Environmental Research 259 (2024) 119565

Contents lists available at ScienceDirect

Environmental Research

journal homepage: www.elsevier.com/locate/envres

Future temperature-related mortality in the UK under climate change scenarios: Impact of population ageing and bias-corrected climate projections

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ABSTRACT

Background: Exposure to heat and cold poses a serious threat to human health. In the UK, hotter summers, milder winters and an ageing population will shift how populations experience temperature-related health burdens. Estimating future burdens can provide insights on the drivers of temperature-related health effects and removing biases in temperature projections is an essential step to generating these estimates, however, the impact of various methods of correction is not well examined.

Methods: We conducted a detailed health impact assessment by estimating mortality attributable to temperature at a baseline period (2007–2018) and in future decades (2030s, 2050s and 2070s). Epidemiological exposure-response relationships were derived for all England regions and UK countries, to quantify cold and heat risk, and temperature thresholds where mortality increases. UK climate projections 2018 (UKCP18)were bias-corrected using three techniques: correcting for mean bias (shift or SH), variability (bias-correction or BC) and extreme values (quantile mapping or QM). These were applied in the health impact assessment, alongside consideration of population ageing and growth to estimate future temperature-related mortality.

Findings: In the absence of adaptation and assuming a high-end emissions scenario (RCP8.5), annual UK temperature-related mortality is projected to increase, with substantial differences in raw vs. calibrated projections for heat-related mortality, but smaller differences for cold-related mortality. The BC approach gave an estimated 29 deaths per 100,000 in the 2070s, compared with 50 per 100,000 using uncorrected future temperatures. We also found population ageing may exert a bigger impact on future mortality totals than the impact from future increases in temperature alone. Estimating future health burdens associated with heat and cold is an important step towards equipping decision-makers to deliver suitable care to the changing population. Correcting inherent biases in temperature projections can improve the accuracy of projected health burdens to support health protection measures and long-term resilience planning.

1. Background

The UK has experienced increasing ambient air temperatures and more frequent and intense heatwaves in recent decades (Kendon et al., 2022). The summer 2022 heatwave saw maximum temperatures of 40 °C for the first time since records began, and such temperature extremes will likely become commonplace without an effective curb on global greenhouse gas emissions (Lowe et al., 2018). Exposure to high ambient temperatures is known to have harmful impacts on human health, including increasing mortality, morbidity and reducing labour productivity and impairing cognitive performance (Gómez-Acebo et al., 2013; Ebi et al., 2021). As climate change progresses, the heat-health impact will also increase without adaptation. Although UK winters are becoming milder (Lowe et al., 2018), cold-related illness and mortality will remain an important priority for public health (Hajat et al., 2014; Kovats et al., 2021) due to the existing large burden of cold-related ill health. Previous work has shown that population ageing will likely offset some of the benefits from warmer winters by increasing cold-related mortality (Kovats et al., 2021; Chen et al., 2024), as older people are more susceptible to the effects of extreme temperatures.

Many temperature-related health risks are preventable (Ebi et al., 2021; Hajat, 2017). Characterising the impacts of climate change on

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https://doi.org/10.1016/j.envres.2024.119565
Received 22 April 2024; Received in revised form 26 June 2024; Accepted 4 July 2024

public health is important for increasing preparedness and adaptation action planning to minimise the risks. National climate change risk assessments synthesise current and future impacts of climate change on natural and human systems and inform governments, stakeholders, and the public on related risks, to help support future planning and policies to mitigate and adapt to climate change. Such assessments for future periods are possible by using climate projection data. The UK Met Office provides bespoke detailed projections of climate variables across the UK, and UKCP18 climate projections are the most detailed to date, incorporating recent advances in climate science as well as greater spatial resolution. Raw climate projection data often have systematic biases which may be apparent when comparing climate model simulations of historical periods to observation data (Sanderson et al., 2017). The magnitudes of these biases have steadily decreased with improvements to climate models (Sanderson et al., 2017), nevertheless, any remaining biases can introduce errors in projected temperatures and thus have the potential to affect projected estimates of health burdens related to climate change. Bias correction or calibration is a necessary step for improving the accuracy of future health burden estimates for appropriate public health responses.

A systematic review of the application of climate information to estimate future mortality found that some studies used raw climate estimates, whereas many of those that calibrated climate data used simple methods of bias corrections which are relatively straightforward to perform (Sanderson et al., 2017). There is an argument for using several calibration approaches in parallel as no single method performs best under all circumstances, although there is recognition that more sophisticated methods such as quantile mapping may perform much better in reproducing higher and lower temperatures in the annual distribution of temperature (Sanderson et al., 2017; Räisänen et al., 2013). In this paper, we consider three calibration methods recommended by the UK Met Office (Fung, 2018); the simplest approach '**shift (SH)'** is a linear scaling to adjust for mean bias and assumes constant biases across the decades (Sanderson et al., 2017; Fung, 2018). The second approach '**bias-correction (BC)'** is a method that corrects for biases in mean and variance, the third, **'quantile mapping (QM)'** approach, preserves the distribution and corrects extreme values (Fung, 2018). We only came across one previous study that examined the effect of 5 different quantile mapping approaches, although that study focused specifically on heat-related emergency department visits in a single US city (Qian and Chang, 2021).

This study was part of the UK government's comprehensive assessment of current and future temperature-related mortality impacts in the UK (Macintyre et al., 2023). The work advances previous health impact assessments by:

i) Using recent observed temperature datasets and mortality data to generate epidemiologic risk profiles for UK regions; recent UK mortality projections apply older exposure-response functions which may not accurately depict the present population risk (Chen et al., 2024; Jenkins et al., 2022), or, use imprecise methods to derive risk estimates due to missing age-specific data (Chen et al., 2024).
ii) Using the latest detailed bias-corrected and population-weighted UKCP18 climate projections to compare the impacts of applying three UK Met Office recommended calibration methods (Fung, 2018); this is the focus of our study and a unique contribution to the existing evidence.
iii) Applying the risk estimates and bias-corrected data to quantify the impact on future temperature-related (heat and cold) mortality across different regions and how this is affected by population growth and ageing.

