Future temperature-related mortality considering physiological and socioeconomic adaptation: a modelling framework

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Summary

Background As the climate changes, it is crucial to focus not only on mitigation measures but also on building climate change resilience by developing efficient adaptation strategies. Although population adaptation is a major determinant of future climate-related health burden, it is not well accounted for in studies that project the health impact of climate change. We propose a methodological framework for temperature-related mortality that incorporates two simultaneous adaptation-sensitivity pathways: the physiological pathway, considering both heat adaptation and cold sensitivity, and the socioeconomic pathway, which is influenced by changes in future adaptive capacities. To demonstrate its utility we apply the framework to a case study mortality time-series dataset from Bavaria, Germany.

Methods In this modelling framework, we used extrapolated location-specific and age-specific baseline exposure–response functions and propose different future scenarios of cold sensitivity and heat adaptation on the basis of varying slopes of these exposure–response functions. We also incorporated future socioeconomic adaptation in the exposure–response functions using projections of gross domestic product under the respective shared socioeconomic pathways. Future adaptable fractions, representing the deaths avoided under each of the future scenarios, are projected under combinations of two climate change scenarios (shared socioeconomic pathway [SSP]1–2.6 and SSP3–7.0) and the respective plausible population projection scenarios (SSP1 and SSP3), also incorporating the future changes in demographic age structure and mortality. The case study for this framework was done for five districts in Bavaria, for both total non-accidental mortality and cardiovascular disease mortality. The baseline data was obtained for the period 1990–2006, and the future period was defined as 2083–99.

Findings In our Bavaria case study, average temperature was projected to increase by 2099 by an average of 1·1°C under SSP1–2.6 and by 4·1°C under SSP3–7.0. We observed the adaptable fraction to be largely influenced by socioeconomic adaptation for both total mortality and cardiovascular disease mortality, and for both climate change scenarios. For example, for total mortality, the highest adaptable fraction of 18·56% (95% empirical CI 10·77–23·67) was observed under the SSP1–2.6 future scenario, in the presence of socioeconomic adaptation and under the highest heat adaptation (10%) provided the cold sensitivity remains 0%. The cold adaptable fraction is lower than the heat adaptable fraction under all scenarios. In the absence of socioeconomic adaptation, population ageing will lead to higher temperature-related mortality.

Interpretation Our developed framework helps to systematically understand the effectiveness of adaptation mechanisms. In the future, socioeconomic adaptation is estimated to play a major role in determining temperature-related excess mortality. Furthermore, cold sensitivity might outweigh heat adaptation in the majority of locations worldwide. Similarly, population ageing is projected to continue to determine future temperature-related mortality.

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Introduction

The most recent report from the Intergovernmental Panel on Climate Change stresses that unless there are immediate large-scale mitigation measures to reduce greenhouse gas emissions, we will be unable to limit global warming to 1·5°C or even 2°C.[1] Therefore, it is crucial to focus not only on mitigation measures but also on building climate change resilience by developing efficient adaptation strategies. Studies projecting climate change-attributable future health burdens can aid in planning these adaptation strategies. Research in the field is growing, with numerous projections on temperature-related total and cause-specific mortality under the different ranges of future climate and population change scenarios,[2–6] which allow us to identify population subgroups that are vulnerable (ie, at risk due to external factors, such as outdoor workers) and susceptible (ie, at risk due to internal factors, such as people with pre-existing health conditions) to climate change-related impacts. However, most projection studies so far do not

Research in context

Evidence before this study

We searched PubMed without any language restrictions for articles published from inception to Nov 28, 2021, using the following search terms: "temperature", "mortality" or "death*", "climate change", and "projection" or "projecting" or "projected" or "future". After screening abstracts and full texts, our literature review showed that most studies on the future projection of climate change-attributable mortality did not account for possible future population adaptation. Moreover, the few studies accounting for population adaptation either focused only on future heat-related acclimatisation or socioeconomic adaptation through changes in future adaptive capacities. Therefore, there are no projection studies accounting for all aspects of future adaptation scenarios, including both heat-related and cold-related physiological as well as socioeconomic adaptation scenarios.

Added value of this study

Future population adaptation is a crucial factor that is not well accounted for in studies that project the health impacts of temperature under climate change. Most studies incorporating population adaptation for projections of the future temperature-related health burden either accounted only for heat adaptation of the population or only for socioeconomic adaptation through changes in adaptive capacities. This study proposes a methodological framework incorporating two simultaneous adaptation-sensitivity pathways: the physiological pathway, considering both heat adaptation and cold sensitivity, and the socioeconomic pathway, which is influenced by changes in future adaptive capacities. We also demonstrate the framework using a mortality time-series dataset from Bavaria, Germany.

Implications of all the available evidence

Concerning the present climate crisis, it is crucial to not only focus on mitigation measures but also to develop efficient adaptation strategies to protect population subgroups that are vulnerable (ie, at risk due to external factors) and susceptible (ie, at risk due to internal factors) to climate change-related impacts. Our developed framework supports a more systematic understanding of the potential effectiveness of adaptation mechanisms. This helps to better estimate the future temperature-related mortality burden under climate change scenarios. We found that socioeconomic adaptation plays a major role in determining the future adaptable fraction, representing the deaths avoided under each of the future scenarios. This evidence is crucial for the evidence-based planning of health policies and adaptation measures.

account for future population adaptation, which means that they potentially overestimate temperature-related health impacts and also miss an opportunity to develop a systematic understanding of the effectiveness of adaptation mechanisms.

