. Therefore, it is of critical importance to consider population aging when projecting future temperature-related health impacts under climate change.

Strengths and Limitations

The strength of our study comprises the projection of change in future temperature-attributable mortality burden under all proposed scenarios of climate (four RCPs) and population projection (five SSPs). We used four projection models for each RCP and downscaled high-resolution data frame to derive the population under each SSP. We also captured and addressed the sources of uncertainties in our analysis, for example, the baseline temperature-mortality ERF, the temperature projection, and the population projection. Additionally, we explored all heat- cold- and the net temperature-related mortality burden separately in each location. We also incorporated both the all ages and the age-specific ERF for the projection of future temperature attributable mortality and compared the results under both conditions considering different age categories.

We acknowledge certain limitations of our study. Our study did not take into account the future adaptation of the population to a changing temperature. All the analyses were performed under the assumptions of no future adaptation, which may overestimate the future temperature-related mortality burden (18). Thus, our results should be interpreted as future temperature-related mortality burden in the absence of adaptation. Moreover, we only applied fixed weather stations for temperature exposure assessment, thus exposure assessment error was inevitable. However, this error might bias our estimates rather towards the null (40). Our study also does not consider the shifts in cause-specific morbidity and mortality that are likely to occur in the future.

5. CONCLUSION

In conclusion, we found that with a projected increase of the older age group in the future population , also the vulnerable group for both heat and cold will increase, thus resulting in a consistent and significant increase in the net temperature-related mortality burden in the future period of 2083-2099 in Bavaria. The results thus demand immediate mitigation and age-specific adaptation strategies to address the problem of climate change.

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REFERENCES

1. Gasparrini A, Guo Y, Hashizume M, Kinney PL, Petkova EP, Lavigne E, et al. Temporal Variation in Heat-Mortality Associations: A Multicountry Study. Environ Health Perspect. 2015;123(11):1200-7.
2. Guo Y, Gasparrini A, Armstrong B, Li S, Tawatsupa B, Tobias A, et al. Global variation in the effects of ambient temperature on mortality: a systematic evaluation. Epidemiology. 2014;25(6):781-9.
3. Hajat S, Vardoulakis S, Heaviside C, Eggen B. Climate change effects on human health: projections of temperature-related mortality for the UK during the 2020s, 2050s and 2080s. J Epidemiol Community Health. 2014;68(7):641-8.
4. Medina-Ramon M, Schwartz J. Temperature, temperature extremes, and mortality: a study of acclimatisation and effect modification in 50 US cities. Occup Environ Med. 2007;64(12):827-33.
5. Ebi KL, Mills DM, Smith JB, Grambsch A. Climate change and human health impacts in the United States: an update on the results of the U.S. national assessment. Environ Health Perspect. 2006;114(9):1318-24.
6. Hajat S, Kosatky T. Heat-related mortality: a review and exploration of heterogeneity. J Epidemiol Community Health. 2010;64(9):753-60.
7. Liu L, Breitner S, Pan X, Franck U, Leitte AM, Wiedensohler A, et al. Associations between air temperature and cardio-respiratory mortality in the urban area of Beijing, China: a time-series analysis. Environ Health. 2011;10:51.
8. Weinberger KR, Haykin L, Eliot MN, Schwartz JD, Gasparrini A, Wellenius GA. Projected temperature-related deaths in ten large U.S. metropolitan areas under different climate change scenarios. Environ Int. 2017;107:196-204.
9. Gasparrini A, Guo Y, Hashizume M, Lavigne E, Zanobetti A, Schwartz J, et al. Mortality risk attributable to high and low ambient temperature: a multicountry observational study. The Lancet. 2015;386(9991):369-75.
10. Intergovernmental Panel on Climate Change (IPCC). Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA; 2013.
11. Kingsley SL, Eliot MN, Gold J, Vanderslice RR, Wellenius GA. Current and Projected Heat-Related Morbidity and Mortality in Rhode Island. Environ Health Perspect. 2016;124(4):460-7.
12. Knowlton K, Lynn B, Goldberg RA, Rosenzweig C, Hogrefe C, Rosenthal JK, et al. Projecting heat-related mortality impacts under a changing climate in the New York City region. Am J Public Health. 2007;97(11):2028-34.
13. Ostro B, Barrera-Gomez J, Ballester J, Basagana X, Sunyer J. The impact of future summer temperature on public health in Barcelona and Catalonia, Spain. Int J Biometeorol. 2012;56(6):1135-44.
14. Peng RD, Bobb JF, Tebaldi C, McDaniel L, Bell ML, Dominici F. Toward a quantitative estimate of future heat wave mortality under global climate change. Environ Health Perspect. 2011;119(5):701-6.