2. Methods

2.1. Characterising temperature effects

We used daily all-cause mortality data and daily ambient temperatures to examine the association between mortality and ambient temperature. Daily death counts for 2007–2018 grouped by age (0–64, 65–74, 75–84, 85+) were obtained for the nine government office regions (GOR) in England, Wales and Scotland.

The HadUK-grid daily outdoor temperature data (derived from ground observations) was used on an identical grid to the UKCP18 projections data (12 km) (Hollis et al., 2019). Exposure estimates for the study areas were generated from daily mean temperatures (derived from the HadUK-grid data) and population-weighted, using 100 m gridded residential population information (Health and Safety Laboratory, 2020) (1 km for Northern Ireland due to data availability (Reis et al., 2017)).

The associations between temperature and mortality were estimated using time series regression models. Heat and cold effects were assessed using all-year models and the analysis was conducted using the distributed lag non-linear model package (in the R programming language), which enables modelling of the non-linear and delayed effects between exposure (temperature) and outcome (mortality) (Gasparrini, 2021). Evidence shows that heat effects on health are mostly immediate, occurring very close to the day of exposure, but cold effects can take place over several weeks following the initial exposure (Armstrong, 2006), therefore a lag of up to 3 days and up to 28 days were defined for heat and cold effects, respectively. As per previous publications, a cross-basis and spline functions were used to flexibly model the relationship between temperature and mortality, taking into account the lag distribution (Gasparrini, 2021; Gasparrini et al., 2015). The temperature-mortality relationship was modelled with a quadratic B-spline, 5 degrees of freedom for temperature and equal knots selected using the function 'equalknots'. The lag-response curve was fitted using a natural cubic spline with an intercept and three internal knots placed at equally spaced values in the log scale. The models also include natural spline for the day of the year and time, to adjust for the seasonal effect within each year, and the long-time trend, and adjustments were also made for the day of the week (Gasparrini, 2021).

Relative risks (95% confidence interval), depicting the heat and cold effects were estimated using regional temperature thresholds determined from the regional temperature distribution of the baseline period (2007–2018). The UK mean heat and cold effects were quantified using random effects meta-analysis of the regional risks. The threshold for estimating heat impacts was assigned at the 93rd percentile of the yearly distribution of daily mean temperature and heat risk was estimated by comparing mortality risk between the 93rd and 99th temperature percentiles; use of this threshold is widely acceptable for the UK populations (Armstrong et al., 2011; Vardoulakis et al., 2014). It is more difficult to determine a threshold for cold impacts; at lower cold thresholds, causal relationships are more robust when there is greater confidence in the pathways to health effects, but such low thresholds may underestimate the mortality attributable to moderate cold (Arbuthnott et al., 2018). We estimated cold risk using the temperature thresholds on the exposure-response curves for England, where mortality risk increases with temperature decline (Fig. 1) (equivalent to the 9th temperature percentile); for each age group and region, cold risk was therefore estimated by comparing mortality between the 9th and 1st temperature percentiles.

2.2. Climate projections and adjusting for bias

Future mortality burdens were estimated using projected daily mean 2 m air temperature (12 km horizontal grid resolution) for 12 ensembles of the RCP8.5 emission scenario from UKCP18. Other RCP scenarios were not assessed due to a lack of data at daily time resolution, which is

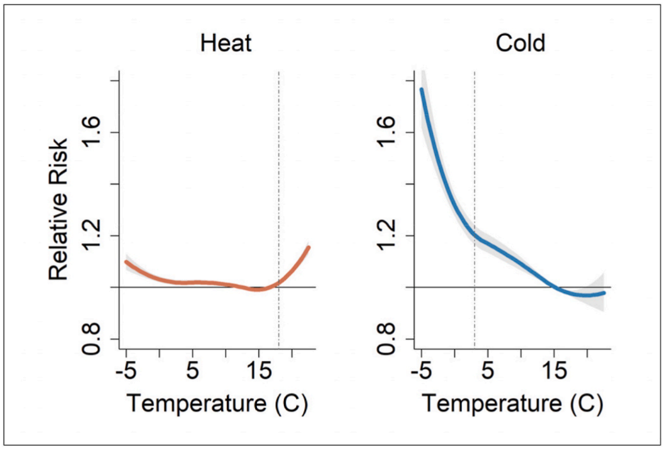

Fig. 1. Cumulative exposure-response associations for temperature-related risk at England level. Models used 0–3 lags for heat and 0–28 for cold. Dashed lines are at the 93rd and 9th percentile.

necessary for assessing temperature-health effects (Murphy et al., 2018).

Climate model data is typically provided in a raw format and should be calibrated before application, usually achieved by comparing climate model performance with a historical period to identify any bias and ensure that this is accounted for in the projected data to produce better quality, and more reliable, future projections (Maraun and Widmann, 2018). We used three bias adjustment methods, here referred to as the ‘SH’, ‘BC’, and ‘QM’ approaches (described further below), applied to the population-weighted daily mean 2 m air temperature from UKCP18 model simulation outputs (Fung, 2018). For calibrating the future projections, we used the reference period of 39 years of population-weighted temperature observations from 1980 to 2019. The SH method was used to adjust the UKCP18 population-weighted daily means by the mean bias over the reference period, separately for each month and combining all ensemble members (Karwat and Franzke, 2021). We assumed $T_{o(t)} = [T_o] + T'_{o(t)}$, and $T_{r(t)} = [T_r] + T'_{r(t)}$, where T_o is the observed temperature, and T_r is raw UKCP18 temperature, while [x] denotes the mean value and x’ denotes the anomaly from the mean value over the reference period. Hence, in the SH method: $T_{SH(t)} = [T_o] + T'_{r(t)}$. The BC method was used to remove biases in the variability of raw model simulations, by taking into account a potential difference between the standard deviations of the observations $\boldsymbol{\sigma}(T_o)$ and the raw UKCP18 simulations $\boldsymbol{\sigma}(T_r)$ (Ho et al., 2012; Hawkins et al., 2013) and rescaling the raw UKCP18 anomalies to match the variability of the observations over the reference period: $T_{BC(t)} = [T_o] + (\boldsymbol{\sigma}(T_o)/\boldsymbol{\sigma}(T_r))\, T'_{r(t)}$. We also used the QM approach to preserve the distribution to capture the variability and to inform any subtle changes in extreme values, as shown in the following equation: $X_{QM}(t) = F_O^{-1}(F_X(X_{fut}(t)))$, where ‘$X_{QM}$’ is the QM adjusted model data, ‘t’ is time, ‘O’ are observations, subscripts refer to baseline and future periods, ‘F’ is the cumulative distribution function mapping modelled data to observations (Gohar et al., 2017).

