UK Health
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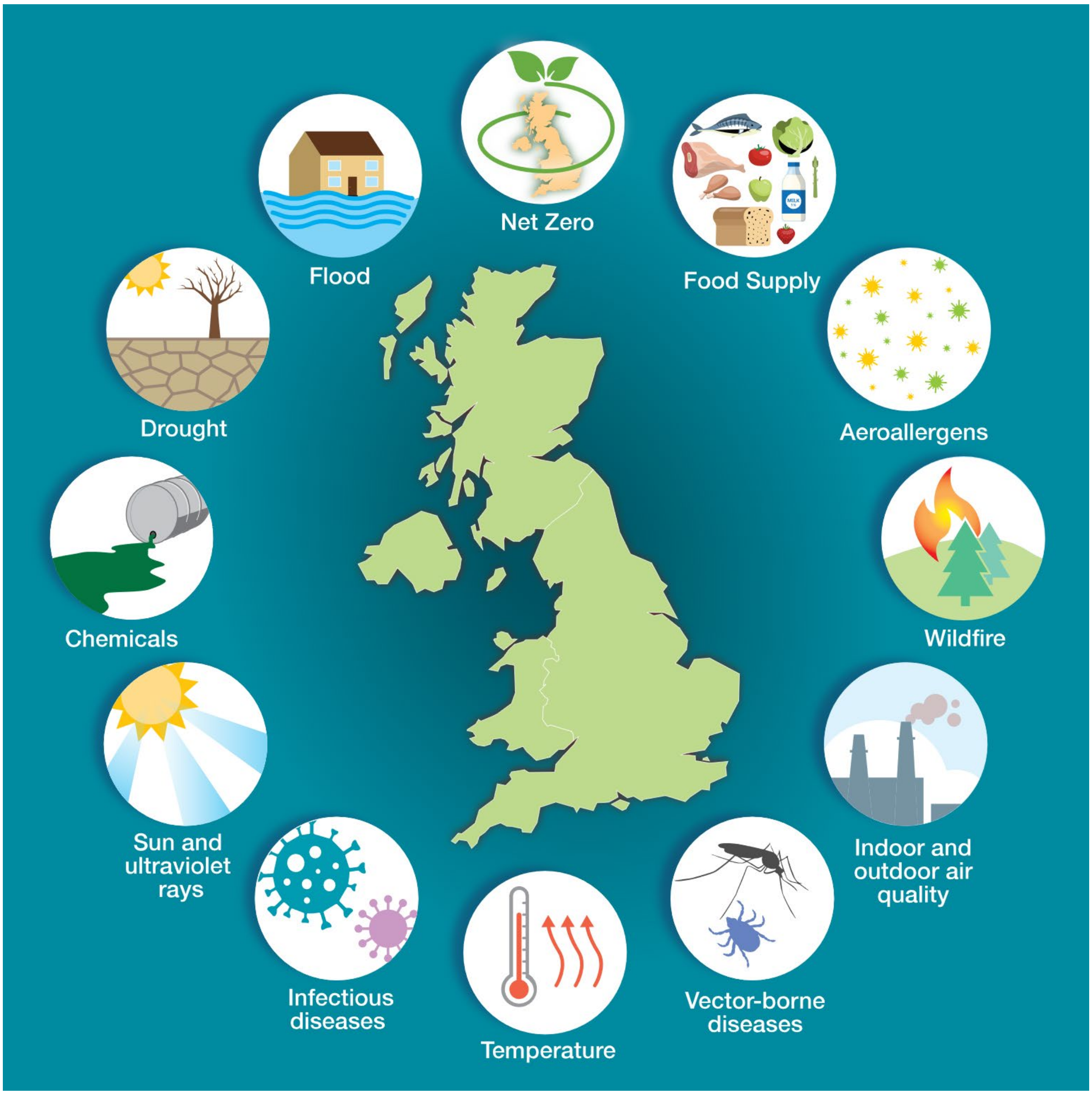
Health Effects of Climate Change (HECC) in the UK: 2023 report

Chapter 2. Temperature effects on mortality in a changing climate



Summary

Exposure to high or low temperatures during periods of hot and cold weather can have negative impacts on human health, and can lead to increased hospitalisations and deaths. Temperatures across the UK are increasing, with the most recent decade being the warmest period since records began, and temperatures over 40°C recorded for the first time ever in the 2022 July heatwave.

This chapter presents new empirical analyses to estimate the likely impacts of changing climate on future temperature-related mortality in the UK. This work was conducted by the UKHSA in partnership with academic experts in temperature-health modelling at the London School of Hygiene and Tropical Medicine, University of St Andrews, University of Oxford, University College London and Australia National University. These new analyses use updated climate projections and epidemiological methods to estimate mortality associated with heat and cold across the UK up to the 2070s.

Notably, these estimates are not predictions of what will happen in the future, but rather projected scenarios of what could happen in the absence of mitigation and adaptation to climate change. They provide a snapshot of a worst-case scenario in which climate warming continues with no efforts of global decarbonisation and no additional adaptation. While this scenario is hopefully unlikely, it does give an indication of the scale of the potential impact of heat on the UK's health without further intervention. The authors use this high end warming scenario – not complemented by lower warming scenarios – as it is the only one available at sufficient resolution to conduct a health impact assessment. Access to additional scenarios is needed to estimate how health will be impacted by different levels of warming. Inclusion of adaptation in models is also a priority for further research to assess different combinations of adaptation and mitigation options. Extreme temperatures have a range of impacts on health, not just on mortallity. The chapter focuses exclusively on mortality, excluding the wider effects of heat on chronic illness, mental health, injury, and other non-fatal outcomes, as the strongest epidemiological links are evident between extreme temperatures and mortality.

The evidence presented in this chapter indicates that, without adaptation, heat and cold-related deaths are projected to increase in the UK due to a combination of climate change and sociodemographic factors. Mortality risk due to heat and cold increases with age. In the future, therefore, although we expect fewer very cold days in the UK, mortality due to moderate cold is actually projected to increase as we have an ageing population. Heat-related deaths – with no additional adaptation and limited global decarbonisation – could increase nearly 6-fold from a 2007 to 2018 baseline average estimate of 1,602 deaths per year, to 10,889 in the 2050s. We can expect both heat- and cold-related deaths to rise until the second half of the century when cold-related deaths would begin to fall. In the first half of the century, cold-related deaths will continue to dominate, despite increasing heat risks, with heat-related mortality increasing over time. These estimates, based on a reasonable worst-case scenario, demonstrate how rising

temperature combined with an ageing population could drive increasing mortality due to heat in the UK in the absence of decarbonisation and adaptation measures.

Public health interventions and wider adaptations can have a major impact in reducing temperature-related risks to health. There is good evidence to support adaptations to 'break-the-link' between temperature and health risks to minimise health harms due to heat and cold. The data in this chapter highlight 3 key insights for public health. Firstly, the greatest driver of both heat- and cold-related deaths in the UK is the vulnerability of older adults to extreme tempertaures. Protecting older adults during cold and hot weather periods, including considering the social determinents of vulnerability, is thus a key lever for minimising health risks. Secondly, while cold-related health risks will continue, heat-related health risks will increase, potentially substantially. Temperatures that may cause inconvenience for most healthy adults can pose a significant health risk to individuals with chronic health conditions and older adults. Interventions should consider populations most susceptible to temperature-related health risk. Thirdly, evidence of substantial variation in geographical and social vulnerability to heat and cold highlights the extent to which there is scope for interventions to be targetted to improve the resillience of places and communities, to protect people most likely to be adversely affected by extreme temperatures.

Interventions to protect health from heat and cold include behavioural changes, national heat and cold alert systems, improvement to housing including energy efficiency measures and shading, and increasing availability of greenspace. Public health authorities should help raise awareness of protective behaviours and interventions, including social determinents of vulnerability such as social connections, in supporting resillience to extreme temperatures, and prioritising those at highest-risk as well as considering the general population. Health and social care also play a role by ensuring mechanisms exist to identify at-risk people, as well as ensuring adequate plans are in place across health and social care settings, and for at-risk individuals. Similarly, environments such as schools, prisons, workplaces and public transport represent spaces where people are exposed to heat and cold and where intervention measures could be targeted to minimise health risks. The substantial variations in impacts of temperature on health highlight the importance of explicitly addressing inequalities when developing and implementing interventions.

The work presented in this chapter demonstrates several important research gaps and priorities, including the need to:

- develop and evaluate adaptation measures, including quantifying health and associated economic impacts
- generate or access higher resolution climate data to support health impact assessment at a range of warming levels
- estimate heat and cold-related mortality across the UK under a range of scenarios that combine different levels of warming and adaptation

- estimate and project heat and cold impacts on morbidity, including chronic diseases and mental health. Future models should also consider premature mortality as years of life lost (YLL) or other health outcome metrics
- improve our understanding, quantitatively and qualitatively, of the drivers of physiological and sociodemographic vulnerability to heat and cold among individuals, households, communities and geographical regions
- undertake comparative (between communities and regions and over time) studies of mechanisms driving vulnerability to temperature, and changes to the temperature-health link over time
- assess interventions targeted at the most at-risk populations to understand barriers to behavioural change and to up-take of interventions, including consideration of equity and social gradients in health risk

In response to evidence that early warning systems have one of the highest cost-benefit ratios of population level interventions in protecting health from adverse weather events, UKHSA launched the 'Adverse Weather and Health Plan (AWHP)' for England in April 2023. The AWHP outlines areas where different sectors (including public, independent, voluntary, health and social care organisations and local communities) can work together to maintain and improve integrated arrangements for planning and response to deliver the best outcomes possible during adverse weather. In June 2023, UKHSA launched an impact-based Weather-Health Alerting system in collaboration with the Met Office. The aim of the move towards impact-based alerting is to provide information on the expected impacts of adverse weather conditions on the health of the population and delivery of health and social care services. Impact-based alerting allows users to understand the likely impacts expected and use that information to make informed decisions about actions they should take.

Contents

Chapter 2. Temperature effects on mortality in a changing climate

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1. Background

1.1 Summary of past 3 reports

In the first ‘Health Effects of Climate Change (HECC)’ report published in 2002, current and future temperature-related mortality was analysed at UK-level only, estimating a 253% increase in heat-related deaths (1,995 additional deaths) by the 2050s and a decrease in cold-related deaths of 25% (20,292 fewer) for a medium-high emission scenario (1). For the second HECC report in 2008, historical periods were analysed, suggesting that health effects of consecutive days of heat are greater than separate individual days, and there may be population adaptation to changing temperatures in the future, but future changes in mortality were not estimated explicitly (2). In the most recent report in 2012, Hajat and colleagues conducted analysis of heat- and cold-related mortality at the regional level in England using UK-focused climate projection data from the UK Met Office (UKCP09) for the 2020s, 2050s and 2080s (3). Heat-related deaths were estimated to rise by 257% by the 2050s for the UK as a whole, with the increase partly driven by population growth and ageing (3, 4). As with the previous reports, specific adaptation actions and interventions were not modelled in future estimates of heat and cold mortality. Although projections of future UK population growth were incorporated by including expected size and age breakdown in future decades, it was assumed the population had not adapted to the effects of heat and cold over time (3, 4).