Future populations are expected to undergo multiple simultaneous adaptation pathways, including the physiological pathway and the socioeconomic pathway, which are influenced by changes in future adaptive capacities. Physiological pathways include changes in the body's response to heat or cold, which might lead to adaptation or increased sensitivity at the same temperature. Similarly, changes in socioeconomic conditions directly influence factors such as purchasing capacities and health-care facilities, which determine our capacity to better adapt during hot days as well as during cold spells.Only a few studies have considered population adaptation when estimating the future temperature-related health burden.[7–15] However, most of these studies only considered physiological adaptive mechanisms,[7–14] whereas only one study accounted for the changes in socioeconomic adaptive capacities.[15]

Studies accounting for physiological adaptive mechanisms have applied various approaches. Earlier approaches include using analogous summers or cities to assume the changes in the future exposure–response associations between temperature and mortality outcomes.[10,11] However, these approaches are based mainly on untestable assumptions, which might result in large uncertainties—for example, assuming the population of one city will react to temperature in the same way as the population from a reference city might not hold true. More recent studies used different methodologies to account for physiological adaptation, which comprises assumptions of population acclimatisation over a few degrees[12,13] or a shift in the exposure–response function (ERF) between temperature and health outcomes.[16] Petkova and colleagues in 2017[8] extensively studied the temperature–mortality association over a period of more than a century (1900–2006) and used the observed shifts in patterns of the temperature–mortality association to account for future adaptation. However, this approach might be challenging in regions where meteorological observations and health records have only been collected for a short period. Furthermore, all the studies mentioned focused on adaptation to heat.[8,13,14] However, cold-related mortality is mostly attributable to moderate cold, which will persist in the future under climate change. Therefore, projection studies are more complete when future changes in the cold–mortality association are included.[17] Existing evidence suggests that cold weather effects will not decrease[18,19] or may even increase[20] under climate change so that both heat and cold effects require investigation.[17]

In addition, future infrastructure changes and socioeconomic challenges might play an important role in influencing adaptation by changing adaptive capacities. A study by Wang and colleagues in 2019[15] defined future adaptive capacity as a factor of future gross domestic product (GDP). However, their study focused only on socioeconomic adaptive capacity without incorporating physiological adaptive mechanisms.

Putting everything together, we concluded that there are gaps in future projections, especially in terms of considering physiological pathway changes, including both heat adaptation (corresponding to a reduced heat-related risk) and cold sensitivity (corresponding to an increased cold-related risk), and changes in socio-economic adaptive capacities. Therefore, the objective of this study was to develop a framework for different physiological adaptation-sensitivity and socioeconomic adaptation scenarios, including adaptive capacities, and to introduce a methodological approach for future projections considering all these factors. This is followed by a demonstration of the proposed framework using time-series data over 17 years on temperature and mortality in Bavaria, Germany, as a case study.

Methods

Proposed framework of future adaptation scenarios

Physiological adaptation-sensitivity pathway

It is difficult to assess the physiological limit of population adaptation to extreme temperatures; however, the historical changes in ERF between temperature and the related health outcomes can provide useful information on the potential range of physiological adaptation. In this framework, we use changes in the present-day ERF to represent the future physiological adaptation-sensitivity pathway. Considering changes in ERF can be decomposed into two approaches: (1) the change in the slope of the ERF and (2) the shift in the mortality temperature. These approaches are based on the observed temporal variation in the temperature–mortality association during baseline. Using the first approach for the proposed framework, future physiological scenarios are expected to follow adaptation (represented by a decrease in the slope of present-day ERF) or sensitivity (represented by an increase in the present-day ERF). Similar approaches for heat adaptation have been applied by previous studies and proposed methodologies.[16,21] Because the temperature–mortality association is unique to every location,[22] analysis of temporal variation of the temperature–mortality association from the available baseline data is recommended while defining the percentage increase or decrease in ERF as well as deriving shifts in the mortality temperature, which are to be incorporated accordingly for the respective locations under investigation.

Socioeconomic adaptation pathway scenarios

The socioeconomic adaptation pathway scenarios incorporate changes in future adaptive capacities. Although there are many factors that can be used to represent adaptive capacities, in order to have broad applicability, such factors should be available in both the historical and future periods and be generalisable globally, including in low-income and middle-income countries with sparse data availability. Thus, we selected GDP projection under the respective shared socioeconomic pathways (SSPs) as a measure of future adaptive capacity. The change in future GDP under each SSP is considered to influence the adaptive capacities, resulting in socio-economic adaptation. Changes in future infrastructure due to increasing GDP would affect adaptive capacities (which could determine the adaptable fraction—eg, investments in urban green space projects, stakeholder capacity to design adaptation measures such as heat warning systems, and the ability of the population to heat or cool their environment).

By incorporating both physiological and socioeconomic adaptation pathways and by considering both adaptation to heat and sensitivity to cold, this framework unifies and further expands the current research attempts to quantify the potential impact of future population adaptations on temperature-related health impacts under climate change (figure 1).