15. Li T, Ban J, Horton RM, Bader DA, Huang G, Sun Q, et al. Heat-related mortality projections for cardiovascular and respiratory disease under the changing climate in Beijing, China. Sci Rep. 2015;5:11441.
16. Chen K, Horton RM, Bader DA, Lesk C, Jiang L, Jones B, et al. Impact of climate change on heat-related mortality in Jiangsu Province, China. Environ Pollut. 2017;224:317-25.
17. Guo Y, Li, S., Liu de, L., Chen, D., Williams, G., Tong, S., . Projecting future temperature-related mortality in three largest Australian cities. Environ Pollut. 2016;208:66–73.
18. Huynen MM, Martens P. Climate Change Effects on Heat- and Cold-Related Mortality in the Netherlands: A Scenario-Based Integrated Environmental Health Impact Assessment. Int J Environ Res Public Health. 2015;12(10):13295-320.
19. Li T, Horton, R.M., Kinney, P., . Future projections of seasonal patterns in temperature-related deaths for Manhattan. Nat Clim Chang. 2013;3:717–21.
20. Vardoulakis S, Dear K, Hajat S, Heaviside C, Eggen B, McMichael AJ. Comparative assessment of the effects of climate change on heat- and cold-related mortality in the United Kingdom and Australia. Environ Health Perspect. 2014;122(12):1285-92.
21. Gasparrini A, Guo Y, Sera F, Vicedo-Cabrera AM, Huber V, Tong S, et al. Projections of temperature-related excess mortality under climate change scenarios. The Lancet Planetary health. 2017;1(9):e360-e7.
22. Statistisches Bundesamt. Bavaria Popualtion 2011 2019 [Available from: https://www.destatis.de/EN/Home/_node.html.
23. 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;485-486:49-61.
24. Breitner S, Wolf K, Peters A, Schneider A. Short-term effects of air temperature on cause-specific cardiovascular mortality in Bavaria, Germany. Heart. 2014;100(16):1272-80.
25. IPCC. Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. In Press; 2018.
26. Warszawski L, Frieler K, Huber V, Piontek F, Serdeczny O, Schewe J. The Inter-Sectoral Impact Model Intercomparison Project (ISI–MIP): Project framework. Proceedings of the National Academy of Sciences. 2014;111(9):3228-32.
27. Weinberger KR, Kirwa K, Eliot MN, Gold J, Suh HH, Wellenius GA. Projected Changes in Temperature-related Morbidity and Mortality in Southern New England. Epidemiology. 2018;29(4):473-81.
28. Lange S. Bias correction of surface downwelling longwave and shortwave radiation for the EWEMBI dataset. Earth Syst Dynam. 2018;9(2):627-45.
29. Vicedo-Cabrera AM, Sera F, Gasparrini A. Hands-on Tutorial on a Modeling Framework for Projections of Climate Change Impacts on Health. Epidemiology. 2019;30(3):321-9.
30. Gao J. Downscaling Global Spatial Population Projections from 1/8-degree to 1-km Grid Cells. National Center for Atmospheric Research; 2017.
31. Kc S, Lutz W. The human core of the shared socioeconomic pathways: Population scenarios by age, sex and level of education for all countries to 2100. Glob Environ Change. 2017;42:181-92.
32. IIASA. SSP Databse (Shared Socioeconomic Pathways)-Version 2.0 2018 [Available from: https://tntcat.iiasa.ac.at/SspDb/dsd?Action=htmlpage&page=about.
33. Gasparrini A, Guo Y, Hashizume M, Lavigne E, Zanobetti A, Schwartz J, Tobias A, Tong S,Rocklöv J, Forsberg B, Leone M, Sario MD, Bell ML, Guo YL, Wu C, Kan H,Yi SM, Coelho M,Saldiva PH, Honda Y, Kim H, Armstrong B. Mortality risk attributable to high and low ambient temperature: a multicountry observational study. The Lancet. 2015;386:369-75.
34. Gasparrini A, Leone M. Attributable risk from distributed lag models. BMC Medical Research Methodology. 2014;14(1):55.

35. R Core Team. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria2017 [Available from: http://www.R-project.org/.

36. Gasparrini A. Distributed Lag Linear and Non-Linear Models in R: The Package dlnm. J Stat Softw. 2011;43(8):1–20.

37. Gasparrini A, Armstrong B, Kenward MG. Multivariate meta-analysis for non-linear and other multi-parameter associations. Stat Med. 2012;31(29):3821-39.

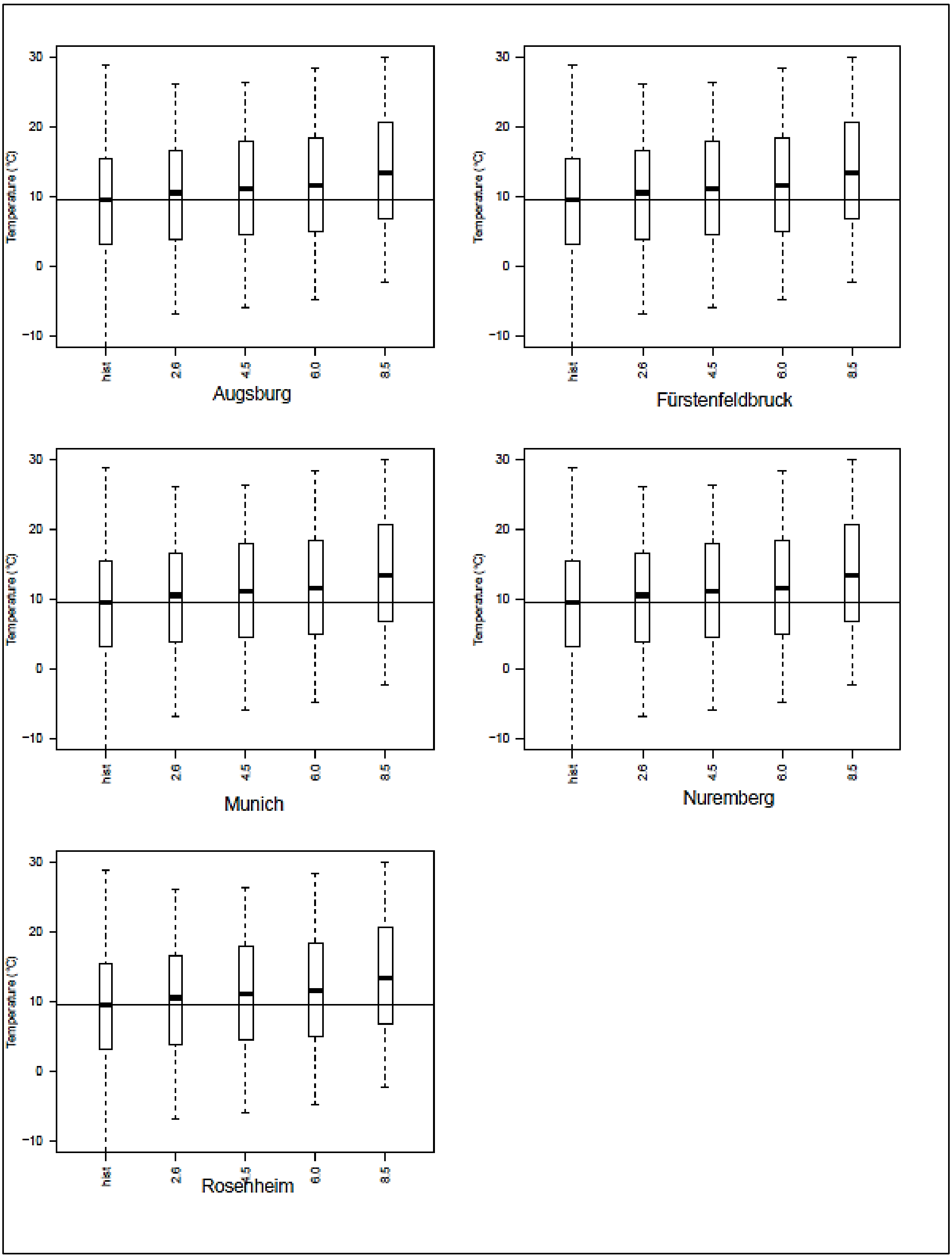
38. Schneider A, Ruckerl R, Breitner S, Wolf K, Peters A. Thermal Control, Weather, and Aging. Curr Environ Health Rep. 2017;4(1):21-9.