2.3. Contribution of changes in the population structure

The analysis considered the effects of changes in the population structure using the Office for National Statistics principal population projections which take into consideration future shifts in the population that might occur based on changes in future levels of fertility, mortality and migration. The national projections are available for the UK countries covering 100 years from 2018. Regional projections for England are only available until 2043; regional projections post-2043 were estimated by applying the 2018 regional population distributions to the 2043 to 2080 national projections. Population data were divided into three periods (2030s, 2050s and 2070s) and were aggregated by age group.

2.4. Impact assessment

We used a previously published approach that uses exposure-response coefficients for heat and cold effects (generated from the aforementioned epidemiological analysis) along with baseline mortality rates (all-cause deaths by age groups) and regional population projections, to estimate the number of heat and cold-related deaths for the baseline period (2007–2018) and the future decades the 2030s, 2050s and 2070s (Hajat et al., 2014). We did not have access to mortality records from Northern Ireland and therefore the exposure-response coefficients were derived from the North West region mortality rates. Furthermore, we assumed no adaptation over the future decades by holding constant the coefficients, regional temperature thresholds and baseline mortality rates in each study area. The health impact assessments were done across all 12 ensemble members of the UKCP18 simulations, and an average for all assessments was determined. The results are reported as mean annual burdens and include the range of maximum and minimum annual burdens (indicated by the upper and lower bounds in Figs. 4 and 5) of the ensemble range. Results are presented both with and without consideration of future changes in population growth and ageing to show how changes in the population structure may contribute to future mortality in a no-adaptation scenario.

3. Results

3.1. Comparing raw and processed climate data

In Fig. 2, panels (1,3,5 and 7) show differences between population-weighted monthly means (derived from daily means from the 12 climate model outputs), compared to observation data. The panels (2), (4) (6) and (8) show ratios between population-weighted monthly standard deviations of various model outputs and observations. The panel rows show the results using raw/unprocessed (1,2), and bias-adjusted, SH (3,4), BC (5,6) and QM (7,8) UKCP18 simulations, for our regions of interest over the reference period (1980–2019). Generally, spring months are colder in the raw projections compared to observations, and summers are hotter. As an example, the raw model suggests March to May is colder than the observations (panel 1) and bias adjustment will lead to these being corrected ‘up’ to match the observations, whereas in September the raw projection model is slightly hotter than observations and will be corrected ‘down’. SH method corrects for mean bias only as shown on panel (3), the variability between climate models persists (panel 4) after using this approach. QM adjusts for different quantiles individually to adjust biases over the entire distribution without specifically trying to correct the mean, while implicitly improving variability, panels (7, 8). BC method performs better as it corrects for both mean bias and variability, panels (5, 6) show BC corrected data is the closest match to the observed temperature. Supplementary Fig. 2 shows that under the RCP8.5 future emission (‘worst-case’) scenario there will be a universal increase in bias-corrected (BC) population-weighted 2 m air temperature, with differences across seasons and regions, for example, the highest mean warming is seen in the summer months, particularly August, and London and West Midlands, which are projected to reach +5 °C in August in the 2070s.

3.2. Regional temperature distribution

London region recorded the highest population-weighted temperature (26.8 °C), and heat and cold threshold (19.2 °C and 3.8 °C, respectively), whereas West Midlands recorded the lowest population-weighted temperature (−7.4 °C), (Table 1).