Application of the adaptation framework in a use-case analysis

The case study application of this framework was done in five districts within the state of Bavaria, Germany (appendix p 2) for two mortality causes separately (ie, total non-accidental mortality and cardiovascular disease mortality).

See Online for appendix

Data sources

Baseline temperature and mortality

The baseline data was obtained for the period 1990–2006. We obtained daily mean temperature for the baseline period from the German Weather Service and the Bavarian Environment Agency. Daily age-specific death counts for both total non-accidental mortality and cardiovascular disease mortality were obtained from the Bavarian State Office for Statistics and Data Processing.

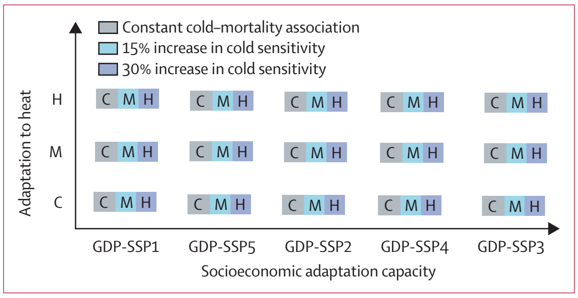

Figure 1: **Combination of the physiological adaptation pathway and socioeconomic adaptive capacity under the proposed framework**
Socioeconomic adaptation capacity on the x-axis is represented by GDP changes under each SSP scenario. The scenarios GDP-SSP1–5 represent GDP changes under the respective SSP1–5 scenarios and are placed in the order of increasing challenges for adaptation. Adaptation to heat on the y-axis is represented by the scenarios C, M, and H, corresponding to a constant, 5% decrease, and 10% decrease in the present-day heat–mortality association. Cold sensitivity is added as a third layer and represented by the scenarios C (grey), M (light blue), and H (dark blue), corresponding to a constant, 15% increase, and 30% increase in the present-day cold–mortality association. GDP=gross domestic product. SSP=shared socioeconomic pathway.

International Classification of Diseases, ninth revision (ICD-9) codes for the period 1990–97 and ICD-10 codes for the period 1998–2006 were used for classifying the causes of death. The dataset we use here (1990–2006), including both mortality and temperature data, has been used in previous publications.[4,23]

Future temperature projection

In our use-case scenario, we defined the future period as 2083–99. The time frame was chosen to make it consistent with the 17-year baseline period and to capture future mortality until the end of the century. The daily mean temperature for the future period was obtained from the bias-adjusted and downscaled spatial dataset of the five global climate models (GCMs) from phase 3b of the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP3b) based on phase 6 of the Coupled Model Intercomparison Project (CMIP6). This spatial dataset includes downscaled daily climate projections on a horizontal grid with 0·5°×0·5° resolution from five GCMs (GFDL-ESM4, IPSL-CM6A, MPI-ESM1, MRI-ESM2, and UKESM1). We obtained location-specific daily temperature series for the future period under all the five GCMs for each of the two climate change scenarios (ie, for SSP1–2.6 and SSP3–7.0), by extracting the weighted mean of the grid cells covering the location. We calibrated the extracted temperature series with location-specific observed data using the calibration method of Hempel and colleagues,[24] and observed temperature from the German Weather Service.

For more on **ISIMIP3b** see https://www.isimip.org/

Population projections, mortality rate projections, and future mortality series

The future mortality series was obtained in two stages, considering changes in both the future population and mortality rate. Initially, we applied the method of Vicedo-Cabrera and colleagues[16] and computed annual series of mortality counts (total and cardiovascular disease) as the average for each day of the year from the baseline daily mortality data to control for the seasonal trends of the observed mortality series.

In the first stage, we obtained population projections for each of the five locations under the two SSPs (SSP1 and SSP3) for the future period from a high-resolution global spatial population projection downscaled from a 1/8-degree to a 1-km grid cell from the National Centre for Atmospheric Research.[25] We corrected them for bias using the observations from the German census authority as reference. From the population projections, we then derived age-specific population growth factors under different SSP scenarios, calculated as the future population divided by the baseline population. In the second stage, we incorporated age-specific future changes in mortality rates for both total non-accidental mortality, using the mortality projections from KC and Lutz in 2017,[26] and cardiovascular disease mortality, using the mortality projections from Sellers in 2020,[27] to derive the mortality rate change factor of the two causes compared with the baseline. The formerly derived age-specific annual mortality series at baseline was then multiplied with the respective age-specific population growth factor and age-specific mortality rate change factor to obtain the final future annual mortality series for total non-accidental and cardiovascular disease mortality.

For the **Federal Statistical Office of Germany** see https://www.destatis.de/EN/Home/_node.html

Statistical analysis

The following statistical analysis would be applied in the proposed framework; however, the detailed parameter selection was based on the case study analysis in Bavaria, Germany.

Baseline ERF

We applied distributed lag, non-linear models with a quasi-Poisson distribution extending the lag period to 21 days to establish the age-specific ERFs for the baseline temperature–mortality association for each of the five locations. Two age categories were defined: younger than 75 years and 75 years or older. We used natural cubic splines centred on the location-specific minimum mortality temperature with three internal knots placed at 10th, 75th, and 90th percentiles of the location-specific mean temperature. The lag–response curve for temperature was modelled with a natural cubic spline with three knots placed at equally spaced values on the logarithmic scale. The regression also included an indicator for the day of the week and a natural cubic spline with seven degrees of freedom per calendar year to control the seasonal and long-term trends. The ERFs were extrapolated for future temperature observations beyond the baseline observations. The relative risk (RR) at each temperature point was obtained from the derived ERF. The RR for temperatures higher than the mortality temperature was defined as heat-RR, and for temperatures less than the mortality temperature as cold-RR.