39. O'Neill BC, Kriegler E, Ebi KL, Kemp-Benedict E, Riahi K, Rothman DS, et al. The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century. Global Environmental Change. 2017;42:169-80.

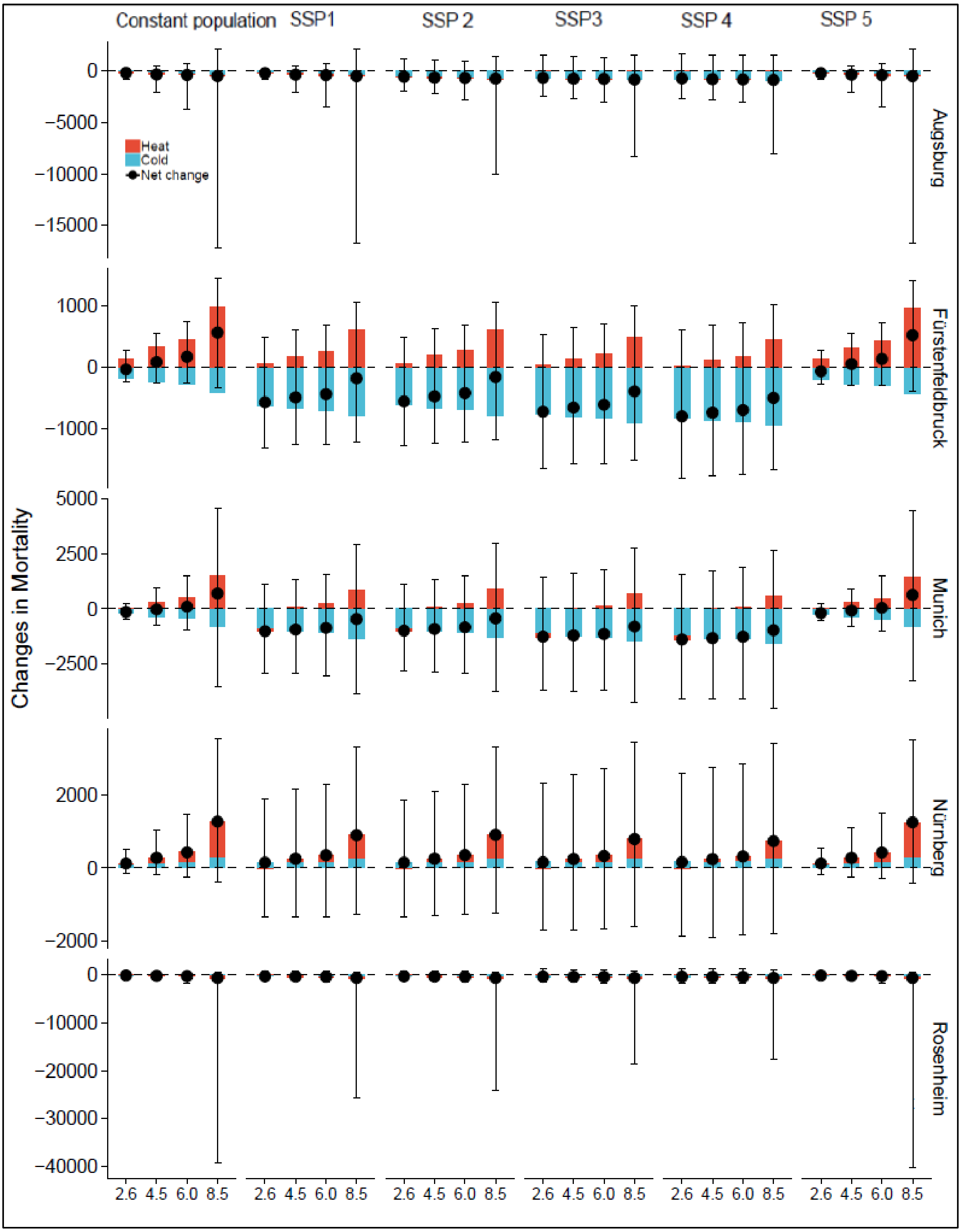
40. Wichmann J, Andersen ZJ, Ketzel M, Ellermann T, Loft S. Apparent temperature and cause-specific mortality in Copenhagen, Denmark: a case-crossover analysis. Int J Environ Res Public Health. 2011;8(9):3712-27.