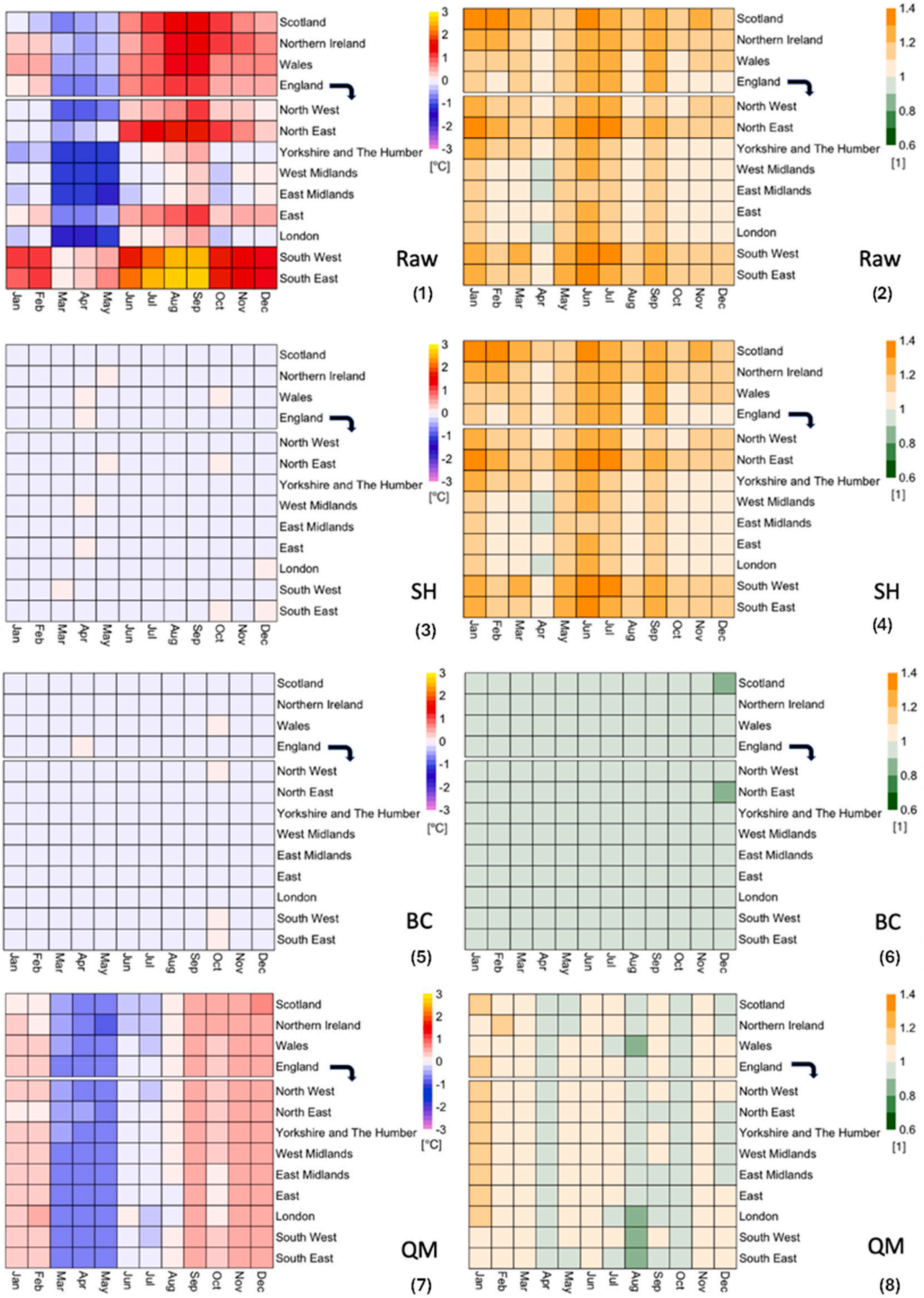

Fig. 2. The panels (1), (3), (5) and (7) show differences between observations and population-weighted monthly means (derived from daily means of model outputs), bias-adjusted in different ways. The panels (2), (4), (6) and (8) show ratios between population-weighted monthly standard deviations of model outputs, processed differently, and observations (also based on daily means). The panels in the first row, (1) and (2) are the raw (unprocessed) results, the second row, (3) and (4), the third row, (5) and (6), and the fourth row (7) and (8) are results of the SH, BC, and QM bias corrected UKCP18 simulations, over the reference period from December 1980 to November 2019.

3.3. Epidemiological analysis

The seasonally adjusted relationships between observed daily mean temperature and the relative risk of death (all ages and all causes) are shown in Supplementary Fig. 1. Heat and cold effects are displayed separately using lag structures 0–3 and 0–28 days, respectively (Supplementary Fig. 1). Across all areas, the risk of death increases as temperatures increase or decrease beyond given thresholds (Table 1). There was a statistically significant increase in mortality risk (from heat and cold exposure) across all the regions (Fig. 3). The London region had the

Table 1

Daily mean population-weighted temperature (°C) for England GOR, Wales, Scotland and Northern Ireland, 2007–2018. Mean temperature is given for the minimum temperature, the 1st, 9th (cold threshold), 93rd (heat threshold) and 99th temperature percentiles.

	Min temp	1st temp percentile	9th temp percentile	93rd temp percentile	99th temp percentile	Max temp
London	−3.7	−0.5	3.8	19.2	22.5	26.8
North East	−5.0	−0.9	2.4	14.7	17.0	19.1
North West	−5.9	−1.0	3.0	16.0	18.7	22.1
South East	−3.9	−0.9	2.7	15.4	18.0	21.5
South West	−3.8	−0.8	3.3	15.0	17.4	19.8
East Midlands	−6.7	−1.3	2.8	17.5	20.4	23.8
West Midlands	−7.4	−1.6	2.9	17.6	20.4	24.2
York Humber	−6.0	−1.2	2.6	16.8	19.6	22.4
East	−5.4	−1.1	2.9	17.5	20.3	24.2
Wales	−5.0	−0.7	3.2	15.6	18.2	21.3
Scotland	−6.0	−1.5	2.0	13.5	15.7	18.8
Northern Ireland	−6.9	−0.5	2.9	14.3	16.3	18.9

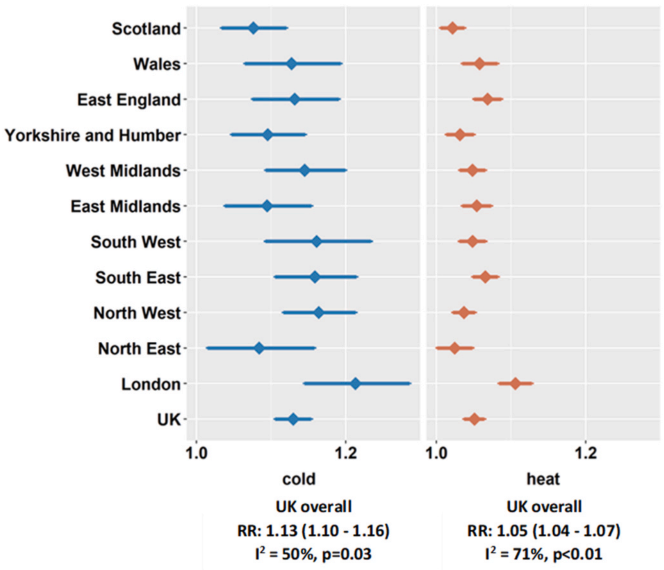

Fig. 3. Heat and cold effect (RR, 95%CI) for England GOR, Wales, Scotland and Great Britain pooled estimates.

highest heat and cold risk, the all-ages heat risk for London was RR 1.11, 95% CI: 1.08–1.13, which was significantly greater than heat risk across all the other regions and the UK pooled average (all ages RR 1.05, 95% CI: 1.04–1.07) (Fig. 3). Heat and cold risk generally increases with age, with the greatest heat risk in those aged 85 years and above except in the North East and the Yorkshire & Humberside regions (Supplementary Table 1 for age-specific risks).