1.2 State of the current science, and chapter aims and objectives

An adverse effect of both high and low temperatures on mortality is observed in most populations, including in UK settings (4 to 7). Heatwave mortality monitoring reports produced by UKHSA (and Public Health England (PHE) prior to 2021) suggest that between 778 and 2,244 excess deaths occurred in the 65 years and older age group each summer in England between 2016 to 2021, with an estimated 2,985 for the summer of 2022 when temperatures in England reached 40°C for the first time since records began (8, 9). Negative health impacts are found to increase beyond certain temperature thresholds. There are separate thresholds for heat and cold effects which can vary by location, and factors like local climate conditions and degree of adaptation, which can depend on population characteristics, behavioural adaptations, and the built environment (7, 10). Mortality from many causes can be affected by ambient temperature, with the highest deaths attributed to respiratory and cardiovascular diseases (11, 12). In the UK, risks from heat and cold vary across the population, with the highest risk of temperature-related mortality found in older populations, those with certain comorbidities and those residing in care homes, with limited or suggestive evidence for other individual-level factors such as education, race, marital status, occupation, and place of death (13, 14). Geographical variations in risk are apparent, and those living in Greater London have been shown to have the highest risk of heat mortality (13, 15), with cold risk also being higher in

London as well as the North West and North East regions (16). There is evidence of direct effects of temperature on morbidity outcomes such as emergency hospital admissions and accident and emergency attendances for cardiac, respiratory, cerebrovascular, and psychiatric conditions (17 to 19). High ambient temperatures have been associated with mental health effects, including increased suicide risk, though knowledge gaps remain (20). Previous assessments of future heat-related health impacts under different climate change scenarios report that heat-related deaths are expected to increase due to higher temperatures, with some studies demonstrating that an increase in the number of older people will also amplify mortality burdens. However, key gaps in knowledge remain in relation to how urbanisation, population ageing and adaptation to increasing temperatures will affect health impacts and burdens, and also in relation to current and future strategies for effective, sustainable, and equitable adaptation to changing temperatures.

1.3 Advances made by this report

In this assessment, the most recent climate projection data for the UK (UKCP18, produced by the UK Met Office and described in Chapter 1 of this report) were used. Recent historical temperature data sets and the most recent mortality data available (including data from Scotland for the first time), were used to perform an updated epidemiological analysis to derive up-to-date risk functions for heat and cold effects on mortality. These risk functions were then combined with the UKCP18 daily temperature projection data, as well as population projection data, to estimate mortality burden into the future. This analysis also includes bias correction (BC) of the raw climate projection data in line with recommendations from the Met Office. The role of adaption in reducing future temperature-related health burdens is briefly discussed, and key considerations and priorities are highlighted.

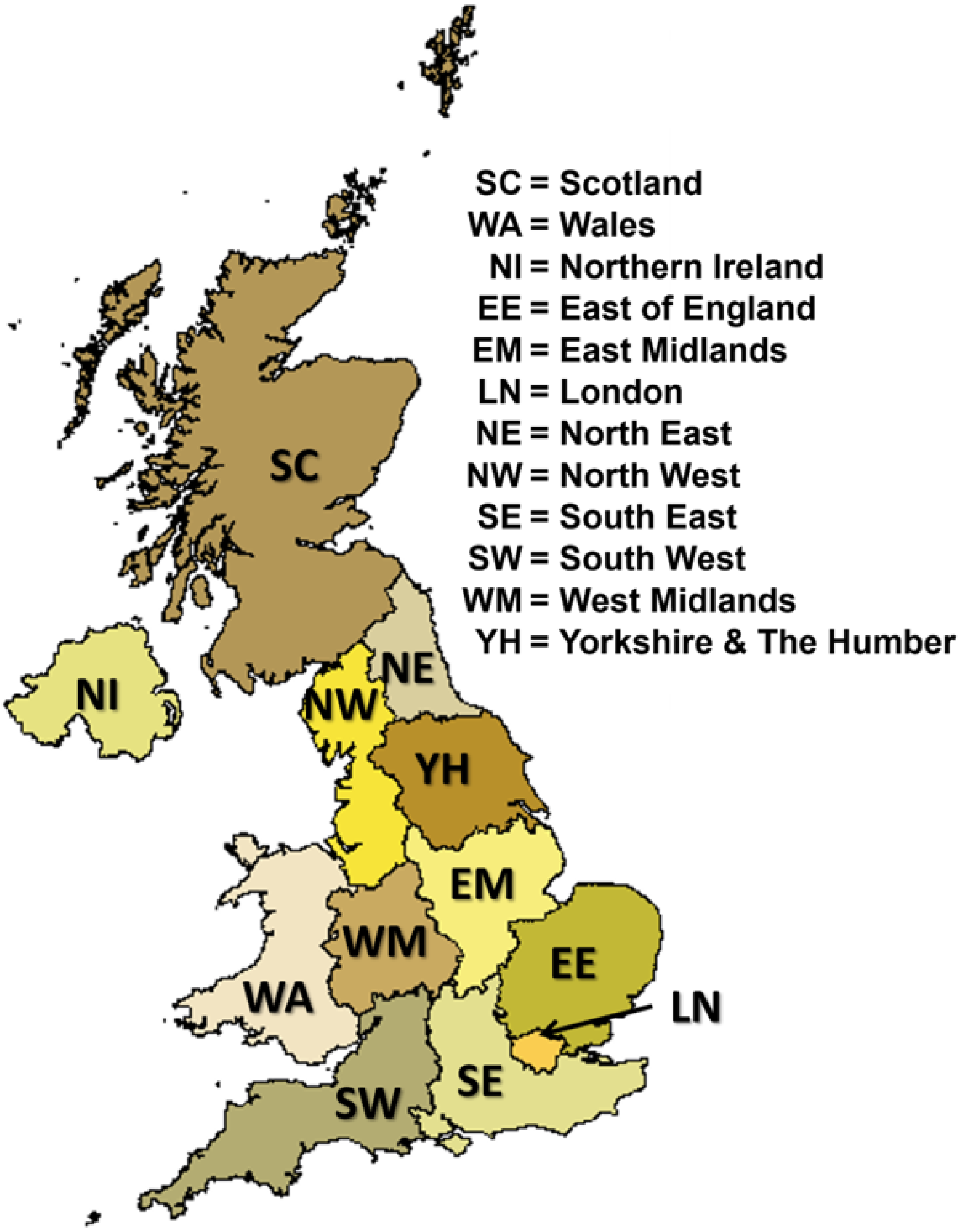
2. Data and methods

2.1 Epidemiological analysis

The relationship between ambient temperature and mortality was analysed using historical data. Data on daily mortality between 2007 and 2018 were obtained for the 9 regions in England, and Wales and Scotland (Figure 1), and converted to separate daily time series format for all-causes and age-specific series for the following age groups: 0 to 64 years, 65 to 74, 75 to 84 and 85 years and older. Mortality records from Northern Ireland were not available and so rates from the North West region in England were used as a proxy. Impacts on morbidity (for example, hospital admissions) were not assessed.

Daily ambient temperature data for the same period were obtained from the HadUK-grid data set, derived from UK surface observations from weather stations interpolated to a uniform grid to match the UKCP18 projections model resolution (12km) (21, 22). At daily time resolution, only maximum and minimum temperature data are available, so daily averages were generated by taking the mean of these. To estimate population exposure to ambient temperatures, the gridded temperature data sets (HadUK-grid observations) were population-weighted to provide a better approximation of temperature exposure by accounting for where people reside, to create regional population-weighted exposure estimates for the 9 regions in England, and for Scotland, Wales and Northern Ireland (Figure 1), using 100m gridded residential population information for England, Scotland and Wales (23), and at 1km for Northern Ireland from UK-CEH Environmental Information Data Centre (24).

Figure 1. Map of the regions in the UK used for the health impact assessment analysis



Time series, quasi-Poisson regression models were used to estimate historical temperature–mortality associations (based on the population-weighted HadUK-grid temperature data). The analysis was conducted in R, using the ‘dlnm’ (distributed lag non-linear model) package that simultaneously models the non-linear and delayed effects between temperature and mortality (25). The delayed effect represents temporal change in mortality after heat or cold exposure and estimates the distribution of immediate and delayed effects of temperature on health that accumulate across a specified time period (lags) (26). A lag of up to 3 days[1] was specified for heat effects and up to 28 days was specified for cold effects, based on evidence that heat impacts are mostly immediate, occurring very close to the day of exposure (27) whereas cold impacts can be distributed over a number of weeks following initial exposure (28). The

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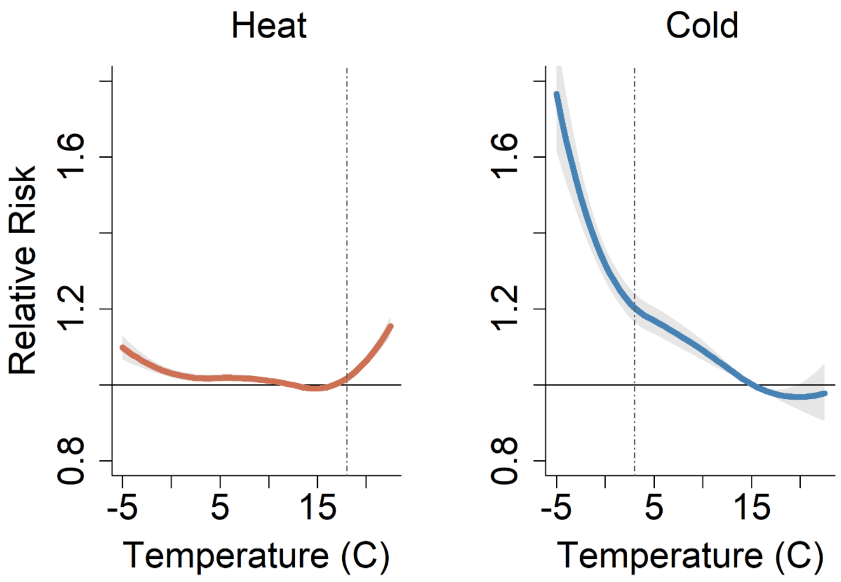
[1] Lags of up to 10 days were tested for heat and the differences in risk and exposure-response coefficients are negligible beyond 3 days.

temperature effects were estimated using a cross basis, and spline functions were used to flexibly model the relationship between temperature and mortality, and the lag-distribution. Detailed information of how the cross-basis operates within the dlnm package has been previously published (25, 29). The models were adjusted for seasonal variation and long-time term trend by fitting a natural cubic spline on the day of year and time variables, respectively, and an indicator for the day of the week. The temperature-mortality associations for each area were reported as relative risks (within a 95% confidence interval, CI), between 2 threshold temperatures using the temperature distribution of each region; mean UK risk was estimated from a random effects meta-analysis of the regional risks (regions as in Figure 1). The threshold for estimating heat impacts was defined at the 93rd percentile of the annual temperature distribution, in agreement with the literature for UK populations (15, 30). Thus, heat risk was quantified by comparing mortality risk at the 93rd and 99th temperature percentiles.

Defining a threshold for estimating cold effects is more challenging, and some studies maintain the need to separate the effects of ‘extreme’ and ‘moderate’ cold. Causal relationships have been confirmed at lower cold thresholds where there is greater certainty in the mechanisms of effect, although this carries the risk of under-estimating deaths attributable to cold (31). Some studies arbitrarily assign this lower threshold at the 2.5th temperature percentile to denote ‘extreme cold’ (29, 32, 33). In this analysis cold risk was estimated using 2 different temperature thresholds based on 2 points on the exposure-response curves for England, where mortality risk peaks and accelerates as temperatures drops (Figure 2). The extreme (lower) cold threshold was assigned at the 9th temperature percentile and a moderate (higher) one at the 60th temperature percentile. The cold effect was estimated by comparing mortality between each of these percentiles and the first temperature percentile. This analysis was repeated for each age-group per region considered in the analysis.

Figure 2. Exposure-response curves for heat- and cold-related risk at England level
Dashed lines mark the heat (93rd percentile) and extreme cold (ninth percentile) thresholds.



2.2 Risk assessment

2.2.1 Climate projections and bias correction

A quantitative health impact assessment (HIA) was conducted to estimate future temperature-related mortality burdens under climate change. The UKCP18 climate projections data from the UK Met Office represent the latest suite of climate projections bespoke to the UK (34). To estimate future mortality burdens associated with temperature effects, historical and future projected daily mean 2m air temperature data (at 12km horizontal grid resolution) of 12-member ensemble climate simulations forced by the historical (until 2014) and RCP8.5 scenarios (from 2015 onwards) were used. UKCP18 provides only the RCP8.5 scenario simulations with spatial and temporal resolution appropriate for a detailed health impact assessment (35), and therefore estimated impacts represent an estimate for a high emission 'worst-case' scenario.