Supplementary Data

Supplement Fig.S1: Distribution of location-wise annual mean temperature during the baseline period (hist) and future period under different climate projection scenarios (RCPs 2.6, 4.5, 6.0, 8.5)

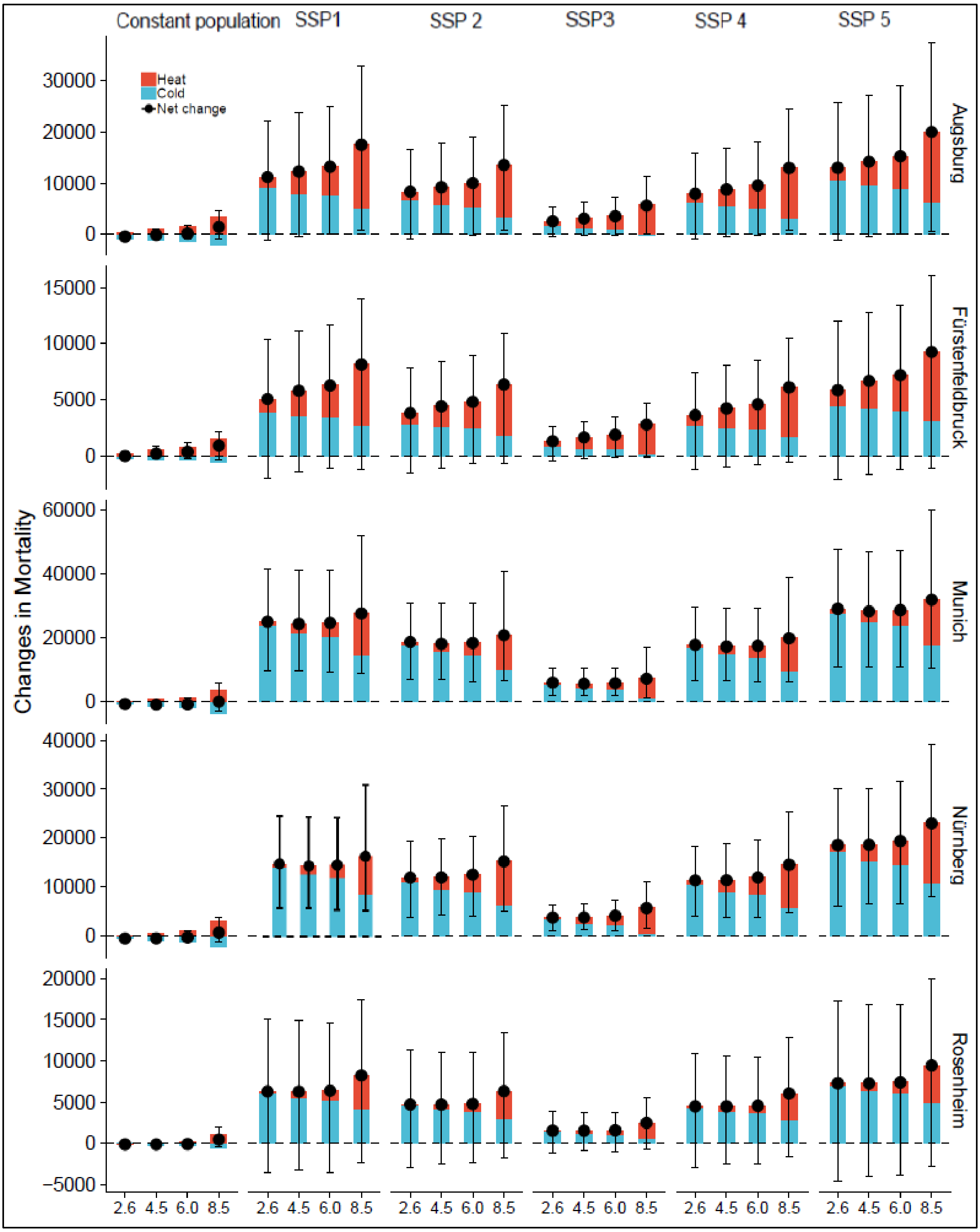


Supplement Fig.S2: Projected location-specific change in the heat-related, cold-related and net temperature-related mortality under all RCPs and SSPs for age<75 years during the future period 2083-2099.



Attributable numbers calculated with the location-specific and age-specific exposure-response function. 2.6=RCP 2.6, 4.5=RCP 4.5, 6.0=RCP 6.0, 8.5=RCP 8.5

Supplement Fig.S3: Projected location-specific change in the heat-related, cold-related and net temperature-related mortality under all RCPs and SSPs for age≥75 years during the future period 2083-2099.



Attributable numbers calculated with the location-specific and age-specific exposure-response function. 2.6=RCP 2.6, 4.5=RCP 4.5, 6.0=RCP 6.0, 8.5=RCP 8.5.