We studied the temporal variation in the heat-RR and cold-RR during the baseline study period to determine the percentage change in excess RR over time (appendix p 3). Based on this analysis, we assumed that heat adaptation includes three scenarios: constant or no heat adaptation (a decrease in the excess RR by 0%), medium adaptation (a decrease in the excess RR by 5%), and high adaptation (a decrease in the excess RR by 10%). Similarly, cold sensitivity includes three scenarios: constant or no sensitivity (an increase in the excess RR by 0%), medium sensitivity (an increase in the excess RR by 15%), and high sensitivity (an increase in the excess RR by 30%). Details of the temporal variation analysis are presented in the appendix (p 3). Shifts in the mortality temperature were not incorporated because we observed inconsistent temporal patterns with large uncertainty from the baseline temporal analysis (appendix p 3).

Derivation of future RR

Under each of the future scenarios, future cold-RR and heat-RR were calculated separately (appendix p 5). Cold-RR incorporated the physiological sensitivity to cold and socioeconomic adaptation. Heat-RR incorporated the physiological adaptation to heat and socioeconomic adaptation. Socioeconomic adaptation was defined as the factor change in the future GDP per capita in relation to the baseline GDP per capita. The incorporation of GDP to determine the change in ERF is based on the log-linear association between RR and GDP. This log-linear association, which has been used in a previous study,[28] was also observed in the case study dataset (appendix p 4). We also investigated the log-linear association in this case study dataset (appendix p 4). We calculated the future cold-RR and heat-RR at each temperature point as:

$$\text{Future cold-RR } (RR_c): \ln(RR_c) = \frac{\ln(\text{physiological sensitivity factor} \times (RR_{bc}-1)+1) + \ln[(RR_{bc}-a)\times x] + a}{2}$$

$$\text{Future heat-RR } (RR_h): \ln(RR_h) = \frac{\ln(\text{physiological adaptation factor} \times (RR_{bh}-1)+1) + \ln\left(\frac{RR_{bh}-b}{x}\right) + b}{2}$$

where c=cold, h=heat, bc=baseline cold-RR, bh=baseline heat-RR, a=intercept of the cold-RR and $\log(GDP_{\text{per capita}})$ model, b=intercept of the heat-RR and $\log(GDP_{\text{per capita}})$ model, $x=\log(GDP_{\text{per capita}}\text{ future})/\log(GDP_{\text{per capita}}\text{ baseline})$.

Projection of future mortality

Age-specific future heat-related and cold-related mortality were calculated and added to derive the net future temperature-related mortality (appendix p 5), as follows:

$$\text{Future heat-related deaths} = Y_{hl} \times P_l \times RR_{hl} \times M_l$$

$$\text{Future cold-related deaths} = Y_{cl} \times P_l \times RR_{cl} \times M_l$$

where l represents the different locations, h=heat, c=cold, Y_{hl} and Y_{cl} are the age-specific baseline mortality series, P_l is the age-specific population change rate, M_l is the age-specific mortality change rate, RR_{hl} is the future heat-related RR, and RR_{cl} is the future cold-related RR.

Calculation of the adaptable fraction

Finally, we calculated the adaptable fraction, which is the number of deaths that can be avoided through adaptation, as:

$$\text{Adaptable fraction} = \frac{\text{Net mortality without adaptation} - \text{net mortality with adaptation}}{\text{Net mortality without adaptation}} \times 100$$

Under each representative concentration pathway (RCP; which are scenarios developed by the Intergovernmental Panel on Climate Change for application in studies to explore uncertainty about future atmospheric levels of CO_2), we incorporated the five GCMs and derived five projections of future adaptable fractions (appendix p 5). The average of estimates under these five projections was considered as the adaptable fractions under each RCP.

To account for uncertainty in both the ERF and the projections of future climate and population models, we used Monte Carlo simulations to obtain 95% empirical CIs (95% empirical CIs). For the derivation of 95% empirical CIs for an estimate under one of the climate scenarios for a single location, we first obtained the empirical distribution across 5000 samples of random parameter sets describing the ERF in the distributed lag, non-linear model under the specific climate scenarios for each of the five GCMs.[2,29] This was done separately for the heat and cold adaptable fractions and for the two age groups, giving us 100 000 simulations for each location. We thus obtained 500 000 Monte Carlo simulations for the five locations that were used in deriving the 95% empirical CIs for the estimate under the corresponding climate scenario for Bavaria.

Role of the funding source

The funder of the study had no role in study design, data collection, data analysis, data interpretation, or writing of the report.