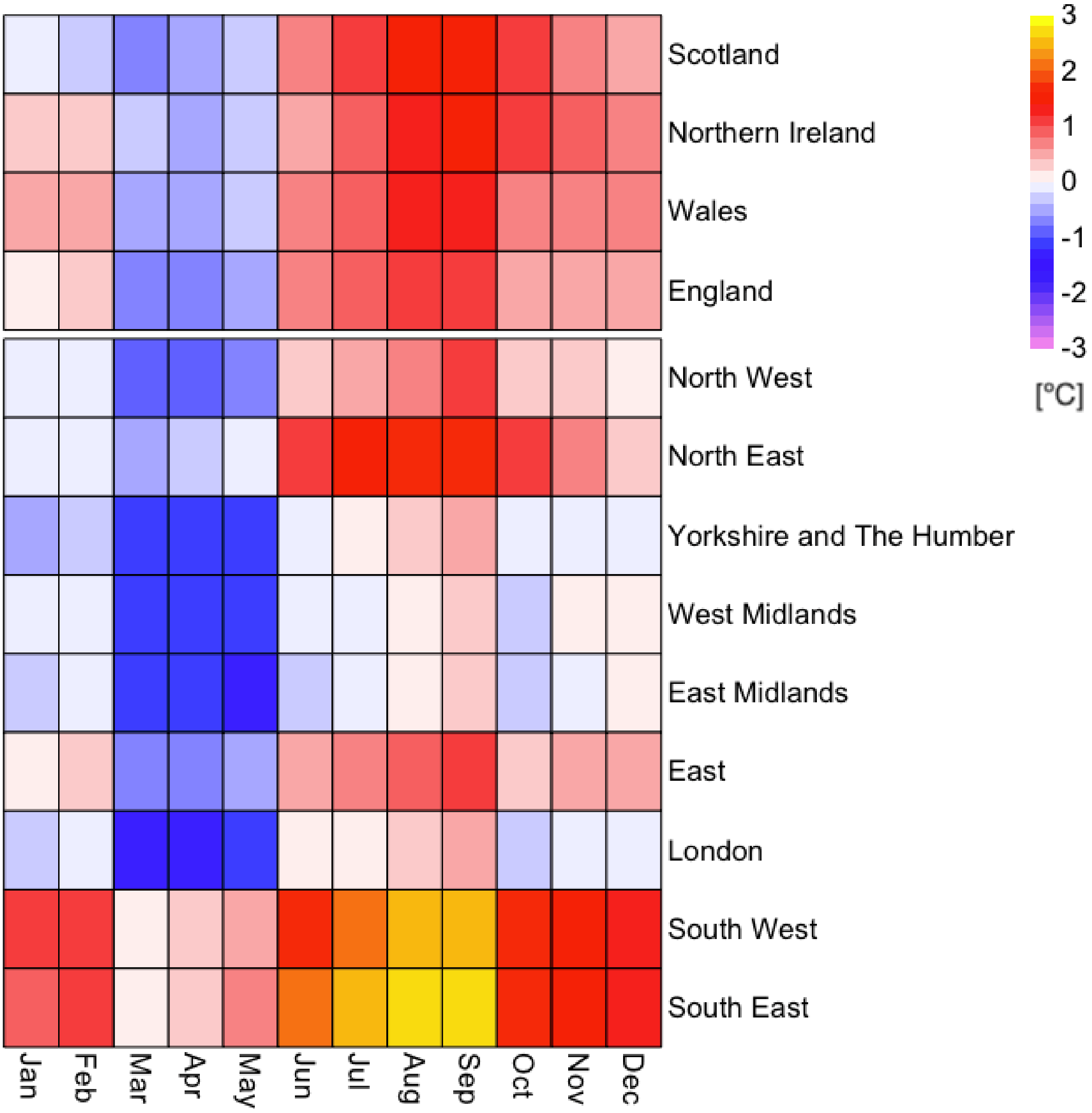
All climate models for practical applications are numerical approximations of the climate system at various levels of complexity and typically with multiple resolutions (36, 37). Hence, historical climate simulations will match observations or reanalysis products with different levels of accuracy depending on the variable, region and period of interest (38). Similarly, the quality of future climate projections depends on how specific variables and regions are susceptible to growth and compensation of systematic errors or biases in time (39, 40). Two calibration methods recommended by the UK Met Office for bias adjustment of population-weighted UKCP18 model simulation outputs were applied (41) to produce improved, and more accurate, future projections of population-weighted daily mean 2m air temperature.

For the bias correction, 39 years of population-weighted temperature observations from December 1980 to November 2019 were used as the reference period for the calibration of the future projections. First, a shift ('SH') method was applied that simply adjusts UKCP18 population-weighted daily means by the mean bias over the reference period separately for each region and calendar month, using the 12-member ensemble mean (42). Note that $T_{obs}(t) = [T_{obs}] + T'_{obs}(t)$, and $T_{raw}(t) = [T_{raw}] + T'_{raw}(t)$, where T_{obs} is observed temperature, and T_{raw} is raw (that is, original, unadjusted) UKCP18 temperature, while [x] denotes the mean value and x' denotes the anomaly from the mean value over the reference period. Hence, the SH method: $T_{SH}(t) = [T_{obs}] + T'_{raw}(t)$. However, due to inherent errors in climate models, besides a bias in the raw mean state, typically there is also a bias in variability of raw model simulations. Thus, a more complete bias correction method also takes into account a potential difference between the standard deviations of the observations $\boldsymbol{\sigma}(T_{obs})$ and the raw UKCP18 simulations $\boldsymbol{\sigma}(T_{raw})$ (for example (43, 44)). The BC method with respect to the SH method also includes rescaling of the raw UKCP18 anomalies to match the variability of the observations over the reference period: $T_{BC}(t) = [T_{obs}] + (\boldsymbol{\sigma}(T_{obs})/\boldsymbol{\sigma}(T_{raw}))\, T'_{raw}(t)$. Figure 3 shows the difference between the population-weighted 2m temperatures of the raw (uncorrected) projection and the observations (over the 1980 to 2019 period). Generally, there is considerable heterogeneity of biases in the UKCP18 raw projection (averaged over 12 ensemble members) across different calendar months and UK regions. Specifically, spring months are colder in the raw projections compared to observations in most of the UK regions, while summer months are mostly hotter (particularly South West and

South East – see 2 bottom rows in Figure 3). Taking London as an example, the raw projection model data in March, April and May is colder than the observations (indicated by dark blue colour in Figure 3), so applying bias correction leads to these being corrected ‘upward’ (warming) to match the observations, whereas in September the raw projection is slightly hotter than observations and will be corrected slightly ‘downward’ (cooling). The expanded Figure in Appendix A shows the improvements due to the application of the BC method (that adjusts both mean and variability) with respect to the SH method (that adjusts only mean) and the raw UKCP18 simulations.

Figure 3. Difference of the raw (uncorrected) UKCP18 simulated and the observed HadUK-grid populations-weighted mean 2m temperatures over the reference period for bias correction: December 1980 to November 2019

Each box shows regional and monthly mean bias averaged over all 12 ensemble members (see also expanded figure in Appendix A showing the reduced errors following application of the SH and BC methods).



Unless explicitly stated, the results presented used the population weighted UKCP18 daily 2m air temperature projections adjusted using the BC method described above.

2.2.2 Population projections and population contribution

The effects of a growing and ageing population were included in the analysis. Population projections were obtained from the Office for National Statistics (ONS) principal projections which reflect changes in the size and structure of the population expected to occur based on assumptions about future levels of fertility, mortality and migration. The projections cover a period of 100 years from 2018 and are available for the UK and its constituent countries (45). Sub-national (regional) projections for England are only available until the year 2043, and thereby regional projections for later decades were estimated by applying the 2018 regional population distributions to the England-wide projections between 2043 and 2080. Population data were aggregated by age group for the 3 decadal periods (2030s, 2050s and 2070s).

2.2.3 Health impact analysis

The heat- and cold-related deaths were estimated for the baseline period (2007 to 2018) and the future decades 2030 to 2039 (2030s), 2050 to 2059 (2050s) and 2070 to 2079 (2070s) using the regional exposure-response coefficients derived from the epidemiological analysis as described earlier in section 2.1. These were used together with baseline mortality rates for all-cause deaths by age-groups (based on the baseline rates during the historical period 2007 to 2018), and regional population projections (section 2.2.2) to conduct the health impact assessment (4). It was not possible to derive specific risk coefficients for Northern Ireland due to the lack of availability of mortality data for this area, and thus coefficients were derived based on mortality rates from the North West region used as a proxy. As per the previous report, exposure-response coefficients, regional temperature thresholds and baseline mortality rates in each region were held constant over the future decades. This has limitations as all these parameters are likely to be affected by future changes in socioeconomic and environmental factors. Furthermore, it is likely that the population may adapt to higher temperatures to some extent, but as this is challenging to quantify in a robust manner, this is not incorporate to the estimates here (46, 47).

The HIA was repeated across all 12 of the available ensemble members of the UKCP18 simulations and a mean was computed. The results are reported as mean annual burdens together with the maximum and minimum (indicated by the upper and lower bounds in Figures 5 to 7) of the ensemble range. Results are presented both with and without incorporating future changes in population size and structure across different age groups to determine the extent of the contribution of changes in the population structure to the estimated burdens, assuming no adaptation (exposure-response coefficients are held constant).

3. Results

3.1 Epidemiological analysis

Table 1 shows the population-weighted temperature distribution by region and UK countries for the historical period 2007 to 2018 (used for epidemiological analysis). London was the warmest region, registering a maximum population-weighted temperature of 26.8°C and the highest heat (19.2°C) and cold thresholds (3.8°C and 13.3°C for extreme and moderate cold respectively). The West Midlands had the lowest recorded population-weighted temperature (−7.4°C) but also one of the highest averaged population-weighted temperatures (24.2°C).

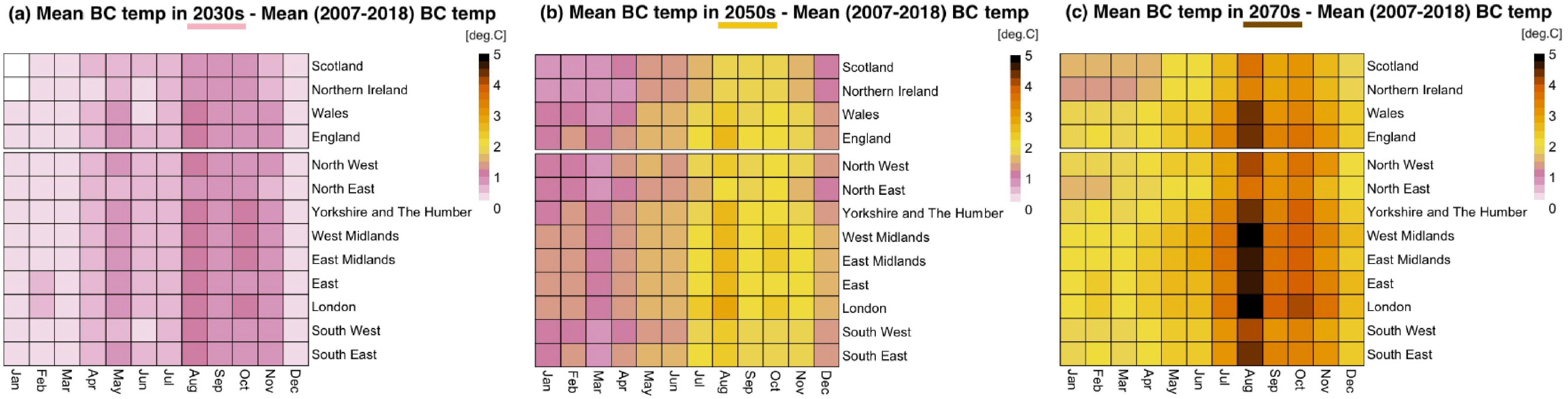
Figure 4 shows that under the RCP8.5 future emission ('worst-case') scenario there will be a universal increase in population-weighted 2m air temperature, with differences across seasons and regions, for example, the highest mean warming is seen in the summer months, particularly August, and London and West Midlands, which are projected to reach +5°C in August in the 2070s.