Supplement Table. S1: Baseline overall temperature-attributable mortality fraction (1990-2006; 17 years)

Administrative areas (MMT)	Attributable Fraction of Deaths		
	Total (CI)	Cold (CI)	Heat (CI)
Augsburg	5.40 (-4.19, 3.62)	5.06 (-3.98, 13.37)	0.34 (-0.23, 0.78)
Fürstenfeldbruck	14.20 (4.09, 22.99)	13.21 (3.7, 21.77)	0.99 (0.41, 1.46)
Munich	6.71 (1.04, 11.70)	6.39 (1.09, 11.70)	0.32 (0.01, 0.59)
Nuremberg	9.31 (2.59, 15.63)	8.73 (1.85, 14.74)	0.57 (0.17, 0.93)
Rosenheim	11.89 (-0.05, 21.96)	11.30 (-0.02, 21.07)	0.59 (0.01, 1.04)
Bavaria	**7.73 (4.02,11.04)**	**7.30 (3.81, 10.65)**	**0.43 (0.21, 0.61)**

Attributable fraction = Temperature-related attributable number of the location / Total deaths in the location

Supplement Table. S2: Baseline age-specific temperature-attributable mortality fraction (1990-2006; 17 years)

Administrative areas	Age categories	Attributable Fraction of Deaths		
		Total (CI)	Cold (CI)	Heat (CI)
Augsburg	Age<75	1.05 (-6.63, 14.41)	1.95 (-5.76, 14.32)	-0.44 (-1.09, 0.52)
	Age≥75	7.28 (2.96, 17.92)	6.61 (2.63, 17.10)	0.67 (0.34, 1.01)
Fürstenfeldbruck	Age<75	11.36 (-3.89,24.53)	10.83 (-3.07, 23.66)	0.53 (-0.70, 1.18)
	Age≥75	10.10 (1.58,22.22)	9.21 (0.80, 21.40)	0.88 (0.47, 1.42)
Munich	Age<75	2.48 (-9.29,11.94)	2.19 (-8.52, 11.22)	0.29 (-0.65, 1.14)
	Age≥75	8.94 (3.66,12.04)	8.62 (3.56, 12.11)	0.31 (-0.13, 0.66)
Nuremberg	Age<75	0.03 (-9.77,9.46)	-0.07 (-10.09, 8.93)	0.11 (-0.56, 0.75)
	Age≥75	12.44 (6.82, 17.82)	11.77 (5.86, 17.05)	0.67 (0.35, 0.93)
Rosenheim	Age<75	5.13 (-14.44,23.57)	5.21 (-14.15, 22.99)	-0.08 (-0.93, 0.81)
	Age≥75	12.31 (-1.79,23.97)	11.59 (-1.59, 23.21)	0.72 (0.28, 1.06)
Bavaria	**Age<75**	**2.76 (-3.01,8.84)**	**2.65 (-2.65,8.49)**	**0.11 (-0.39,0.55)**
	Age≥75	**9.60 (7.49, 13.98)**	**9.08 (7.14, 13.45)**	**0.51 (0.43, 0.73)**

Attributable fraction = Age-specific temperature-related AN of the location/ Total deaths of the specific age-group in that location

Supplement Table. S3: Projected change in location-specific net temperature-attributable mortality number (ΔAN) during the future period (2083-2099; 17 years): projected using the location-specific ERF for all ages.

Administrative Area	RCP	Population Scenario					
		Population constant	SSP1	SSP2	SSP3	SSP4	SSP5
Augsburg	2.6	-481 (-1102,336)	-526 (-1166,317)	-706 (-1519,301)	-2,460 (-5849,1376)	-1,471 (-3309,606)	1,409 (-1415,3431)
	4.5	-129 (-1349,1714)	-178 (-1424,1648)	-372 (-1679,1513)	-2,263 (-5656,1710)	-1,196 (-3256,1267)	1,520 (-1334,4858)
	6.0	257 (-1409,2905)	205 (-1432,2801)	-5 (-1722,2572)	-2,047 (-5664,1845)	-895 (-3288,1957)	2,038 (-1658,6256)
	8.5	2,266 (-2014,7841)	2,193 (-2149,7781)	1,904 (-2226,7311)	-922 (-5337,3748)	672 (-3214,5515)	4,729 (-2231,12818)
Fürsten-feldbruck	2.6	-55 (-394,462)	-169 (-564,423)	-321 (-799,355)	-1,726 (-3254,213)	-967 (-1913,240)	1,235 (128,2175)
	4.5	287 (-291,1199)	163 (-454,1114)	-2 (-689,999)	-1,534 (-3123,474)	-706 (-1780,667)	1,695 (417,2962)
	6.0	513 (-221,1644)	383 (-393,1531)	208 (-619,1418)	-1,407 (-3036,680)	-534 (-1727,982)	1,998 (520,3470)
	8.5	1,472 (-84,3242)	1,312 (-230,3086)	1,100 (-459,2902)	-870 (-2899,1340)	194 (-1537,2144)	3,282 (935,5407)
Munich	2.6	-1,075 (-1586,-187)	1,560 (343,3679)	1,560 (2,2527)	-6,637 (-10129,-2637)	-2,099 (-3041,-835)	7,708 (2794,13340)
	4.5	-994 (-2204,1164)	1,655 (51,4466)	1,655 (-430,3451)	-6,587 (-10219,-2261)	-2,024 (-3500,316)	7,837 (3030,14063)
	6.0	-645 (-2178,2756)	2,066 (-19,6245)	2,066 (-444,5195)	-6,371 (-10260,-1766)	-1,700 (-3520,1716)	8,394 (2756,15743)
	8.5	1,532 (-3079,10575)	4,637 (-687,15397)	4,637 (-1246,14025)	-5,020 (-10395,2292)	326 (-4225,8975)	11,880 (2686,27509)
Nuremberg	2.6	-416 (-790,189)	104 (-300,682)	104 (-606,300)	-3,317 (-5707,-595)	-1,532 (-2616,-211)	2,931 (289,5560)
	4.5	-250 (-1029,1242)	282 (-489,1787)	282 (-826,1366)	-3,216 (-5837,-156)	-1,391 (-2751, 521)	3,172 (531, 6297)
	6.0	132 (-1066,2314)	691 (-507,2892)	691 (-885,2481)	-2,982 (-5772,298)	-1,066 (2780,1366)	3,726 (397,7523)
	8.5	2,039 (-950,6823)	2,732 (-279,7703)	2,732 (-756,7003)	-1,819 (-5657,2798)	555 (-2683,5096)	6,491 (1262,13604)
Rosenheim	2.6	-154 (-329,297)	44 (-399,724)	40 (-330,434)	-1,242 (-2601,427)	-1,242 (-2601,427)	1,889 (-1588,5093)
	4.5	-209 (-460,266)	-15 (-394,655)	-11 (-417,380)	-1,279 (-2713,582)	-1,279 (-2713,582)	1,800 (-1261, 4949)
	6.0	-203 (-549,498)	-8 (-473,727)	-6 (-486,565)	-1,274 (-2763,631)	-1,274 (-2763,631)	1,810 (-1533,4753)
	8.5	347 (-1054,2416)	575 (-914,2758)	571 (-937,2507)	-9,06 (-2840,1450)	-906 (-2840,1450)	2,702 (-1632,7094)
Bavaria	**2.6**	**-2,181 (-4100,-512)**	**1,013 (-1160,3511)**	**-555 (-2595,1698)**	**-15,382 (-21364,-8487)**	**-7,310 (-21364,-8487)**	**14,811 (7484, 21935)**
	4.5	**-1,295 (-5720,4489)**	**108 (-2778,7958)**	**303 (-4264,6179)**	**-14,878 (-21636,-7158)**	**-6,596 (-21636,-7158)**	**16,023 (6775, 26192)**
	6.0	**55 (-4513,9881)**	**3,337 (-1396,13797)**	**1,671 (-2997,11716)**	**-14,082 (-21237,-4745)**	**-5,469 (-21237,-4745)**	**17,966 (8133, 33616)**
	8.5	**7,658 (-3639,33045)**	**11,450 (-392,39477)**	**9,438 (-2118,36148)**	**-9,537 (-19970,7966)**	**842 (-19970,7966)**	**29,084 (10698,67917)**