Results

Climate, population, and mortality projections

The average temperature during the baseline period was 9·8°C, which was seen to increase during the future period by an average of 1·1°C under the SSP1–2.6 climate change scenario and by 4·1°C under the SSP3–7.0 climate change scenario (figure 2). Both population and GDP increments are higher under the SSP1 scenario than under the SSP3 scenario (figure 3A, B). With changes in

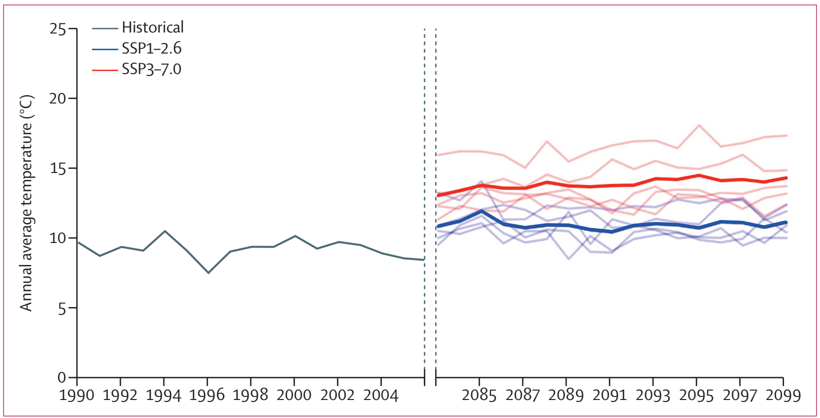

Figure 2: **Annual average air temperature during the baseline and projected future periods**

Temperature during the baseline period is the station-measured temperature, and temperature during the future period is projected by the five GCMs from ISIMIP3b based on CMIP6. Each darker line represents the average of the GCMs; faint lines represent the temperature under the six climate models (CMIP6); the dark line is the average of these six models. CMIP6=phase 6 of the Coupled Model Intercomparison Project. GCM=global climate model. ISIMIP3b=phase 3b of the Inter-Sectoral Impact Model Intercomparison Project. SSP=shared socioeconomic pathway.

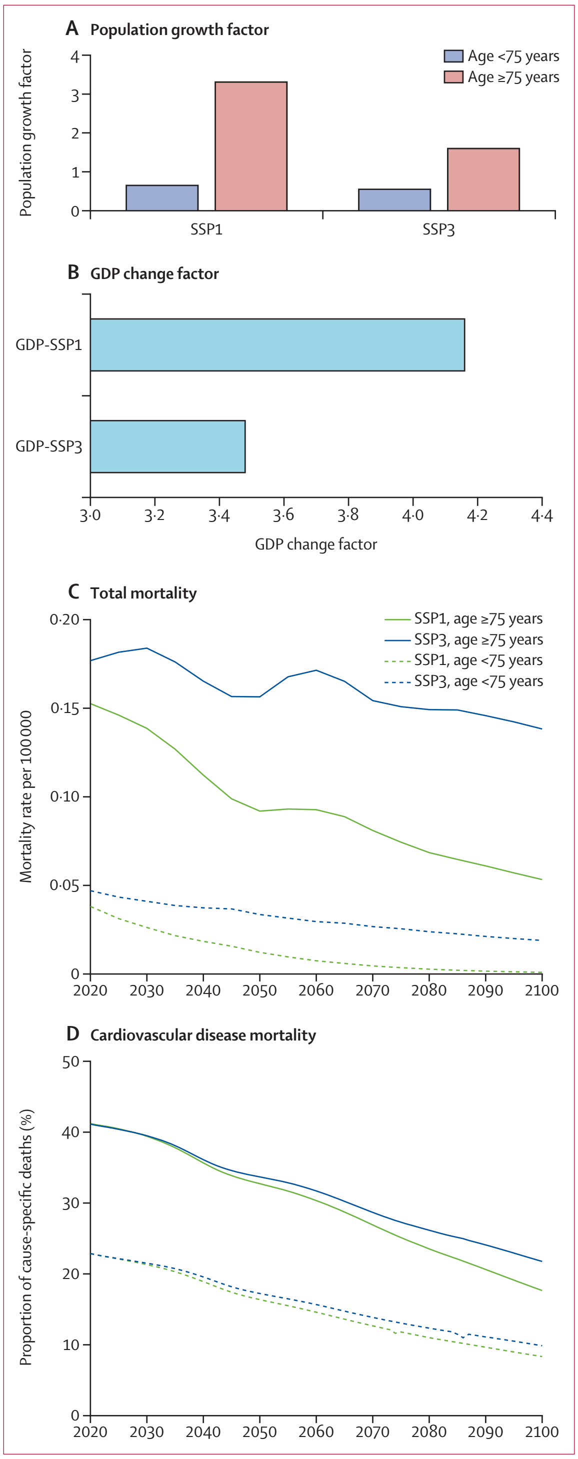

Figure 3: **Changes in future population, GDP, and mortality rates**
(A) Comparison of projected population growth factor under different SSPs; the factor is calculated as the fraction of future population divided by the baseline population. (B) Projected GDP change factor under different SSPs; the factor is calculated as the fraction of future GDP divided by present-day GDP. (C) Projected trends in total mortality per 100 000, as projected by KC and Lutz,[26] by age group and by SSP. (D) Projected trends in proportion of cardiovascular disease mortality to total mortality as projected by Sellers,[27] by age group and by SSP. GDP=gross domestic product. SSP=shared socioeconomic pathway.

future infrastructure and health-system improvement, the mortality rate for total and cardiovascular disease mortality is expected to decrease under both SSP1 and SSP3 (figures 3C, D).