Table 1. Distribution of daily mean population-weighted temperature (°C) across the regions, showing values at first, ninth, 60th and 99th temperature percentiles between 2007 and 2018

Population-weighting temperatures provides better approximation of temperature exposure by considering where more people are located.

All values in °C	Minimum temperature	1st temperature percentile	9th temperature percentile	60th temperature percentile	93rd temperature percentile	99th temperature percentile	Maximum temperature
London	−3.7	−0.5	3.8	13.3	19.2	22.5	26.8
North East	−5.0	−0.9	2.4	10.0	14.7	17.0	19.1
North West	−5.9	−1.0	3.0	11.2	16.0	18.7	22.1
South East	−3.9	−0.9	2.7	10.6	15.4	18.0	21.5
South West	−3.8	−0.8	3.3	10.7	15.0	17.4	19.8
East Midlands	−6.7	−1.3	2.8	11.9	17.5	20.4	23.8
West Midlands	−7.4	−1.6	2.9	11.9	17.6	20.4	24.2
Yorkshire and the Humber	−6.0	−1.2	2.6	11.4	16.8	19.6	22.4
East of England	−5.4	−1.1	2.9	12.0	17.5	20.3	24.2
Wales	−5.0	−0.7	3.2	10.9	15.6	18.2	21.3
Scotland	−6.0	−1.5	2.0	9.2	13.5	15.7	18.8
Northern Ireland	−6.9	−0.5	2.9	10.0	14.3	16.3	18.9

Figure 4. Panels (a), (b), and (c) show differences for each region and month separately of populations-weighted mean 2m temperatures (bias corrected, BC method) in 2030s, 2050s, and 2070s, respectively, relative to the 2007 to 2018 baseline period (with available mortality data for epidemiological analysis)



(a) Mean BC temp in 2030s - Mean (2007-2018) BC temp

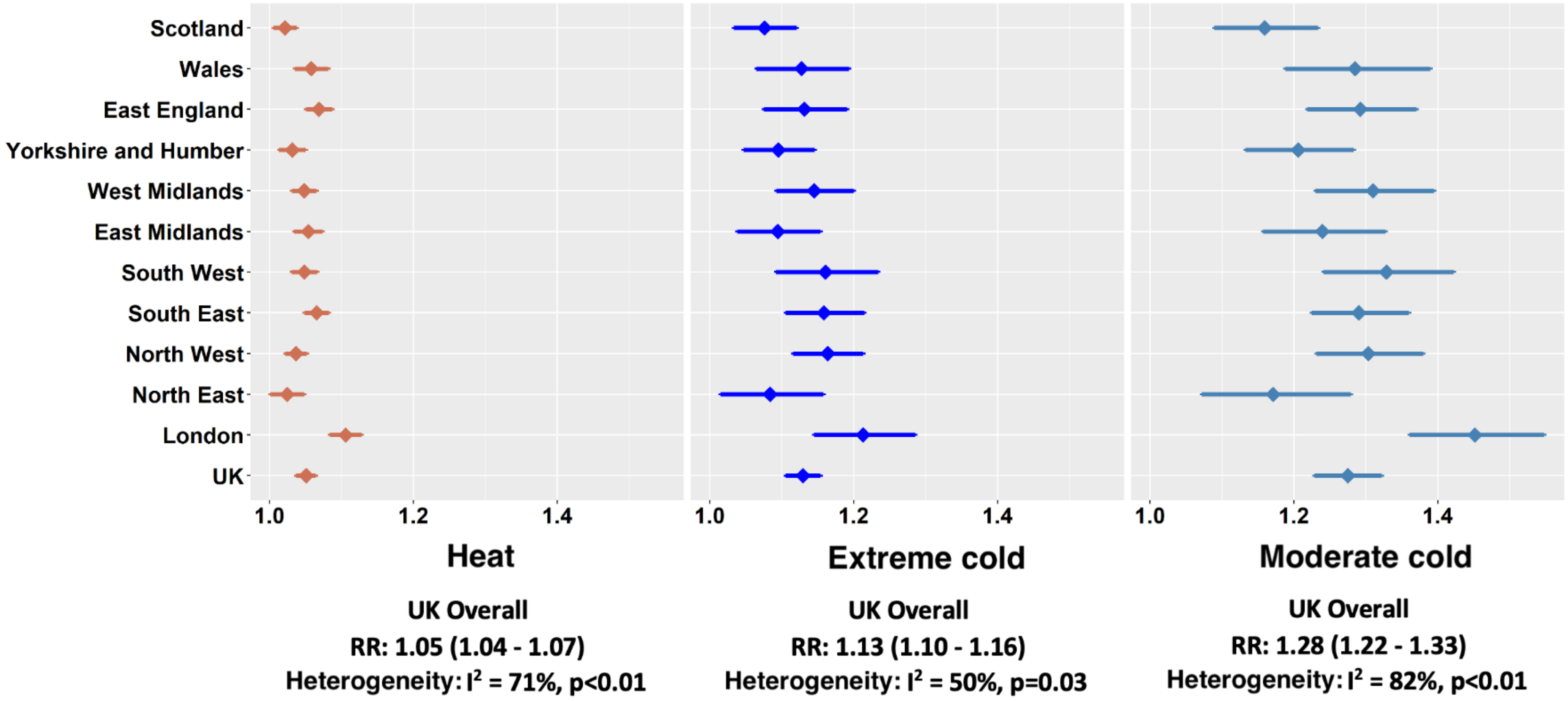
(b) Mean BC temp in 2050s - Mean (2007-2018) BC temp

(c) Mean BC temp in 2070s - Mean (2007-2018) BC temp

All regions saw a statistically significant increase in mortality risk (relative risk, RR) associated with both heat and cold exposure (RR >1). The London region had the highest heat risk (RR 1.11, 95% CI: 1.08 to 1.13, all-ages), and this was significantly greater than heat risk across all the other regions (Figure 5). Across all regions, cold carried a greater mortality risk than heat, with the London region again having the greatest risk (Figure 5). Modelling cold effects using the extreme (lower) temperature threshold (9th percentile) resulted in lower cold-related mortality risk across all the regions; for London this corresponded to a RR of 1.21 (95% CI: 1.15 to 1.29, all-ages) in comparison to cold mortality risk using the moderate (higher) threshold (60th percentile) with RR of 1.45 (95% CI: 1.36 to 1.55, all-ages). Age-specific heat and cold risks are reported in Appendix B. In general, heat and cold risk increases with age, with the greatest heat risk in those aged 85 years and older.

Figure 5. All-ages temperature-mortality effect for all of UK, England (regions), Wales and Scotland presented as relative risk, RR (95% CI), where RR=1 equates to no effect

Cold effect was modelled by comparing mortality risk between the first and 60th temperature percentiles (moderate cold threshold), and first and ninth temperature percentile (extreme cold threshold). Heat effect was modelled by comparing mortality between the 93rd and 99th temperature percentiles. To demonstrate, for heat the RR in London is 1.11, corresponding to an 11% increase in risk of mortality at the 99th temperature percentile (22.5°C, see Table 1) compared to the 93rd percentile (19.2°C). For heat, UK overall RR is 1.05 (95% CI: 1.04 to 1.07). The I-statistic (I2) shows the total variation in the risk estimates that is due to true regional differences rather than due to chance, a larger I2 suggests the variations are due to true differences. For heat, UK overall RR is 1.05 (95% CI: 1.04 to 1.07), I2=71%, p<0.01; for moderate cold, UK overall RR is 1.13 (95% CI: 1.10 to 1.16), I2=50%, p=0.03; for extreme cold UK overall RR is 1.28 (95% CI: 1.22 to 1.33), I2=82%, p<0.01.



3.2 Projecting future mortality burden

Heat-related deaths are projected to increase in future decades to just over 21,000 in the 2070s (Figure 5), assuming a high end ‘worst-case’ emissions scenario, population ageing and growth, and no future adaptation. Cold-related deaths are also projected to increase for a period before declining, with deaths from extreme cold declining by the mid-century and deaths from moderate cold peaking around the same time and seeing a decline by the 2070s (Figure 6).

Despite the projected increase in heat-related mortality across all decades, cold will continue to present a substantial mortality burden, although this is heavily dependent on how cold-related mortality is defined and quantified, as the choice of cold threshold (moderate versus extreme) has significant implications on the total estimated cold-related burden (Figure 6). Projected mortality is significantly lower when an extreme (lower) threshold is assigned (9th temperature percentile compared to 60th). The threshold varies by region (highest in London at 3.8°C and lowest in Scotland at 2°C, Table 1), with the assumption that deaths are attributable to the effects of cold only on days where ambient temperature occurs at or below these temperatures. In comparison, the moderate (higher) cold threshold (60th percentile) assumes cold deaths occur at or below 13.3°C and 9.2°C in London and Scotland, respectively (Table 1). Assigning a lower cold threshold when modelling cold-related mortality likely captures mortality that is directly linked to extreme cold (31), which, according to these estimates account for a lower mortality burden than heat-related deaths (Figure 6).

Figure 7 shows the annual UK age-specific heat and cold deaths, estimated as rate per 100,000 population. These results indicate the burden of heat and cold is higher in the older age groups. For heat-related deaths, the burden progressively increases in the future decades; by the 2070s under a ‘worst-case’ scenario, the estimated mortality rate from heat in those aged 85 years and older will be at around 277 deaths per 100,000, compared to 53 deaths per 100,000 during the baseline period. Cold-related death rates show the opposite trend and are estimated to decline over the same period, although the total burden from moderate cold will still exceed that from heat well into the 2070s (Figure 6). In Table 2, the annual regional projected heat and cold mortality (rate per 100,000 population) shows regional variation, with London, Wales, East of England and the South East showing the highest heat-related mortality. Northern Ireland shows very high estimated heat- and cold-related mortality rates (Table 2), but these are an artefact related to the use of the underlying mortality rates from the North West region of England on a relatively smaller population in Northern Ireland (see method section 2.2.3).

Figure 6. UK heat and cold deaths for all ages at baseline (2007 to 2018) and projected for 2030s, 2050s and 2070s (based on bias corrected UKCP18 data)

The bars represent the mean across the 12 climate model realisations and the error bars are minimum and maximum ranges of the scenarios. Population growth and ageing are included.