3.4. *Risk assessment*

The health impact assessment shows UK annual heat-related mortality deaths will increase from the baseline into future decades 2030s, 2050s and 2070s. In contrast, mortality associated with cold is predicted to be at its highest in the 2030s before declining in the 2050s and 2070s (Fig. 4). The highest burden from heat and cold exposure is from those aged 85 years and older. The use of bias corrected vs. raw UKCP18 projections has a substantial impact on estimating the total heat-related deaths, for example, mortality estimates using calibrated temperature (BC approach) suggest annual UK heat deaths will increase from 1602 at baseline to 21,544 in the 2070s, these estimates show close to a two-fold increase when compared mortality is estimated using unprocessed (raw) temperature (increase from 3760 at baseline to 36,586 in 2070s. Bias correction using BC and QM gives the most conservative estimates compared to correction using SH: estimated deaths at 2070 are 21,544 (BC), 22,133 (QM) and 27,971 (SH) (Fig. 4), see Supplementary Tables 2–5 for estimates presented as rates per 100,000 people.

Bias correction has less of an impact on estimated cold-related deaths (Fig. 4), and the use of BC corrected temperatures suggests annual UK deaths will decline from a baseline of 3017 to 908 in the 2070s, which is comparable to the projected decline using non-corrected temperature (decline from 3681 to 1077).

Although mortality rates from heat will increase into the future in both a static and a dynamic population, population growth and the increase in the proportion of older people has a considerable impact on mortality, and result in a nearly threefold difference between projected mortality rates that assume no changes in the population structure in future decades (75.5 per 100,000 people) vs. projections that assume future growth in the population aged 85 years plus (277.3 per 100,000 people) (using BC adjusted temperatures) (Fig. 5). Taking into consideration the changes in population structure has similar effect on the mortality rates from extreme cold (Fig. 5). As before, failure to correct for biases in the projected temperatures overestimates the heat burden, although this has little impact on the cold burden (Fig. 5).

4. Discussion

Our results show that there is likely to be a sharp increase in heat-related mortality in future decades. Changes in future population structure specifically ageing has a significant contribution to the projected burden, and this contribution is greater than that resulting from changes in temperature alone. We demonstrate the importance of bias adjustment of climate projection data for use in health impact assessments. BC processed UKCP18 temperatures were the closest match to the observed temperatures, and SH processed data the furthest match. QM approach gave a similar projected mortality burden to BC despite not correcting for mean biases. In addition, bias correction had a greater impact on the projected heat burden compared to the cold-related burden. Recognising that no single bias correction method performs best under all circumstances, there is an argument for using several calibration approaches in parallel (Räisänen et al., 2013). However, there is presently no evidence on how various bias correction methods impact projected temperature-related deaths, our study is the first to report heat and cold mortality estimated using temperature projections (calibrated using three different methods) and contrasted against raw estimates.

Assuming a high-end emissions scenario and correcting for biases in the temperature projections using the BC approach, the annual UK heat-related mortality could rise from 2.5 per 100,000 people to 6 per 100,000 in the 2030s, 15.1 per 100,000 in the 2050s and 29.4 per 100,000 in 2070s. The burden at baseline matches what has been previously reported for the UK and Northern European countries in general (Hajat et al., 2014; Masselot et al., 2023), and is markedly lower than the heat-related mortality reported in countries located in the Western, Eastern and Southern parts of Europe (Masselot et al., 2023). The projected burden is a greater increase than what other previous UK studies