Adaptable fractions under future adaptation scenarios

We projected future heat-related and cold-related adaptable fractions separately and derived the net adaptable fraction under all combinations of the proposed physiological and socioeconomic adaptation scenario pathways for total mortality (figure 4) and cardiovascular disease mortality (figure 5). Under both SSP1–2.6 and SSP3–7.0, we observed that socioeconomic adaptation largely influenced the adaptable fraction for both causes. No significant net adaptable fraction is expected in the absence of socioeconomic adaptation for total mortality. Furthermore, under all scenarios, the cold adaptable fraction is less than the heat adaptable fraction. The proportion of older people is much higher under SSP1–2.6 than under SSP3–7.0 and, in the absence of socioeconomic adaptation, the net adaptable fraction under SSP1–2.6 is lower than it is under SSP3–7.0. In addition, we found that the adaptable fraction for cardiovascular disease mortality was not significant even when considering socioeconomic adaptation.

Total mortality

The highest adaptable fraction for SSP1–2.6 was observed under socioeconomic adaptation, 10% heat adaptation, and 0% cold sensitivity, for which the adaptable fraction was 18·56% (95% empirical CI 10·77 to 23·67). Under the same adaptation scenario combination, the adaptable fraction was only 0·25% (–6·23 to 4·43) in the absence of socioeconomic adaptation. Similarly, the adaptation scenario associated with the highest excess mortality consists of 0% heat adaptation and 30% cold sensitivity in the absence of socioeconomic adaptation, under which there was a negative adaptable fraction of –2·55% (–10·72 to 2·81; figure 4; appendix p 6).

The direction of estimates was similar but with smaller magnitude for SSP3–7.0. Under the previous scenario of highest adaptable fraction, the adaptable fraction was 15·96% (95% empirical CI 6·83 to 19·83). Similarly, under the previous adaptation scenario associated with the highest excess mortality, a negative adaptable fraction of –1·91% (–10·51 to 3·23) was observed (figure 4; appendix p 6).

Cardiovascular disease mortality

The patterns of adaptable fractions for cardiovascular disease mortality were similar to those for total mortality but with a smaller magnitude. Under the highest adaptable scenario for SSP1–2.6 observed for total mortality (ie, socioeconomic adaptation, 10% heat adaptation, 0% cold sensitivity), the cardiovascular disease adaptable fraction was 14·88% (95% empirical CI –5·05 to 19·78). Under the same adaptation scenario combination, the adaptable fraction was only 0·35% (–12·90 to 7·30) in the absence of socioeconomic adaptation. Similarly, under the lowest adaptation combination of SSP1–2.6 observed for total mortality, a negative adaptable fraction of –3·93% (–20·58 to 4·28) is to be expected (figure 5; appendix p 7). The direction of estimates was similar but with smaller magnitude for SSP3–7.0. Under the scenario with the highest adaptation fraction for SSP3–7.0, the adaptable fraction was 12·31% (95% empirical CI –14·95 to 16·45). A negative adaptable fraction (–3·21% [–29·82 to 11·21]) was observed under the scenario with the highest adaptable fraction for SSP3–7.0 (figure 5; appendix p 7).

Discussion

In this Article, we propose a framework of future scenarios incorporating measures of both physiological adaptation-sensitivity and socioeconomic adaptation. Based on the proposed framework, we estimated the future net changes, including changes in the impact of both heat and cold, in the burden of total and cardiovascular disease mortality under all framework combinations, taking Bavaria, Germany, as a case study. Under all future scenarios, we found that socioeconomic adaptation played a major role in determining the future adaptable fraction. However, even with increased socioeconomic adaptive capacity, physiological adaptation-sensitivity could also influence the net adaptable fraction. Under all scenarios, the cold adaptable fraction was found to be lower than the heat adaptable fraction. Therefore, in the absence of socioeconomic adaptation, cold sensitivity might outweigh heat adaptation, thereby leading to increased excess deaths in the future. No significant adaptable fraction was observed for cardiovascular disease mortality even when considering socioeconomic adaptation.

Comparing the results from the two climate change scenarios (SSP1–2.6 and SSP3–7.0) in the presence of socioeconomic adaptation, the net adaptable fraction is higher under SSP1–2.6 than it is under SSP3–7.0. This difference is because of the higher GDP per capita under the socioeconomic scenario SSP1 than under SSP3, which would result in a higher adaptive capacity. However, in the absence of socioeconomic adaptation and considering only physiological adaptation sensitivity, the adaptable fraction under the climate change scenario SSP3–7.0 is seen to be slightly higher than that under SSP1–2.6, which is due to a much higher proportion of older people in the population under SSP1 than under the SSP3 scenario. A higher proportion of older people directly increases the proportion of susceptible people, leading to excess temperature-related mortality. Similarly, our results show that climate-sensitive outcomes, such as cardiovascular disease mortality, will continue to increase in the future, even with better adaptive capacities.

Heat-related impacts of climate change on cardiovascular disease are being discussed as an emerging important threat.[30] However, our analysis including physiological adaptation showed that cold sensitivity could be the major determining factor for future projections regarding the physiological adaptation-sensitivity scenario. Studies exploring the effect of temperature over time throughout the whole temperature range are sparse,[18–20] with results suggesting either that the cold–mortality association will be constant[18,19] or that susceptibility to cold will increase in the future.[20] Nevertheless, with studies estimating the present-day cold-attributable burden to be generally higher than the heat-attributable burden,[22] we can expect the future temperature-attributable health burden to be largely influenced by changes in the cold ERF rather than the heat ERF, especially in countries with temperate to cold climatic conditions.