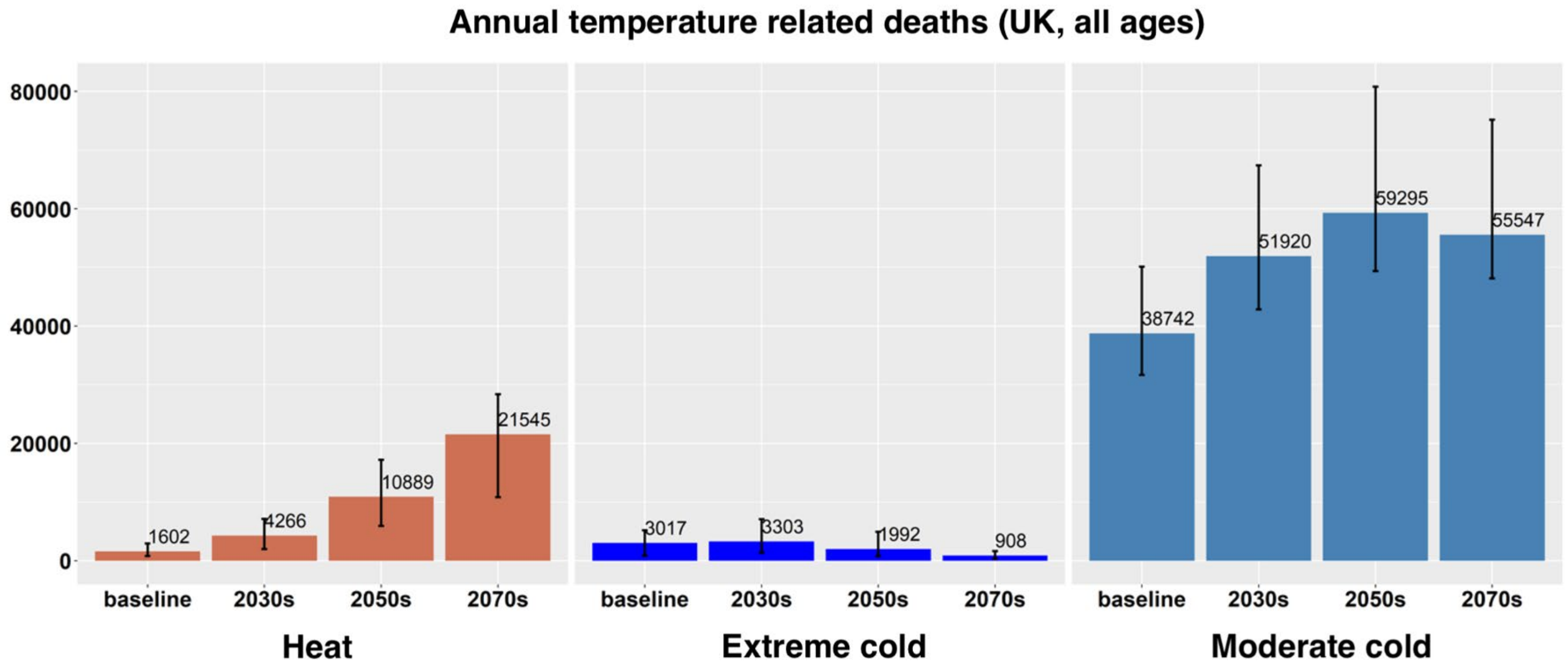


Figure 7. UK heat and cold age-specific temperature-related mortality rates per 100,000 population, baseline (2007 to 2018) and projected for 2030s, 2050s and 2070s (based on bias-corrected UKCP18 data) The bars represent the mean across the 12 climate model realisations and the error bars are minimum and maximum of the scenarios, including dynamic population (population growth and ageing).

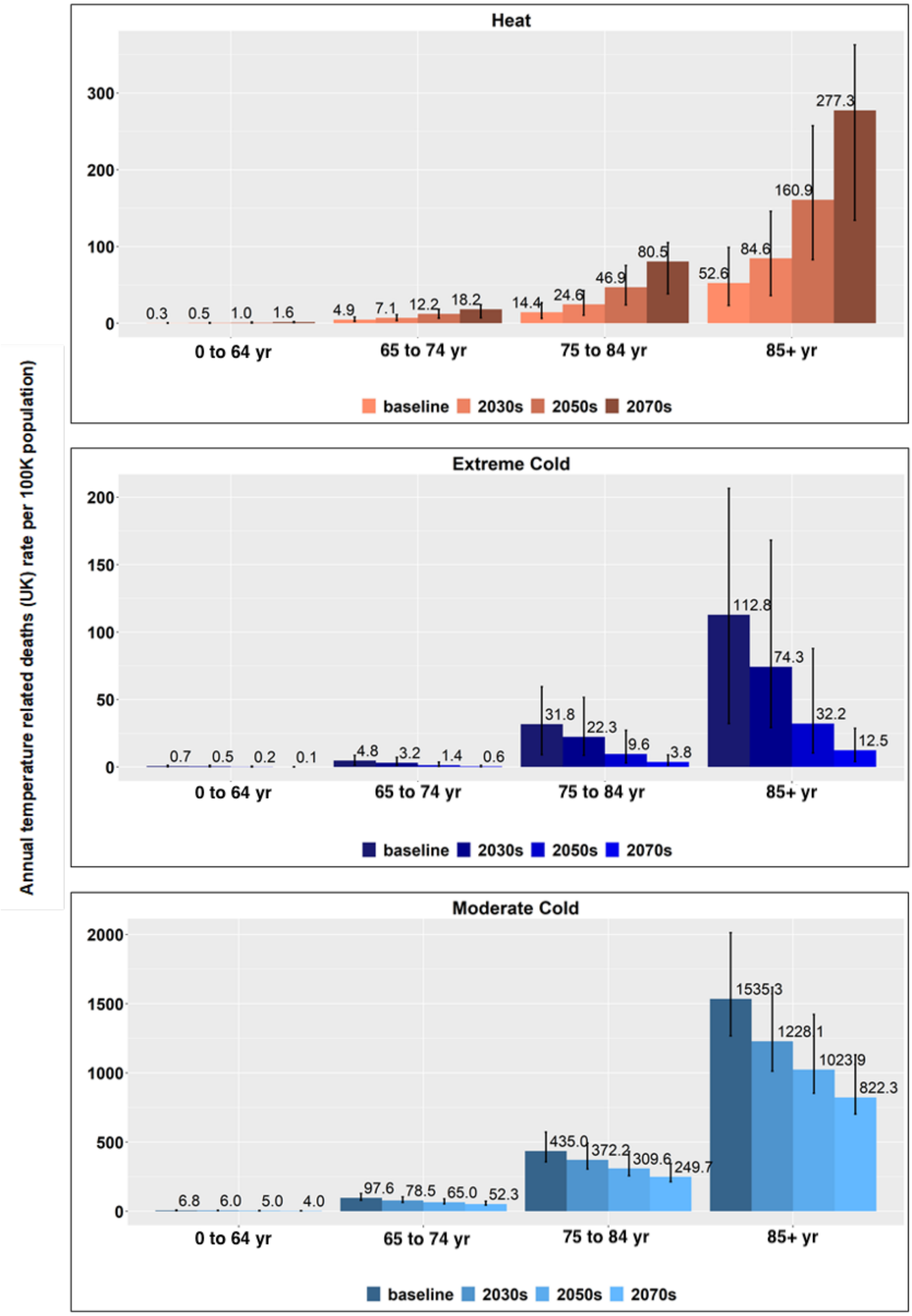


Table 2. Annual average estimates of temperature-related mortality rate in UK regions per 100,000 population for all ages

Lowest and highest estimates are based on the lowest and highest climate model realisations (from the suite of 12 provided in UKCP18).

Table 2a. Heat

Region	Baseline: mean	Baseline: lowest	Baseline: highest	2030s: mean	2030s: lowest	2030s: highest	2050s: mean	2050s: lowest	2050s: highest	2070s: mean	2070s: lowest	2070s: highest
London	3.93	2.27	6.46	8.34	4.75	12.43	17.72	11.10	25.86	30.65	17.53	41.00
North East	0.91	0.40	1.67	1.96	0.83	3.34	3.78	1.94	6.22	6.65	3.02	8.63
North West	1.82	0.98	3.17	4.20	1.87	7.23	10.23	5.12	16.84	19.71	9.06	25.81
South East	2.89	1.24	5.59	7.50	3.52	12.42	18.93	10.32	29.48	37.21	19.35	49.40
South West	2.63	1.07	5.14	6.72	2.69	12.04	17.24	9.35	28.82	34.53	15.84	45.72
East Midlands	2.51	1.19	4.73	5.86	2.99	9.94	14.39	7.54	22.92	27.64	14.38	36.34
West Midlands	2.36	1.06	4.26	4.86	2.42	8.42	11.58	6.15	18.89	21.58	10.93	28.69
Yorkshire and Humber	1.41	0.72	2.58	3.25	1.55	5.54	7.33	3.72	11.93	13.65	6.68	17.80
East of England	3.13	1.39	6.16	7.66	3.76	12.19	19.31	10.67	28.96	37.18	20.41	48.85
Wales	3.14	1.41	5.76	7.56	3.06	13.55	18.73	9.75	31.50	37.00	16.31	48.82
Scotland	1.12	0.44	2.05	2.80	0.82	5.07	7.55	2.96	12.54	15.24	6.48	19.24
Northern Ireland*	4.37	1.73	8.35	11.81	3.40	22.15	33.98	14.98	55.32	71.62	29.57	91.02
UK	2.52	1.16	4.66	6.04	2.64	10.36	15.06	7.80	24.11	29.39	14.13	38.44

Table 2b. Extreme cold

Region	Baseline: mean	Baseline: lowest	Baseline: highest	2030s: mean	2030s: lowest	2030s: highest	2050s: mean	2050s: lowest	2050s: highest	2070s: mean	2070s: lowest	2070s: highest
London	4.25	1.14	6.64	3.97	1.75	8.19	2.25	0.83	4.86	0.96	0.32	1.87
North East	3.02	0.91	6.06	2.81	0.74	6.89	1.31	0.36	4.03	0.54	0.08	1.26
North West	5.46	1.51	9.31	5.05	1.89	10.87	2.81	1.08	7.06	1.30	0.50	2.31
South East	5.19	1.48	8.00	5.19	2.36	10.43	2.86	1.08	6.00	1.18	0.36	2.23
South West	5.87	1.75	9.35	6.03	2.73	11.45	3.69	1.53	7.41	1.66	0.51	3.07
East Midlands	3.52	1.01	5.76	3.33	1.39	7.04	1.87	0.75	4.55	0.85	0.36	1.61
West Midlands	5.25	1.57	8.43	4.65	2.05	9.33	2.82	1.12	6.55	1.31	0.56	2.41
Yorkshire and Humber	3.28	0.87	5.86	3.00	1.01	6.97	1.55	0.56	4.30	0.68	0.16	1.41
East of England	4.56	1.21	7.42	4.55	2.07	9.64	2.63	0.83	6.07	1.10	0.41	2.24
Wales	5.15	1.51	8.31	5.51	2.36	11.03	3.27	1.28	7.11	1.47	0.58	2.49
Scotland	3.07	0.94	6.24	3.29	0.96	7.75	1.94	0.39	6.01	0.90	0.14	1.98
Northern Ireland*	12.69	3.63	29.89	13.78	4.78	38.50	8.60	1.74	33.77	4.02	1.15	14.06
UK	5.11	1.46	9.27	5.10	2.01	11.51	2.97	0.96	8.14	1.33	0.43	3.08