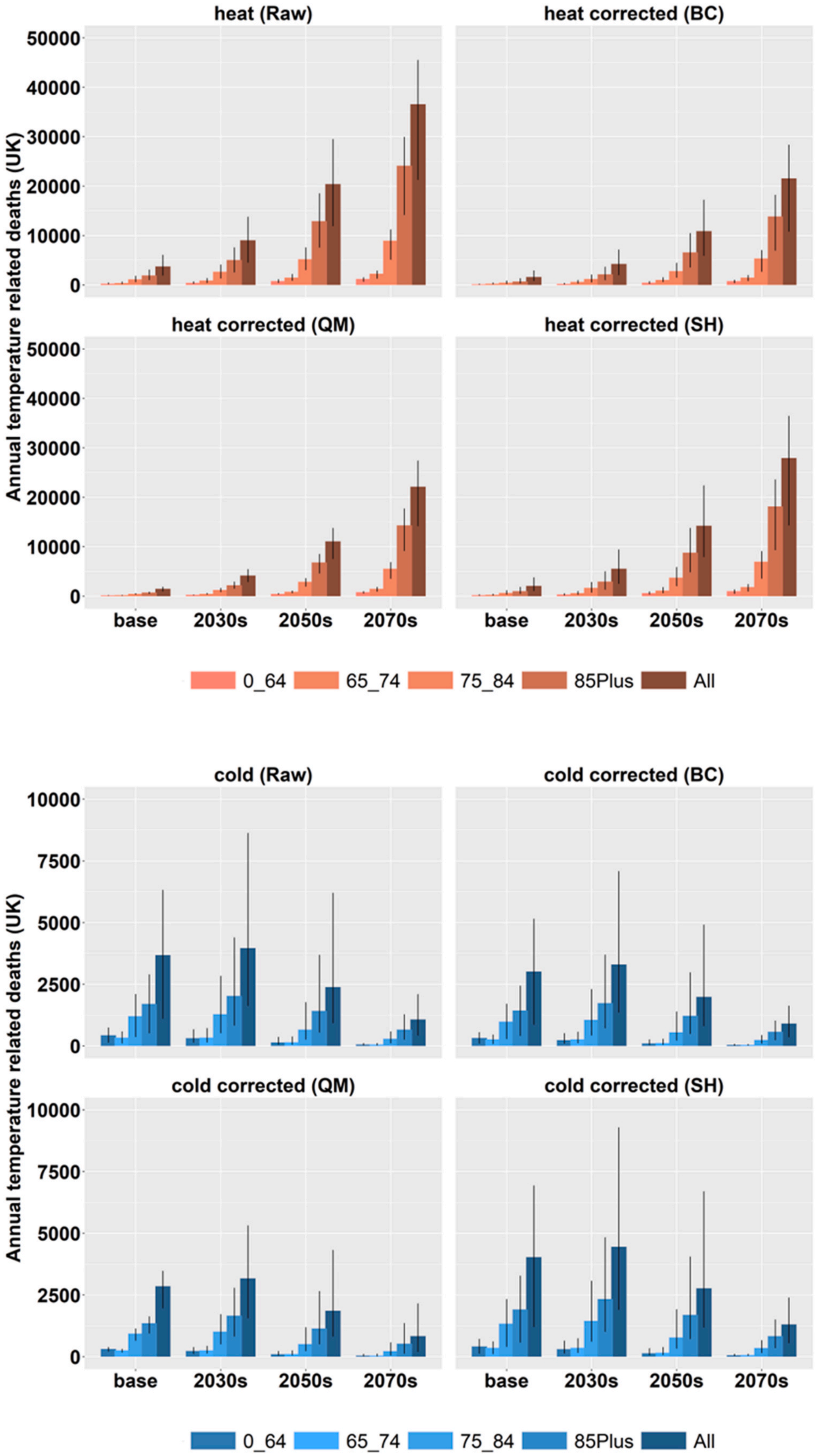

Fig. 4. UK age-specific annual heat and cold deaths, a comparison of raw and bias-corrected estimates using BC, SH and QM methods.

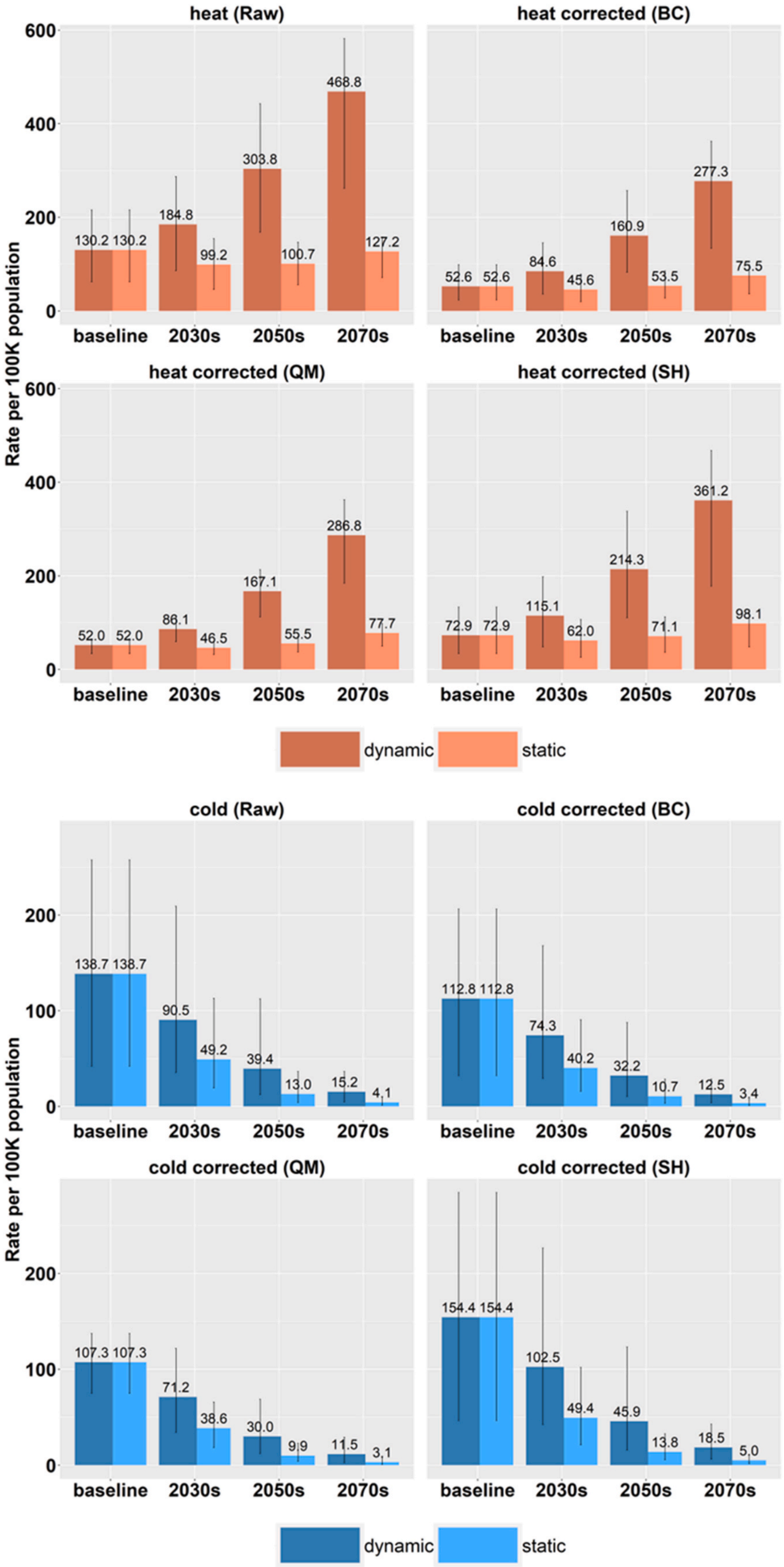

Fig. 5. Mortality rates for heat and cold (85 years plus only) at baseline and in future decades and comparing raw and bias correction estimates (BC, SH and QM). The lighter shade results are without population effect (no population growth and no ageing) and the darker shade are for a dynamic population.

have reported (Hajat et al., 2014), the differences may be attributed to our revised methodology and updated revised exposure-response relationships. We also found that mortality from extreme cold will peak in the 2030s before declining by the 2050s. Our estimates for cold-related mortality are much lower than previous estimates (Hajat et al., 2014) partly due to where the cold threshold is set; we quantified burden from cold by estimating deaths that occur at or below the 9th percentile, as opposed to the 60th percentile where there is more evidence for a causal association (Arbuthnott et al., 2018).