Supplement Table. S4: Projected change in cold- and heat-attributable mortality number (ΔAN) during the future period (2083-2099; 17 years) for Bavaria: sum of projection using the location-specific ERF for all ages.

	RCP	Population Scenario					
		Population constant	SSP1	SSP2	SSP3	SSP4	SSP5
Cold	2.6	-3,217 [-5649,-1362]	-221 [-2703,3239]	-1,652 [-4121, 1415]	-15,191 [-21225, -8291]	-7,847 [-21225, -8291]	12402 [1384, 18896]
	4.5	-5,436 [-9339,1254]	-2,654 [-6487,2466]	-3,982 [-7961,805]	-16,542 [-23394,-8923]	-9,729 [-23394,-8923]	9,059 [1429,19028]
	6.0	-6,498 [-1024,3235]	-3,818 [-7313,154]	-5,097 [-8759,-1310]	-17,190 [-24050,-9716]	-10,628 [-24050,-9716]	7,456 [1237, 15669]
	8.5	-11,080 [-16328,5410]	-8,853 [-13653,-2882]	-9,918 [-15032, -4022]	-19,977 [-28000, -11155]	-14,528 [-28000, -11155]	543 [-5006, 10630]
Heat	2.6	1,035 [-52,3724]	1234 [-196,4165]	1,098 [-252, 3912]	-190 [-1079, 1365]	537 [-1079, 1365]	2,410 [2046, 18861]
	4.5	4,141 [930,12080]	4,562 [1104,13142]	4,285 [986,12506]	1,664 [-176,6444]	3,134 [-176,6444]	6,964 [2023,18805]
	6.0	6,553 [1509,18265]	7,155 [1739,19846]	6,767 [1592,18868]	3,180 [244, 10198]	5,159 [244, 10198]	10,510 [2931, 28071]
	8.5	18,738 [4749,46276]	20,303 [5256,50560]	19,356 [4990, 48201]	10,440 [2259, 27289]	15,370 [2259, 27289]	28,541 [7797, 70086]

Supplement Table. S5: Projected change in location-specific net temperature-attributable mortality number (ΔAN) during the future period (2083-2099; 17 years) for the two age categories (projected using the age-specific location-wise ERF)