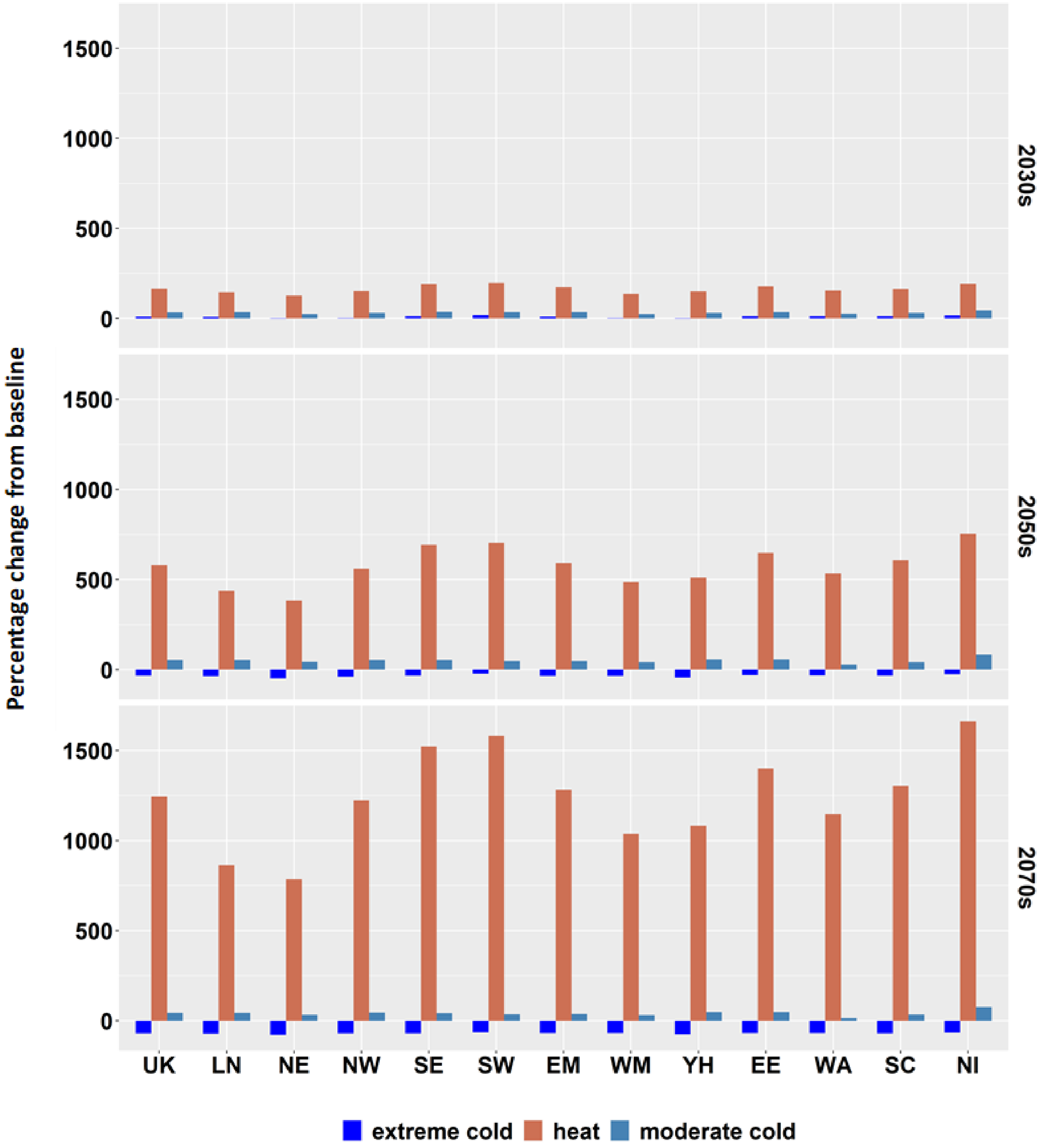
Table 2c. Moderate cold

Region	Baseline: mean	Baseline: lowest	Baseline: highest	2030s: mean	2030s: lowest	2030s: highest	2050s: mean	2050s: lowest	2050s: highest	2070s: mean	2070s: lowest	2070s: highest
London	53.49	43.79	67.47	62.71	52.80	78.64	68.77	58.01	89.61	62.33	55.14	81.51
North East	38.51	31.48	50.72	45.79	36.67	61.32	47.28	38.24	67.60	42.38	35.64	58.33
North West	65.13	53.55	84.16	77.69	63.90	100.87	85.47	71.09	116.50	77.68	68.17	104.47
South East	56.87	45.28	73.01	69.53	57.24	89.07	72.49	60.17	96.32	64.17	55.83	85.91
South West	69.16	55.27	90.32	80.94	66.09	105.56	83.62	68.79	113.52	73.51	63.31	101.87
East Midlands	53.81	44.41	68.31	62.49	51.97	79.34	65.80	55.23	87.81	59.31	51.87	78.24
West Midlands	63.31	51.80	80.79	69.05	57.39	88.10	75.27	62.84	100.90	67.26	58.79	89.74
Yorkshire and Humber	47.21	38.99	60.39	57.07	46.84	73.49	62.68	52.26	85.07	57.34	49.79	76.11
East of England	61.83	50.53	78.43	73.82	61.67	93.19	80.01	67.45	105.73	72.58	63.77	95.34
Wales	63.56	51.14	83.25	75.47	61.48	99.25	76.05	62.38	104.48	68.84	58.96	95.39
Scotland	40.26	33.17	53.55	49.96	40.12	67.67	54.49	44.87	78.63	52.74	43.90	72.74
Northern Ireland*	219.12	183.93	299.91	293.75	241.48	405.92	367.98	306.81	540.21	357.82	296.80	514.77
UK	69.36	56.95	90.86	84.85	69.80	111.87	94.99	79.01	132.20	88.00	75.16	121.20

* Northern Ireland shows very high heat and cold-related mortality rates. This is related to applying mortality rates from the North West region on a relatively smaller population in Northern Ireland (see method section 2.2.3).

In the absence of adaptation, heat-related deaths across the UK are estimated to increase from 1,602 over the baseline period of 2007 to 2018 into future decades. Taking a high-emission scenario (RCP8.5) and including population growth and ageing, the estimated increase is nearly 166% (4,266 total deaths per year) in the 2030s, 580% (10,889 total deaths per year) in the 2050s and 1,244% (21,545 total deaths per year) in the 2070s (Figure 6). The North East shows the smallest increase and Northern Ireland the greatest (Figure 8). Moderate-cold-related deaths (based on moderate-cold threshold) show a small but steady increase from baseline into future decades, increasing by 34% (51,919), 53% (59,294) and 43% (55,546) in the 2030s, 2050s and 2070s, respectively (Figure 8). Extreme-cold-related deaths show a slight increase from baseline into the 2030s, but a decline from baseline into the later decades; the largest decline is in the 2070s where extreme cold-related deaths are expected to fall by 70% (3,017 baseline to 908 deaths per year by the 2070s) (Figure 6 and Figure 8). Increases in overall burdens of cold-related mortality (despite rising temperatures in future decades) are largely driven by changes in the UK population, that is, population growth and ageing, which are discussed in more detail in the next section.

Figure 8. Percentage change from baseline (2007 to 2018) to 2030s, 2050s and 2070s for all-ages temperature-related deaths across the UK, results from the UKCP18 bias corrected estimates (BC adjustment), also taking into account population growth and ageing



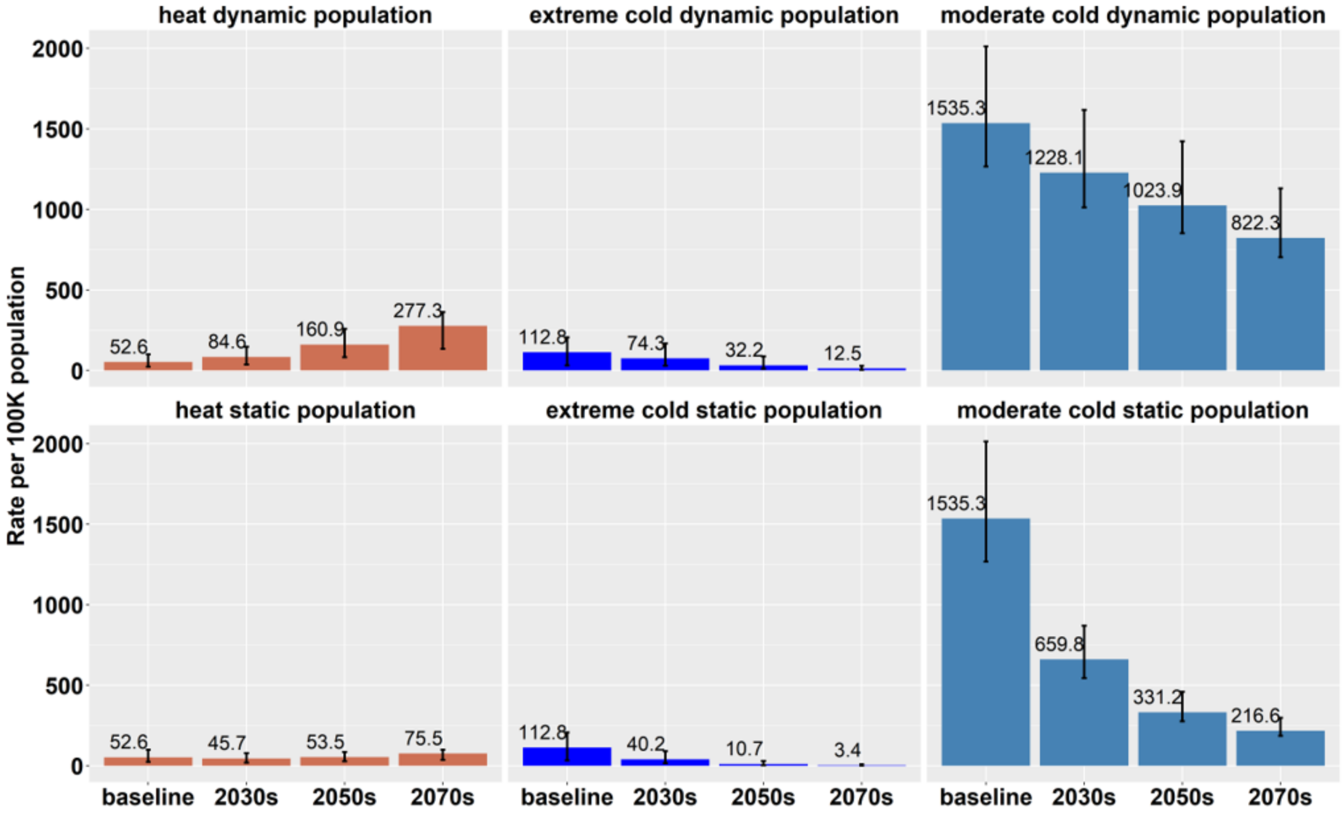
3.3 Impact of population changes on future projected burdens

Both cold- and heat-related mortality estimates increase when population projections (growth and ageing) are taken into account, mainly due to the large increase in the size of older age groups (75 to 84 and 85 years and older). The population of those aged 85 years and older in the UK is expected to increase more than 3.5 times between the 2000s to 2070s, while the average population increase across all ages is 1.2 times.

The impact of population age and size change on heat-related mortality is substantial; incorporating this change in the population age structure in the analysis shows that heat-related mortality in the 2070s is nearly 3 times higher when population projections are included, compared to the mortality estimate for a static population (277 versus 76 heat-related deaths per 100,000 population) (Figure 9). This is consistent with a previous study showing that demographic change had a strong impact on projected heat-related mortality in the UK over the 21st century (30). Cold-related deaths also increase when the analysis includes changes in population structure (Figure 9). As both heat and cold risk increase with age (Figure 7 and Appendix B), burdens of both heat- and cold-related mortality are amplified in future when accounting for an ageing population; the overall increase in temperature with climate change in future further amplifies burdens associated with heat but diminishes that associated with cold (Figure 9).

Ageing may exert a greater influence on estimated future weather-related mortality burdens than changes in temperature alone. Consideration of population age structure into the future decades is important and mortality assessments based on an all-age risk coefficient (rather than age-specific risk coefficients) may underestimate the projected burden.

Figure 9. Temperature-related mortality (rate per 100,000 population) in the oldest age group (85 years and older), comparing models that take into account future changes in the population structure (dynamic population) with models that assume no change in population structure (static population)



4. Discussion

4.1 Discussion of results

Across all regions of the UK there is an increase in the risk of mortality associated with ambient high and low temperatures, with London having the highest relative risk and thresholds for effects for both heat and cold effects (Figure 5). Higher relative risks associated with heat in London compared to other UK regions are also reported by other studies (4, 7, 30). The higher heat risks in London may be partly explained by higher temperature exposure ranges, potentially due to the urban heat island (often referred to as 'UHI') effect, whereby higher temperatures are observed in more built-up areas than in the surrounding rural areas (48). The high cold risk in London may be due to the prevalence of older housing stock, single-person households, and pockets of socioeconomic deprivation. However, it should be noted that London has a relatively young population compared to other parts of the country (with older people generally being more susceptible to the effects of heat and cold than younger people). The UK-level risk of mortality (all-ages) associated with high temperatures was RR of 1.05 (95% CI: 1.04 to 1.07), and risks associated with low temperature were 1.13 (95% CI: 1.11 to 1.15) and 1.28 (95% CI: 1.23 to 1.32) (all-ages) based on extreme and moderate cold thresholds, respectively (Figure 5).