The highest heat and cold mortality burden in the oldest age groups is similar to findings from other studies (Hajat et al., 2014) and is driven by increased mortality risk in this population (Supplementary Table 1). We also found regional variations in risk, with the London region showing significantly greater mortality risks from both heat and cold. The higher heat effect observed in London has been reported before and may be related to the impact of urban heat islands where there is greater heat retention in more built-up areas (Hajat et al., 2007). The higher cold effect may be related to deprivation, housing quality and methodological differences in assigning the cold threshold.

In the UK, the number of people aged 85 and older will increase threefold from the baseline period of 2007–2018 to mid 2070s. Comparing 2018 to 2075, the overall population is projected to grow by nearly 20% and by over 200% in the 85 years plus group. Supplementary Fig. 2 shows an increasingly ageing population, the proportion of those aged 0–64 years is projected to decline, and the oldest group is projected to grow in the future decades. Population ageing will contribute to increases in the total number of heat-related deaths but will diminish projected declines in cold-related deaths. Taking into account future population changes and higher future temperatures (BC corrected temperatures), the mortality rate from heat is estimated to change from a current baseline of 53 deaths for every 100,000 to an estimated 277 deaths for every 100,000 in the 2070s, in contrast, if we assume no changes in the population structure and higher future temperatures, the mortality rate from heat is estimated as 75 deaths for every 100,000 in the 2070s.

This study has several strengths, firstly, we use the latest suit of bespoke climate projections for the UK (UKCP18) and apply population-weighting to estimate future likely temperature exposure across all 12 ensemble members of the model simulation. Secondly, we use exposure-response coefficients that span a more recent baseline period (2007–2018) and examine the effect of including population ageing and population growth on future burden, compared against the impact of temperature changes alone. The study makes a substantial contribution to the current evidence, by comparing the impact of three approaches to calibrating temperature data and reporting the results on the impact of this correction on the estimated mortality burden across decades and UK regions.

There are some limitations to consider when interpreting these results. Exposure-response coefficients, regional temperature thresholds and baseline mortality rates were held constant over the future decades. However, all these parameters are likely to be affected by future changes in socioeconomic and environmental factors, though they are currently difficult to project robustly. Furthermore, it is highly likely that as temperatures rise, populations adapt to higher temperatures to some extent (through behavioural changes) (Arbuthnott et al., 2016; Gosling et al., 2017) but we did not incorporate population adaptation in this analysis as this is difficult to quantify in the absence of a universally agreed methodology and little empirical data linking adaptation methods and health impacts (Cordiner et al., 2024). Another limitation is that our estimates are based on a high emissions and unlikely scenario (RCP8.5), this was the only scenario available with an appropriate resolution for health impact studies in the UK. We did not control for the potential confounding effect of air pollution and relative humidity as previous studies observed little confounding effect of either (Hajat et al., 2014; Armstrong et al., 2011).

In summary, the BC method of correction was the most robust as it corrects for both mean bias between the historical observations and projections, as well as the variation between climate models. The QM method also performed relatively well as it improved the variability by correcting for extreme values. We show that the application of raw uncalibrated temperature projections in impact assessments may substantially overestimate the predicted future heat related. Bias correction should be an important consideration during health impact assessments, on par with other sources of uncertainties including consideration of population changes and future adaptation and assigning of temperature thresholds. Future studies should focus on modelling the effect of adaption to increasing temperatures, characterising the impact of vulnerable groups (not only in relation to age) and estimating the impact of cascading and compounding risks, that include other climate hazards related to droughts, wildfires, flood risks and others.

Funder information

This study is funded by the National Institute for Health and Care Research (NIHR) Health Protection Research Unit in Environmental Change and Health (NIHR, 200909), a partnership between the UK Health Security Agency and between UKHSA and the London School of Hygiene and Tropical Medicine (LSHTM), in collaboration with University College London and the Met Office. The views expressed are those of the author(s) and not necessarily those of the NIHR, UK Health Security Agency, London School of Hygiene and Tropical Medicine, University College London, the Met Office or the Department of Health and Social Care. NF is funded by the European Union's Horizon 2020 research and innovation programme under the Marie Sklodowska-Curie grant agreement No. 846824, and by the Oxford OPEN Fellowships.

CRediT authorship contribution statement

Peninah Murage: Writing – review & editing, Writing – original draft, Visualization, Resources, Methodology, Formal analysis, Conceptualization. **Helen L. Macintyre:** Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Conceptualization. **Clare Heaviside:** Writing – review & editing, Methodology, Conceptualization. **Sotiris Vardoulakis:** Writing – review & editing, Methodology, Conceptualization. **Neven Fučkar:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis. **Ruksana H. Rimi:** Writing – review & editing, Methodology, Formal analysis. **Shakoor Hajat:** Writing – review & editing, Supervision, Resources, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envres.2024.119565.

References

Arbuthnott, K., Hajat, S., Heaviside, C., Vardoulakis, S., 2016. Changes in population susceptibility to heat and cold over time: assessing adaptation to climate change. Environ. Heal. 15, S33.