Administrative Area	Age category	RCP	Population Scenario					
			Population constant	SSP1	SSP2	SSP3	SSP4	SSP5
Augsburg	Age<75	2.6	-199 (-832,198)	-578 (-2033,1139)	-567 (-1998,1130)	-687 (-2498,1496)	-741 (-2719,1660)	-221 (-834,224)
		4.5	-346 (-2120,455)	-674 (-2302,1082)	-664 (-2247,1033)	-767 (-2738,1386)	-814 (-2852,1557)	-364 (-2137,444)
		6.0	-395 (-3737,731)	-706 (-2841,1060)	-697 (-2759,1001)	-794 (-3000,1334)	-839 (-3069,1521)	-413 (-3543,679)
		8.5	-492 (-17162,2174)	-769 (-10983,1433)	-761 (-10092,1429)	-848 (-8271,1496)	-888 (-8026,1499)	-508 (-16670,2153)
	Age≥75	2.6	-464 (-825,116)	11193 (-1129,21908)	8316 (-999,16686)	2564 (-486,5330)	7913 (-941,15777)	13010 (-1150, 25692)
		4.5	-142 (-861,1052)	12257 (-338,23775)	9198 (42,17881)	3078 (-134,6310)	8768 (-333,16916)	14190 (-411,27233)
		6.0	147 (-852,1790)	13217 (68,25027)	9992 (-210,19012)	3542 (-172 ,7208)	9539 (-223,18136)	15254 (-56,28963)
		8.5	1440 (-973,4578)	17495 (820,32922)	13533 (693,25324)	5610 (41,11321)	12977 (770,24573)	19997 (557,37549)
Fürstenfeldbruck	Age<75	2.6	-32 (-231,268)	-566 (-1303,492)	-551 (-1265,487)	-718 (-1636,533)	-794 (-1790,618)	-63 (-280,273)
		4.5	88 (-248,557)	-487 (-1258,601)	-471 (-1238,628)	-652 (-1569,641)	-734 (-1759,696)	56 (-284,552)
		6.0	173(-258,741)	-433 (-1241,686)	-415 (-1210,680)	-605 (-1555,709)	-692 (-1735,721)	138 (-296,735)
		8.5	566(-332,1442)	-177 (-1211,1057)	-156 (-1178,1052)	-389 (-1497,1003)	-495 (-1670,1024)	523 (-388,1413)
	Age≥75	2.6	-18 (-283,381)	5062 (-1940,10390)	3808 (-1492,7832)	1301 (-411,2589)	363 (-1272,7387)	5854 (-2053,11953)
		4.5	204 (-251,863)	5796 (-1452,11084)	4416 (-1134,8387)	1656 (-245,3092)	4222 (-1053,8023)	6667 (-1637,12808)
		6.0	345 (-233,1154)	6265 (-1070,11720)	4804 (-630,8926)	1883 (-124,3442)	4599 (-774,8524)	7188 (-1183,13426)
		8.5	910 (-372,2141)	8134 (-1195,14002)	6352 (-703,10911)	2786 (-176,4715)	6102 (-589,10435)	9260 (-1117,15999)
Munich	Age<75	2.6	-142 (-443, 270)	-1018 (-2920, 1144)	-993 (-2844,1115)	-1268 (-3731,1427)	-1393 (-4077,1585)	-192 (-543,272)
		4.5	-22 (-728,944)	-940 (-2959,1354)	-914 (-2908,1345)	-1202 (-3731,1427)	-1333 (-4088,1729)	-75 (-819,906)
		6.0	99 (-942,1534)	-861 (-3026,1555)	-833 (-2924,1487)	-1135 (-3720,1784)	-1272 (-4102,1872)	45 (-1011,1493)
		8.5	705 (-3515 ,4567)	-467 (-3885,2910)	-434 (-3775, 2988)	-802 (-4228,2765)	-970 (-4502,2685)	638 (-3267,4466)
	Age≥75	2.6	-831 (-1206,58)	24951 (9517,41269)	18589 (7033,30756)	5866 (2094,10388)	17697 (6394,29543)	28969 (10649,47700)
		4.5	-1038 (-1835,237)	24266 (9596,41057)	18023 (6720,30684)	5535 (1901,10351)	17146 (6394,29543)	28210 (10907,47010)
		6.0	-939 (-1923,1147)	24594 (9068,40880)	18294 (6246,30755)	5693 (1725,10503)	17410 (5967,29184)	28574 (10577,47068)
		8.5	-52 (-2958,5782)	27530 (9068,40880)	20724 (6521,40649)	7112 (1237,17077)	19769 (6298,38630)	31829 (10358,59774)
Nuremberg	Age<75	2.6	128 (-138,501)	155 (-1353,1898)	155 (-1337,1874)	163 (-1714,2354)	167 (-1865,2606)	129 (-185,547)
		4.5	282 (-197,1044)	256 (-1330,2165)	256 (-1313,2099)	248 (-1720,2574)	244 (-1922,2786)	280 (-246, 1094)
		6.0	434 (-248,1488)	355(-1333,2297)	357 (-1284,2317)	332 (-1675,2731)	321 (-1859,2865)	429 (-285, 1510)
		8.5	1281 (-372 ,3562)	905 (-1285,3340)	916 (-1252,3330)	798 (-1607,3460)	744 (-1799,3449)	1259 (-432 ,3529)
	Age≥75	2.6	-513 (-766,120)	16000 (5420,25995)	11925 (3838,19461)	3776 (1127,6417)	11353 (3968,18453)	18573 (5993,30067)
		4.5	-499 (-1019,496)	16045 (5877,26283)	11963 (4234,19806)	3798 (1210,6586)	11390 (3858,18791)	18624 (6471,30163)
		6.0	-288 (-1066,1156)	16744 (5691,27213)	12541 (4102,20403)	4136 (1090,7328)	11952 (3858,18791)	19398 (6541,31589)
		8.5	695 (-1133,3764)	19998(6926,34270)	15235 (5055,26527)	5709 (1565,11036)	14567 (4869,25380)	23007 (8094,39098)
Rosenheim	Age<75	2.6	-50 (-233,152)	-239 (-1073,936)	-234 (-1050,874)	-293 (-1384,1234)	-320 (-1565,1355)	-61 (-197,98)
		4.5	-131 (-852,100)	-292 (-1226,904)	-287 (-1204,853)	-338 (-1511,1187)	-361 (-1627,1338)	-141 (-818,61)
		6.0	-189 (-1666,96)	-329 (-1525,847)	-325 (-1475, 837)	-369 (-1666,1181)	-389 (-1753,1301)	-197 (-1688,99)
		8.5	-580 (-39295,561)	-583 (-25700,722)	-583 (-24105,703)	-584 (-18469,956)	-585 (-17536,1078)	-580 (-40350,550)
	Age≥75	2.6	-100 (-232,227)	6308 (-3574,14988)	4727 (-2981,11416)	1565 (-1154,3978)	4505 (-2893, 10879)	7307 (-4589,17351)
		4.5	-103 (-273,294)	6297(-3161,14919)	4718 (-2528,11007)	1559 (-853,3838)	4496 (-2461,10641)	7294 (-3977,16913)
		6.0	-72 (-320,498)	6402(-3161,14919)	480 (-2372,10980)	1610 (-927,3790)	4580 (-2460,10458)	7410 (-3808,16878)
		8.5	488 (-379 1984)	8256 (-2261,17451)	6339 (-1734,13461)	2506 (-620,5529)	6070 (-1592,12878)	9466 (-2702,19962)
Bavaria	**Age<75**	**2.6**	**-296 (-1123,507)**	**-1,888 (-5458,1480)**	**-2,189 (-5247,1436)**	**-2,802 (-6741,1837)**	**-3,081 (-7418,1989)**	**-407 (-1317,469)**
		4.5	**-129 (-2130,1777)**	**-1,828 (-5619,1709)**	**-2,080 (-5521,1700)**	**-2,711 (-6911,2030)**	**-2,998 (-7457,2158)**	**-244 (-2268,1647)**
		6.0	**123 (-3413,2990)**	**-1,680 (-6037,1915)**	**-1,913 (-5880,1969)**	**-2,572 (-7091,2187)**	**-2,872 (-7639,2283)**	**3 (-3621,2826)**
		8.5	**1,480 (-43672,9010)**	**-830 (-32734,4208)**	**-1,018 (-30385,4314)**	**-1,826 (-26172,3527)**	**-2,193 (-25629,3193)**	**1,333 (-44063,8452)**
	Age≥75	**2.6**	**-561 (-3206,615)**	**47,669 (37519,86731)**	**35,596 (27226,64737)**	**15,072 (8436,21365)**	**45,100 (26186,61857)**	**55,269 (43325,100293)**
		4.5	**74 (-4789,1957)**	**48,873 (37128,89261)**	**36,610 (27881,67201)**	**15,626 (7552,23206)**	**46,023 (26214,64298)**	**56,641 (43301,103926)**
		6.0	**665 (-4030,5391)**	**50,835 (38706,96532)**	**38,251 (28510,73658)**	**16,864 (8610,27956)**	**48,080 (27246,70445)**	**58,855 (44818,111136)**
		8.5	**3,412 (-3965,19555)**	**62,331 (42859,139903)**	**47,864 (32000 ,109101)**	**23,724 (10041,49838)**	**59,485 (30698,105325)**	**71,811 (49158,158371)**