By the 2070s, annual heat-related mortality is estimated to increase from a baseline of 1,602 (2007 to 2018) to 21,545 (in 2070s, by 1,244%) including population growth and ageing and in the absence of future adaptation, for a high-emission scenario (RCP8.5) (Figure 6). Moderate cold-related deaths that assume a higher cold threshold are also projected to increase by 43% (from 38,742 baseline to 55,547 for 2070s), whereas extreme cold-related deaths that assume a lower cold threshold will decline by 70% (from 3,017 baseline to 908 for 2070s) (Figure 6). Much of the increase in estimated heat-related mortality is driven by projected demographic changes for the UK, in particular continued ageing of the population, which also slightly diminishes projected reductions in cold-related mortality (Figure 9). Over this period to the 2070s, the overall population is projected to grow by 18%, though growth is much higher in the older age groups, being 223% in the 85 years and older age group by 2075 compared to 2018 (45). Cold-related deaths associated with extreme cold decline from mid-century whereas deaths associated with moderate cold continue to show an increase to the 2050s before beginning to decline in 2070s (Figure 6). This can be partly attributed to a reduction in extreme low temperatures in future decades, but also suggests moderate cold will continue to be a health risk for the most vulnerable. The analysis also highlights the strong impact on overall future burdens of using age-specific risk coefficients, which should be considered in future analyses of this kind, particularly in the context of an ageing population. Policies relating to healthy ageing will therefore be key considerations alongside climate change adaption and mitigation policies to minimise the potential health impacts in a warmer world.

The BC method for bias adjustment of the UKCP18 climate projections is applied by region and each calendar month separately, hence it is applied flexibly (that is, the magnitude of bias correction applied is specific to the region and timeframe) so that the overall adjustment varies noticeably between different regions and months (Figure 3 and Appendix A). Hence, the applied bias correction (BC method) of the population-weighted 2m air temperature that accounts both for a shift in the mean state and rescales variability in the UKCP18 projections have different influences on the overall estimated heat- and cold-related exposure: there is a more significant reduction in regionally population-weighted ambient temperatures for higher temperatures since biases in raw (uncorrected) projections are the most pronounced and positive from June to September (particularly in South West and South East England, see Figure 3).

This analysis did not separately consider the impact of extreme heat (including a specific heatwave term) which previous studies have assumed to be at or beyond the 97.5th temperature percentile (4, 29, 32). However, inclusion of a lag of 0 to 3 days in the epidemiological analysis may reflect to some extent the impact of sustained high temperatures during a heatwave, and there is weak evidence for a heatwave term when using non-linear modelling including lag terms (as used here) as opposed to more simple linear methods (49). Previous analysis in the UK found very few consecutive days with very high temperatures (with the exception of London region), and these would not have large effects on heat-related burdens, although there is evidence that the frequency of very hot days may increase in the future (34, 35). Although a log-linear threshold model provides the most consistent basis from which to estimate future burdens, there is evidence that a log-linear assumption may underestimate heat-related risk at very high temperatures (27). For this reason, the analysis here employed distributed lag non-linear (dlnm) models to allow for a potential non-linear mortality response and effect estimates are presented as risks associated with the temperature extremes. Results here are based on the newly derived exposure-response functions, though it is acknowledged that future exposures may be different from the historical ones that the exposure-response relationships are based on; exposure-response relationships may change in future as more extreme temperatures are observed, as changes in other risk factors that impact heat-health effects occur, or as populations adapt (50).

Care must be taken when attributing causal effects of exposures to health outcomes. Here, established statistical techniques are applied (see section 2.1) to quantify the relationship between daily ambient population-weighted temperature and observed mortality counts, which is then used in a HIA, assuming that impacts on mortality are attributable to the effects of cold exposure on days below the given temperature threshold, though without determining explicitly a direct causal relationship between ambient temperature and health outcomes. Other metrics[2] are commonly used by analysts and health practitioners to assess winter health burdens

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[2] The Excess Winter Deaths (EWD) metric is commonly used by analysts and health practitioners to assess winter health burdens associated with winter weather, based on the ratio between average daily deaths in December to March versus other months. It is not possible to determine the impact of cold weather alone versus other pressures at this time of year that might influence mortality (for example influenza, NHS pressures, and other respiratory diseases). EWD is widely used, though there are significant issues on the suitability of this metric regarding the attribution to effects of cold temperatures specifically (106, 107) and care must be taken to appropriately compare different metrics, and when attributing health impacts to environmental exposures as opposed to circulating seasonal infections such as influenza (108). A further complexity is that some portion of circulating influenza will be due to cold exposure, while EWD estimates the burden of mortality due to influenza alone without distinguishing these from cold effects (109).

associated with winter weather, often based on the ratio between average daily deaths in winter versus other months, and therefore do not determine the impact of cold weather alone versus other factors that might influence mortality (for example influenza, NHS pressures, and other respiratory diseases).

The future burdens of temperature-related mortality presented in this report represent higher-bound estimates since they are based on a high emissions scenario (RCP8.5), which was the only scenario available with daily resolution necessary for health impact studies in the UK. RCP8.5 generally represents a scenario with few emission controls and may be interpreted as a 'baseline' high emission (often considered a 'worst-case') scenario in the absence of concerted efforts to reduce global greenhouse gas emissions. Given commitments made under the Glasgow Climate Pact (agreed at COP26 in Glasgow in November 2021), such a high emission scenario may be viewed as less likely, but is by no means implausible and thus remains relevant as a scenario to explore high-end forcing, and high climate sensitivities are shown in some climate models (51). Adaptation has not been modelled explicitly, however since it is likely to be a key driver in determining future vulnerability to temperature effects and weather extremes (52), more extensive climate change HIAs should seek to explore the potential impact of possible future acclimatisation and adaptation on temperature-health impacts (53).

While there is evidence of a relationship between direct effects of temperature on morbidity outcomes such as emergency hospital admissions and accident and emergency attendances for cardiac, respiratory, cerebrovascular, and psychiatric conditions (17 to 19), the strength of the relationship between all-cause mortality and temperature is more robust and mortality data is more readily accessible. Nevertheless, given the increasing demands on health and care facilities, future assessments should look to include this to better understand the potential future risks for health and care services. High ambient temperatures have also been associated with effects on mental health (including increased suicide risk) though knowledge gaps remain, and the associations are more difficult to unpick (20). Prevalence of common mental disorders has risen by around one-fifth in both men and women in England between 1993 and 2014 (54). With increasing prevalence of psychiatric disorders in the adult population in England, and with prevalence unequal across different ethnicity, deprivation, and employment statuses (55), considerations for mental health are important from an equity perspective and may become increasingly important to understand in the context of climate change. Longer-term systemic impacts of heatwaves through impacts to ecosystems and through potential economic disruption will also have implications for public health.

4.2 Gaps in current modelling

4.2.1 Climate modelling

The 12 ensembles of regional (12km) climate model projections from the UKCP18 suite used here have better resolved regional details than 25km model projections used in the previous assessment (based on UKCP09) along with a more advance dynamical core and physics parametrisations (34). However, there is a need for even more refined, multi-scenario and higher resolution climate information for estimation of actionable climate-related risk critical for adaptation strategies and mitigation decisions (56). Therefore, the UK Met Office continues to push the modelling envelope with the development of km-scale climate models that can, for example, dynamically resolve convective clouds and storm events in the atmosphere as well as provide highly accurate sub-daily weather information. User-oriented application of such very-high-resolution climate models represents not only a grand challenge in dynamical and numerical sense, but also from technical and support framework perspective that needs to be surmounted in this decade, or soon afterwards, as heatwaves and many other extreme events threatening human health are clearly intensifying and becoming more frequent in a changing climate. In the regional climate model used for UKCP18 in our analysis, urban effects are represented with a simple tile approach to capture sub-grid scale differences in land surface characteristics (57) and represent an improvement in including urban effects (for instance, the urban heat island) compared to previous UPCK09 projections (which did not include urban surfaces). However, the effects of the urban heat island are unlikely to be fully captured by the UKCP18 projections, and hence heat exposure and heat-related mortality is likely to be under-estimated. Studies suggest that there are inequalities in population exposure to the urban heat island (58). As more is understood about the characteristics of urban heat islands and their effects on population exposure, this could represent an area for further improvement in understanding exposure to heat and will require high-resolution data on the building stock and its features.

4.2.2 Population modelling

In projecting future impacts, population changes have a significant impact on overall total burdens. Future population modelling is complex and relies on assumptions about future trends in fertility, migration, and mortality trends based on past trends. Such trends may not be consistent into the future, and effects of the COVID-19 pandemic on future trends are still emerging. Insights from the most recent Census are just starting to emerge and findings from this can be expected to be included in future population projections.

As the impacts of temperature on health often occur by impacting those with existing morbidities, the baseline rates of these diseases and how these may evolve into the future can also impact projections of health impacts. Modelling these effects into the future can be challenging due to many factors influencing morbidities and comorbidities, and modelling has started to explore projecting a range of diseases conditional on sociodemographic characteristics, health behaviours and existing morbidities as they age, though there are important limitations to consider (59). Following the COVID-19 pandemic there may be changes to the pool of susceptible individuals in terms of cardiovascular effects and comorbidities that might influence mortality rates. For example, there is evidence that cardiovascular diseases appear to be consistently higher post-pandemic (60), and there is emerging evidence of an increased risk of cardiovascular mortality associated with previous COVID-19 infections (61). It is yet unclear if this is a pattern that will continue in future years. In the analysis presented here, constant rates of mortality are assumed, though this together with baseline health patterns may change in future, with implications for future temperature-related impacts on health.

4.2.3 Adaptation

The results presented here clearly underline the need for population adaptation to rising temperatures to minimise associated health risks. As the level of adaptation required will depend on the emissions pathway that is followed, actions to mitigate climate change can also help limit projected negative impacts. Assessment of adaptation measures and a detailed consideration of human responses to rising temperatures in future projections is currently challenging, with no established methodology, and a need for frameworks to help assess uncertainties (62). Therefore, when attempting to analyse the future likely impacts of climate on health, assessing quantitatively the role of adaptation in such projections may be considered a key uncertainty in this context. For temperature effects on health, adaptation may take the form of personal cooling strategies, behavioural interventions and public health heat action and response plans, as well as longer-term planned adaptation of key infrastructure, including interventions in the built and natural environment, such as retrofit to buildings, or landscape management interventions (63). Longer term planned adaptation of key infrastructure that may be at risk from heat can also help in protecting health during heatwaves as well as improving the resilience of hospitals and healthcare centres to hot weather. Key points on the evidence on some of these measures is outlined below. Health effects related to indoor environments and climate change are fully covered in Chapter 5.

In the built environment, external shutters on windows can be effective in protecting against heat-health impacts in heatwaves, with one study estimating a 30% to 60% reduction in risk (64). Energy efficiency adaptations such as wall, floor and loft insulation, triple glazing, and draught reduction can keep buildings warmer in winter (potentially protecting against some cold-related mortality) but concerns have been raised about their potential to increase summer overheating if not implemented carefully with appropriate provision of ventilation or used together with other measures (such as shading, shutters or additional ventilation) (64, 65). In response to increasing temperature, many households around the world are turning to the use of air conditioning systems. It is estimated that somewhere between 2% and 5% of UK domestic buildings have some form of portable or fixed cooling system (66), and by 2050, it is expected that 5% to 32% of English households will have air conditioning (67). However, there are concerns around resilience during power cuts (68), as well as waste heat from such systems adding to the urban heat island effect. Such active cooling measures introduce additional energy demand (exacerbating greenhouse gas emissions unless renewable energy is used), and associated energy costs. Air conditioning can increase household energy spending by 35% to 42% (based on a study on temperate industrialised countries), which may drive some households into summertime energy poverty (69), and potentially exacerbate inequalities (63, 70). Use of air conditioning may also add waste heat to the outdoor environment, potentially exacerbating the urban heat island effect.

Altering the reflectiveness or albedo of buildings and urban infrastructure such as roofs, pavements and roads (so that they reflect sunlight rather than absorb it) is another intervention aimed at reducing urban temperatures (71). A UK-based study found that reflective ‘cool’ roofs could potentially offset 18% of seasonal heat-related mortality associated with the urban heat island (25% during heatwaves) corresponding to 7% of all heat-related mortality, with no worsening of cold-related health effects in winter and benefits increasing with climate change (72, 73).