By contrast, a previously proposed modelling framework[16] suggests that the future population will adapt to increased heat. Nevertheless, some large studies suggest varying temporal trends (ie, decrease, constant, or increase) in the heat ERF across different locations.[31] For example, a constant heat ERF across time was observed

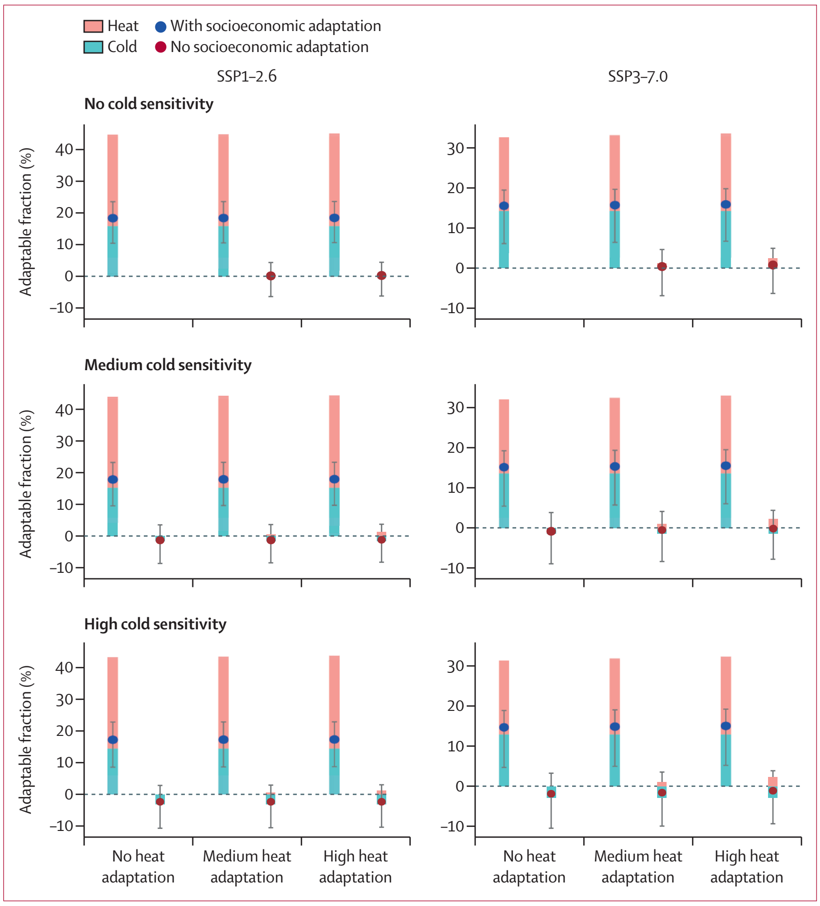

Figure 4: **Adaptable fraction for total mortality under combination of future physiological and socioeconomic adaptation scenarios**

No heat adaptation corresponds to a decrease in the excess relative risk (RR) by 0%, medium adaptation to a decrease in the excess RR by 5%, and high adaptation to a decrease in the excess RR by 10%. No cold sensitivity corresponds to an increase in the excess RR by 0%, medium sensitivity to an increase in the excess RR by 15%, and high sensitivity to an increase in the excess RR by 30%. SSP=shared socioeconomic pathway.