Arbuthnott, K., Hajat, S., Heaviside, C., Vardoulakis, S., 2018. What is cold-related mortality? A multi-disciplinary perspective to inform climate change impact assessments. Environ. Int. 121, 119–129.

Armstrong, B., 2006. Models for the relationship between ambient temperature and daily mortality. Epidemiology 17, 624–631.

Armstrong, B.G., et al., 2011. Association of mortality with high temperatures in a temperate climate: England and Wales. J. Epidemiol. Community Health 65, 340–345.

Chen, K., et al., 2024. Impact of population aging on future temperature-related mortality at different global warming levels. Nat. Commun. 15, 1796.

Cordiner, R., Wan, K., Hajat, S., Macintyre, H.L., 2024. Accounting for adaptation when projecting climate change impacts on health: a review of temperature-related health impacts. Environ. Int. 188, 108761.

Ebi, K.L., et al., 2021. Hot weather and heat extremes: health risks. Lancet 398, 698–708.

Fung, F., 2018. How to Bias Correct, UKCP18 Guidance. https://www.metoffice.gov.uk/binaries/content/assets/metofficegovuk/pdf/research/ukcp/ukcp18-guidance—how-to-bias-correct.pdf.

Gasparrini, A., 2021. Distributed lag linear and non-linear models for time series data. https://cran.r-project.org/web/packages/dlnm/vignettes/dlnmTS.pdf.

Gasparrini, A., et al., 2015. Mortality risk attributable to high and low ambient temperature: a multicountry observational study. Lancet 386, 369–375.

Gohar, L.K., Lowe, J.A., Bernie, D., 2017. The impact of bias correction and model selection on passing temperature thresholds. J. Geophys. Res. Atmos. 122 (12), 045-12,061.

Gómez-Acebo, I., Llorca, J., Dierssen, T., 2013. Cold-related mortality due to cardiovascular diseases, respiratory diseases and cancer: a case-crossover study. Publ. Health 127, 252–258.

Gosling, S.N., et al., 2017. Adaptation to climate change: a comparative analysis of modeling methods for heat-related mortality. Environ. Health Perspect. 125, 087008.

Hajat, S., 2017. Health effects of milder winters: a review of evidence from the United Kingdom. Environ. Heal. 16, 109.

Hajat, S., Kovats, R.S., Lachowycz, K., 2007. Heat-related and cold-related deaths in England and Wales: who is at risk? Occup. Environ. Med. 64, 93–100.

Hajat, S., Vardoulakis, S., Heaviside, C., Eggen, B., 2014. Climate change effects on human health: projections of temperature-related mortality for the UK during the 2020s, 2050s and 2080s. J. Epidemiol. Community Health 68, 641–648.

Hawkins, E., Osborne, T.M., Ho, C.K., Challinor, A.J., 2013. Calibration and bias correction of climate projections for crop modelling: an idealised case study over Europe. Agric. For. Meteorol. 170, 19–31.

Health and Safety Laboratory, 2020. National population database. National Population Database Tool.

Ho, C.K., Stephenson, D.B., Collins, M., Ferro, C.A.T., Brown, S.J., 2012. Calibration strategies: a source of additional uncertainty in climate change projections. Bull. Am. Meteorol. Soc. 93, 21–26.

Hollis, D., McCarthy, M., Kendon, M., Legg, T., Simpson, I., 2019. HadUK-Grid—a new UK dataset of gridded climate observations. Geosci. Data J. 6, 151–159.

Jenkins, K., Kennedy-Asser, A., Andrews, O., Lo, Y.T.E., 2022. Updated projections of UK heat-related mortality using policy-relevant global warming levels and socio-economic scenarios. Environ. Res. Lett. 17, 114036.

Karwat, A., Franzke, C.L.E., 2021. Future projections of heat mortality risk for major European cities. Weather. Clim. Soc. https://doi.org/10.1175/WCAS-D-20-0142.1.

Kendon, M., et al., 2022. State of the UK climate 2021. Int. J. Climatol. 42, 1–80.

Kovats, S., Brisley, R., 2021. Health, communities and the built environment. In: Betts, R., Haward, A., Pearson, K.V. (Eds.), The Third UK Climate Change Risk Assessment Technical Report. Climate Change Committee.

Lowe, J., et al., 2018. UKCP18 science overview report. https://www.metoffice.gov.uk/pub/data/weather/uk/ukcp18/science-reports/UKCP18-Overview-report.pdf.

Macintyre, H.L., et al., 2023. Chapter 2. Temperature effects on mortality in a changing climate. In: Health Effects of Climate Change (HECC) in the UK.

Maraun, D., Widmann, M., 2018. Statistical Downscaling and Bias Correction for Climate Research. Cambridge University Press.

Masselot, P., et al., 2023. Excess mortality attributed to heat and cold: a health impact assessment study in 854 cities in Europe. Lancet Planet. Health 7, e271–e281.

Murphy, J., Harris, G., Sexton, D., Kendon, E., Bett, P., 2018. UKCP18 Land Projections: Science Report.

Qian, W., Chang, H.H., 2021. Projecting health impacts of future temperature: a comparison of quantile-mapping bias-correction methods. Int. J. Environ. Res. Publ. Health 18, 1992.

Räisänen, J., Räty, O., 2013. Projections of daily mean temperature variability in the future: cross-validation tests with ENSEMBLES regional climate simulations. Clim. Dynam. 41, 1553–1568.

Reis, S., et al., 2017. UK gridded population 2011 based on census 2011 and land cover map 2015. https://doi.org/10.5285/0995e94d-6d42-40c1-8ed4-5090d82471e1.

Sanderson, M., Arbuthnott, K., Kovats, S., Hajat, S., Falloon, P., 2017. The use of climate information to estimate future mortality from high ambient temperature: a systematic literature review. PLoS One 12, e0180369.

Vardoulakis, S., et al., 2014. Comparative assessment of the effects of climate change on heat- and cold-related mortality in the United Kingdom and Australia. Environ. Health Perspect. 122, 1285–1292.