Supplement Table. S6: Projected change in location-specific cold- and heat-related mortality number (ΔAN) during the future period (2083-2099; 17 years) for Bavaria for the two age categories: sum of projections using the age-specific location-wise ERF

Age category		RCP	Population Scenario					
			Population constant	SSP1	SSP2	SSP3	SSP4	SSP5
Age<75	Cold	2.6	-440 (-1263,294)	-1,826 (-5413,1539)	-2,171 (-5296,14929)	-2,732 (-6641,1968)	-2,986 (-7302, 2103)	-542 (-1456,295)
		4.5	-790 (-2142,352)	-2,086 (-5882,1540)	-2,403 (-5807,1534)	-2,924 (-7173, 2033)	-3,161(-7698,2233)	-885 (-2313,395)
		6.0	-961 (-2435,412)	-2,210 (-6176,1646)	-2,515 (-6024,1678)	-3,018 (-7268, 2055)	-3,246 (-7902,2287)	-1,052 (-2618, 456)
		8.5	-1,617 (-3973,742)	-2,688 (-7150, 1885)	-2,948 (-7112,1833)	-3,379 (-8197, 2265)	-3,575 (-8696, 2486)	-1,695 (-4145,836)
	Heat	2.6	144 (-392;881	-61 (-396, 394)	-18 (-395, 414)	-71 (-446,285)	-95 (-468,248)	134 (-380, 844)
		4.5	661 (-1147,2847)	258 (-719,1676)	323 (-765, 1708)	213 (-583,1350)	164 (-586,1175)	641 (-1014, 2803)
		6.0	1,083 (-2592,4321)	530 (-1572, 2675)	601 (-1651,2695)	446 (-1482, 2191)	375 (-1361, 1951)	1,055 (-2516,4209)
		8.5	3,097 (-44859,11092)	1,857 (-28179, 7183)	1,930 (-29602,7286)	1,553 (-24031, 5887)	1381 (-21027,5391)	3,028 (-41570,10998)
Age≥75	Cold	2.6	-1,109 (-4258,-619)	43,193 (32071,81568)	32,082 (23578,61135)	13,134 (6499, 20015)	40,869 (22315, 58340)	50,172 (37758, 94437)
		4.5	-1,685 (-7334, -1056)	38,781 (26438,77632)	28,434 (18762, 57725)	10,198 (3384, 18819)	35,988 (17674, 55009)	45,290 (31207,90028)
		6.0	-1,957 (-8084, -2598)	36,701 (25000,72448)	26,714 (17703, 53355)	8,787 (3086, 16066)	33,643 (16948,50651)	42,987 (29880,84221)
		8.5	-3,203 (-13103,-4583)	27,046 (14457,617389)	18,738 (8965,45101)	2,490 (-2508, 11440)	23,173 (7953,42317)	32,318 (18222,71597)
	Heat	2.6	549 (-284,2473)	4476 (1654,12536)	3,515 (1186,10087)	1,938 (214,5060)	4,231 (1118, 9732)	5,096 (1932,14186)
		4.5	1,758 (603,8135)	10,092 (4407,30842)	8,176 (3474, 25354)	5,429 (1633, 14094)	10,035 (3405,24675)	11,351 (4962,34682)
		6.0	2,622 (1048,12141)	14,133 (5958,43942)	11,538 (4723, 36151)	8,077 (2311, 20478)	14,437 (4579,35267)	15,867 (6642,49209)
		8.5	6,615 (3368,30293)	35,284 (13959,103943)	29,127 (11225, 85633)	21,234 (6215, 49566)	36,312 (10965,83294)	39,493 (15514,115028)