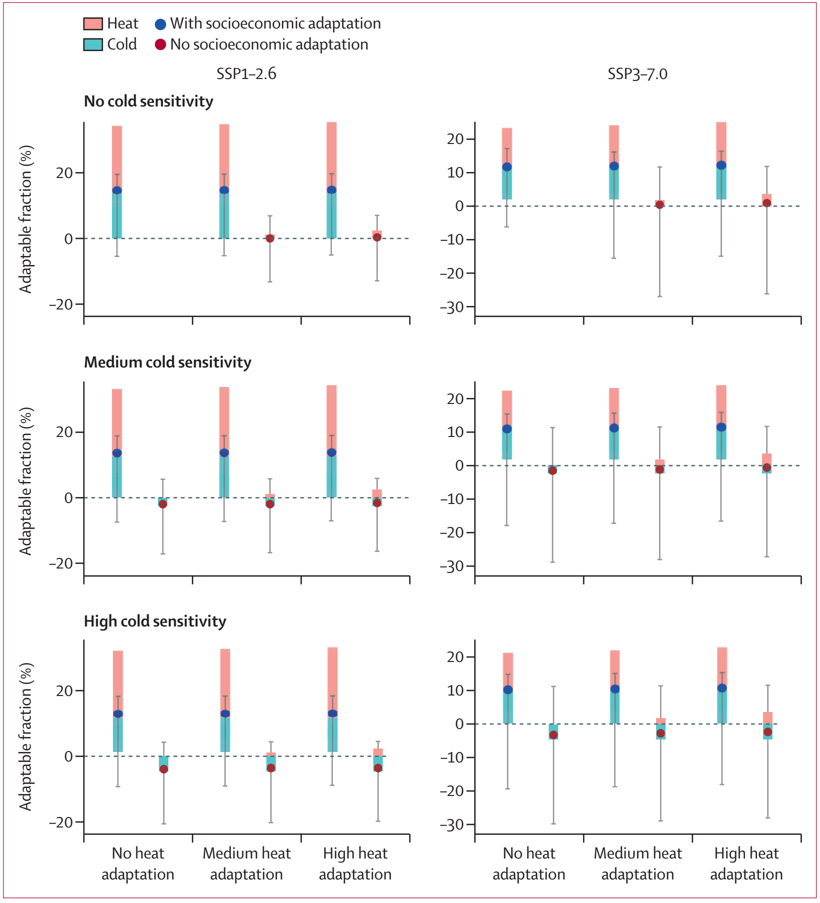

Figure 5: **Adaptable fraction for cardiovascular disease mortality under combination of future physiological and socioeconomic adaptation scenarios**

No heat adaptation corresponds to a decrease in the excess relative risk (RR) by 0%, medium adaptation to a decrease in the excess RR by 5%, and high adaptation to a decrease in the excess RR by 10%. No cold sensitivity corresponds to an increase in the excess RR by 0%, medium sensitivity to an increase in the excess RR by 15%, and high sensitivity to an increase in the excess RR by 30%. SSP=shared socioeconomic pathway.

for temperate regions such as the UK, whereas an increasing trend was noted for countries such as Australia.[31] These studies suggest that the future population in some locations might not adapt to heat as expected but could rather develop a sensitivity to heat. Therefore, for temperate regions such as Bavaria, where the population is not used to heat (especially heatwaves), the heat ERF might increase in the future or at least stay constant. An increase in both heat and cold sensitivity would mean much higher excess mortality in the future. In the scenario in which the cold ERF largely determines the mortality burden and is potentially expected to increase, socioeconomic adaptation would be the solution to increase climate change resilience. Such adaptation could be achieved with efficient adaptation strategies targeting vulnerable population subgroups, such as older people and those with underlying health conditions.

In any case, the future adaptable fraction in our case study in Bavaria is dominated largely by socioeconomic adaptation. Changes in future infrastructure related to increasing GDP could improve adaptive capacities. Increasing GDP could mean an increase in the heating and cooling (eg, increased prevalence and usage of air conditioning) capacity of the population, and the possibility of increased investments in urban green space projects, efficient urban planning measures with reduction of urban heat islands, and an overall increase in the stakeholder capacity to design adaptation measures such as heat warning systems.[32]

Our study provides a framework of future adaptation to temperature-related health outcomes incorporating measures of both physiological adaptation-sensitivity and socioeconomic adaptive capacities, to both hot and cold temperatures under climate change. The strength of our study comprises the projection of future adaptable fraction under the proposed scenarios incorporating all major aspects of future uncertainty, including climate, population, demographic, socioeconomic, and mortality changes. Furthermore, high-resolution, bias-corrected, and downscaled GCMs participating in the CMIP6 were used to derive air temperatures under each of the climate scenarios as well as a downscaled, high-resolution data frame to derive the corresponding population projection under each SSP. We also captured and addressed the sources of uncertainties in our analysis, including the baseline temperature–mortality ERF, the temperature projection, and the population projection. The primary limitation of our case study is that the adaptation framework and modelling choices might not be directly applicable in a larger dataset across various climatic and geographical locations because they were based on observations of our case-study data. Furthermore, we did not incorporate future shifts in the minimum mortality temperature because we did not observe this for our case study dataset. In addition, we only used fixed weather stations for temperature exposure assessment during the baseline period, which might have introduced some bias in the exposure classification. However, this type of bias is rather towards null (ie, it does not lead to over or under estimation).[23] Furthermore, the incorporation of GDP to define the adaptive capacity might not have encompassed all aspects of socioeconomic adaptation.

In our Bavaria case study we found that socioeconomic adaptation plays a major role in determining the proportion of temperature-related deaths that can be averted through adaptation (adaptable fraction). In addition, we found that the cold ERF, rather than the heat ERF, and climate-sensitive outcomes such as cardiovascular disease mortality dominate our future temperature-related excess mortality estimates.In the absence of socioeconomic adaptation, we project excess mortality in the susceptible population. Strategic adaptation plans to increase socioeconomic adaptative capacity, such as effective early warning systems, equitable green infrastructure, targeted investments in health systems, and sustainable heating and cooling strategies, would be crucial to facilitate a climate resilience development pathway as the world warms.

Contributors
MR, KC, and AS designed the study. MR coordinated the work, and took the lead in drafting the manuscript and interpreting the results. MR, KC, and AS developed the statistical methods. MR did the statistical analysis and KC verified that analysis. KC and AS provided substantial scientific input in interpreting the results and drafting the manuscript. SB provided the data. MR, SB, and KW directly accessed and verified the underlying data. SB, KW, AP, AS, and KC reviewed and edited the manuscript. All authors had full access to all the data in the study and final responsibility to submit for publication.

Declaration of interests
We declare no competing interests.

Data sharing
The baseline mortality data was obtained from the Bavarian State Office for Statistics and Data Processing under a data agreement and cannot be made publicly available. Researchers can refer to the corresponding author for data access upon reasonable request.

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