Green infrastructure such as trees, parks and gardens are generally cooler than surrounding more built-up areas. Many studies review and estimate the benefits of green and blue (water) infrastructure, and the use of building interventions in terms of reducing local temperatures and improving heat-related health and wellbeing, particularly in cities (10, 48, 72, 74, 75). Shading provided by street trees is critical for improving thermal comfort in urban areas by reducing the mean radiant temperature, which is the dominant influence on human thermal comfort under warm and sunny outdoor conditions (75). Urban trees have been estimated to reduce land surface temperatures 2 to 4 times more than reductions associated with treeless urban greenspaces in European cities (76). A UK modelling study suggests that a 5% increase in mature deciduous trees can reduce mean hourly surface temperatures by 1°C over the course of a summer’s day (77), and a 10% increase in green cover in the most urbanised areas could offset the projected warming estimated for Manchester in the 2080s (78), though background climate, humidity and soil moisture can impact the effectiveness of greenspace for cooling (79). The cooling effect of greenspace may extend beyond the boundaries of the space and be dependent on the vegetation type (80). In one London-based modelling study, cooling distance increased linearly with increasing area of greenspace, though the associations with amount of cooling and vegetation type (trees, grassland) were non-linear, with the study suggesting that greenspaces of 3 to 5 hectares, situated 100m to 150m apart may provide a comprehensive cooling service on calm warm nights in cities with similar climate and characteristics to London (81). Cities with greater amounts of greenspace have been found to have lower heat-mortality relative risks compared with cities with less greenspace, and a 20% increase in greenspace has been associated with a 9% decrease in the heat-related attributable fraction (82). The Lancet Countdown on Health and Climate Change also provides recommendations and policy briefs for the UK, including action across 3 areas, including access to green space (83). The health effects related to greening and other nature-based solutions connected with climate change mitigation actions are considered in Chapter 14.

As well as adaptation interventions in the built environment, adaptive behaviours and increasing the resilience of key infrastructure such as workplaces, hospitals, schools, care homes, and other health and care centres can improve adaptation to high temperatures. Adaptive behaviours may include avoiding sun exposure during the middle of the day, avoiding extreme physical exertion, checking ambient room temperatures, closing curtains or blinds in sunny buildings, and ventilating during cooler times at night, ensuring access to cool liquids, and looking out for vulnerable community members. Some adaptation actions may be more difficult for some populations to achieve, particularly justice-involved populations (for example, people in prisons or custodial facilities) who may not be able to follow general advice and guidance to move somewhere cooler, open windows, or take a cold shower on demand, meaning they have less capacity to adapt to increased temperatures. Due to the large burden of cold effects on health, adaptation actions for addressing heat should be carefully considered to ensure that this is not at the expense of protecting against cold. Incorporating potential adaptation measures into quantitative assessments of health impacts associated with temperature is currently challenging. Some studies have looked at measures of effect modifiers, or compared epidemiological studies between cities with different climates and assumed different levels of adaptation, though these incorporate many assumptions about levels of physiological adaptation or uptake of measures such as air conditioning (84 to 88).

There is no established best practice methodology for assessing quantitatively the role of adaptation in future estimates of heat mortality. While different methods have been proposed (including shifting the absolute or relative threshold temperature, reducing the slope of the exposure response coefficient, or some combination of these), a significant limitation of this approach is that these shifts have no underlying empirical basis from epidemiological studies (47). Some studies have started to incorporate adaptation based upon historical trends and applied this to future projections; however, there is no recommended best practice way of doing this (84, 87, 89 to 91). Individual adaptive mechanisms may have different effects on mortality and future adaptive capacity is likely to reach a limit, although these limits are currently unknown (87). There is consensus that different adaptation scenarios would need to be modelled alongside different climate and population change models to allow for more accurate projections and scenarios to be explored, but data regarding specific interventions would be required (84, 87, 91). Understanding impacts of adaptation measures to temperature-related health burdens should be a focus of future research, to support decision-makers with long-term planning for climate and health adaptation.

4.3 Public health response

Many of the deaths that occur during heatwave events are likely to be preventable, and mortality is not confined to areas with the highest temperatures, demonstrating the importance of taking protective action even in places where temperatures are less extreme. People who are at risk of harm may not think to take action to protect themselves, as many people welcome the hot weather. In England, the ‘Adverse Weather and Health Plan (AWHP)’ launched in April 2023 outlines areas where different sectors (including public, independent, voluntary, health and social care organisations and local communities) can work together to maintain and improve integrated arrangements for planning and response to deliver the best outcomes possible during adverse weather (92). The Plan brings together and builds on the previous Heatwave Plan for England (launched in 2004 in response to the summer heatwave of 2003) and the ‘Cold Weather Plan for England’, first published in 2011 (93, 94). Key action areas in the Plan include service delivery, capacity building, organisational arrangements, communication, risk management, early warning systems, and policy development and accountability. A key aim in the Plan is to improve long-term planning at all implementation levels and promote a change of focus from response and recovery to resilience and preparedness (92).

As the AWHP has only recently been launched, an evaluation has not yet taken place. An evaluation of the previous Heatwave Plan for England conducted in depth interviews with key informants from 5 local authorities and recommended reviewing guidance so that people are better protected during all periods of hot weather, not just during heat-alert periods, emphasising the importance of longer-term adaptation planning for adverse heat impacts (95). The evaluation also recommended ensuring that people are better informed about their own risks and any actions they can take to better protect themselves, with messages targeted at different groups of the public (95).

The AWHP highlights those considered to be at higher risk during very hot or cold weather, including people who are over 65 years, babies and young children (aged 5 and under), those with certain underlying health conditions or taking certain medications, or who are already ill or dehydrated, pregnant women, people experiencing alcohol or drug dependence, or homelessness (including those unable to make adaptations to their living environment), people who may be living on their own and isolated or unable to care for themselves, people who are housebound or have otherwise low mobility, people living in deprived circumstances, and people who are physically active and spend a lot of time outside (for example, runners, cyclists and walkers). Those living in houses with mould or who are fuel poor are also more at risk during cold weather (96). Those living in urban areas, south-facing top-floor flats, homes with little shading or windows only on one side of the property or restricted opening (which may limit ventilation) may also be at greater risk as these environments can become hotter than others during heatwaves. As well as actions that can be taken during the heatwave period itself (such as staying out of the heat, cooling yourself down, keeping your living environment cool, and looking out for others), measures for reducing heat-health effects over the longer term are also provided (such as putting up external shading, using pale reflective paints, improving insulation, and growing trees and leafy plants near windows), along with guidance for what to do when you feel unwell (92). Perception of risk and vulnerability during heatwaves may affect behaviour and uptake of public health measures to reduce risks from heat, with risk perception often being poor among vulnerable groups. Future work should explore risk communication related to particular factors that are key determinants of risk perception among groups at risk from hot weather (97).

UKHSA have been collaborating with the Met Office since 2018 on transitioning the current heat-health and cold weather alert services in England, which are based on probabilities of temperature thresholds being reached, to impact-based alerting, which will provide users with more information about the likely impact they can expect because of the weather conditions. In turn, this information can help local responders when undertaking their local risk assessments to understand what actions they may need to take, based on the impacts expected because of the weather. Impact-based warning is widely used in other weather hazard areas and has been a consistent request from users that UKHSA’s alerts are aligned with those of other warning systems. This is also one of the key policy or scientific commitments under the second National Adaptation Programme, with the Third Climate Change Risk Assessment (CCRA3) indicating that early warning systems have one of the highest cost-benefit ratios of population level interventions.

5. Conclusions

5.1 Research priorities

Some of the observed impacts may result from short-term mortality displacement in frail individuals, especially in relation to the heat effect where a maximum lag structure of 3 days was used. Previous studies have estimated that between 10% and 70% of heat-associated mortality may be associated with short-term (up to a month) mortality displacement, while there is little evidence for short-term mortality displacement associated with cold exposure (98). To better comprehend potential impacts of temperature in the context of climate change and an ageing population, future health impact assessments could consider years of life lost (YLL) as an additional outcome to take into account population life expectancy and the age at which mortality occurs (99).

In general, higher resolution climate data or model output are more representative of heat and cold exposure, and capture features like the urban heat island. Advances in climate modelling capability will likely lead to higher resolution output and therefore more representative estimates of the health burden from heat and cold. High-resolution information on the built and natural environment will also be beneficial for understanding risks and can inform adaptation.

As always, particular attention should be given to the most vulnerable in society, and those who are most at risk from heat and cold, for example older people and those with cardiovascular and respiratory illness. This will require detailed demographic and social science research inputs in future assessments.

As discussed earlier in section 4.2.3, incorporating adaptation into estimates should be explored in future research where possible, though established methodologies for this are still emerging. Future research should seek to identify the underlying drivers of heat- and cold-related health effects, particularly in the case of deaths occurring in winter as not all will be driven by cold effects alone, with important overlaps with circulating seasonal infection, for example influenza.

5.2 Implications for public health

Increased frequency and intensity of heatwaves is a key health risk from climate change, particularly for vulnerable groups including older people, and this analysis demonstrates that risks from heat are likely to significantly increase in future. Managing this risk is a key challenge for public health bodies and the health and care sector to ensure the health system is more resilient to higher temperatures. This can include raising awareness amongst the public and healthcare workforce on what the risks are, and what actions can be taken to protect people during heatwaves, and to improve resilience of health and care settings to hot weather, including adaptation measures in nursing and residential homes. The AWHP outlines important recommendations where the public sector, independent sector, voluntary sector, health and social care organisations and local communities can work to maintain and improve integrated arrangements for planning and response to deliver the best outcomes possible during adverse weather (92). It should be noted that risks associated with cold, though reduced, will remain high in future, and should not be ignored at the expense of planning for heat. Besides direct impacts to mortality and morbidity, there is also evidence relating heat to mental health outcomes. For example, one global review finds higher suicide risk with heat, and increased risk of mental health-related hospital admissions and emergency department attendance during periods of higher temperature (20). In addition, the study recommends that as the evidence evolves, plans for public health response to hot weather should consider including mental health impacts (20).

Transport systems may be detrimentally affected by heat, potentially leading to subsequent impacts on accessing health and social care, education or work. In London, deep tube lines can be 10°C hotter than temperatures at street level, and some high-emission scenarios suggest that by the 2050s, almost all passengers will experience discomfort in all deep London Underground lines during the summer (100). Overheating on public transport can also result in increased demand for air conditioning, and mechanical cooling systems on buses putting pressure on engines to work harder, therefore adding to air pollution and potentially exacerbating the urban heat island effect. Overheated transport could lead to a loss of workdays as heat-vulnerable individuals, such as older people or pregnant women may not be able to travel (101).

Educational settings may also see risks during hot weather. The Department for Education (DfE) advises schools to remain open during heatwaves and for staff to take measures to safeguard children. A survey of 135 teachers found that 100% of respondents felt high temperatures affected the productivity of students and 52% felt productivity was “significantly” affected (101). Many respondents called for more cooling options in schools, and improved building design (101). The Environmental Audit Committee (EAC) recommended that the DfE should issue guidance for head teachers about safe temperatures in schools and relaxing the school uniform policy as appropriate during hot weather (101). Although specific guidance on safe indoor temperatures in schools is not currently available, the DfE have produced advice on relaxing uniform policies to allow pupils and staff to wear clothing to help them keep cool (102).

There is an absence of evidence for the UK on overheating risks in settings such as prisons and custodial facilities, highlighted as an area where more evidence for specific interventions is needed to inform guidance (96). Populations in prisons or custodial facilities may be at risk of poorer health outcomes when compared to the community due to pre-existing medical conditions, and hot weather events may cause disproportionately worse health outcomes. Residents and staff of prisons and young offender institutes may not be able to follow general advice and guidance (such as to move somewhere cooler, open windows or take a cold shower on demand) to protect against the effects of hot weather, due to the inherent restrictions within this environment, and it may be that interventions can only be made at institution or place-based level.

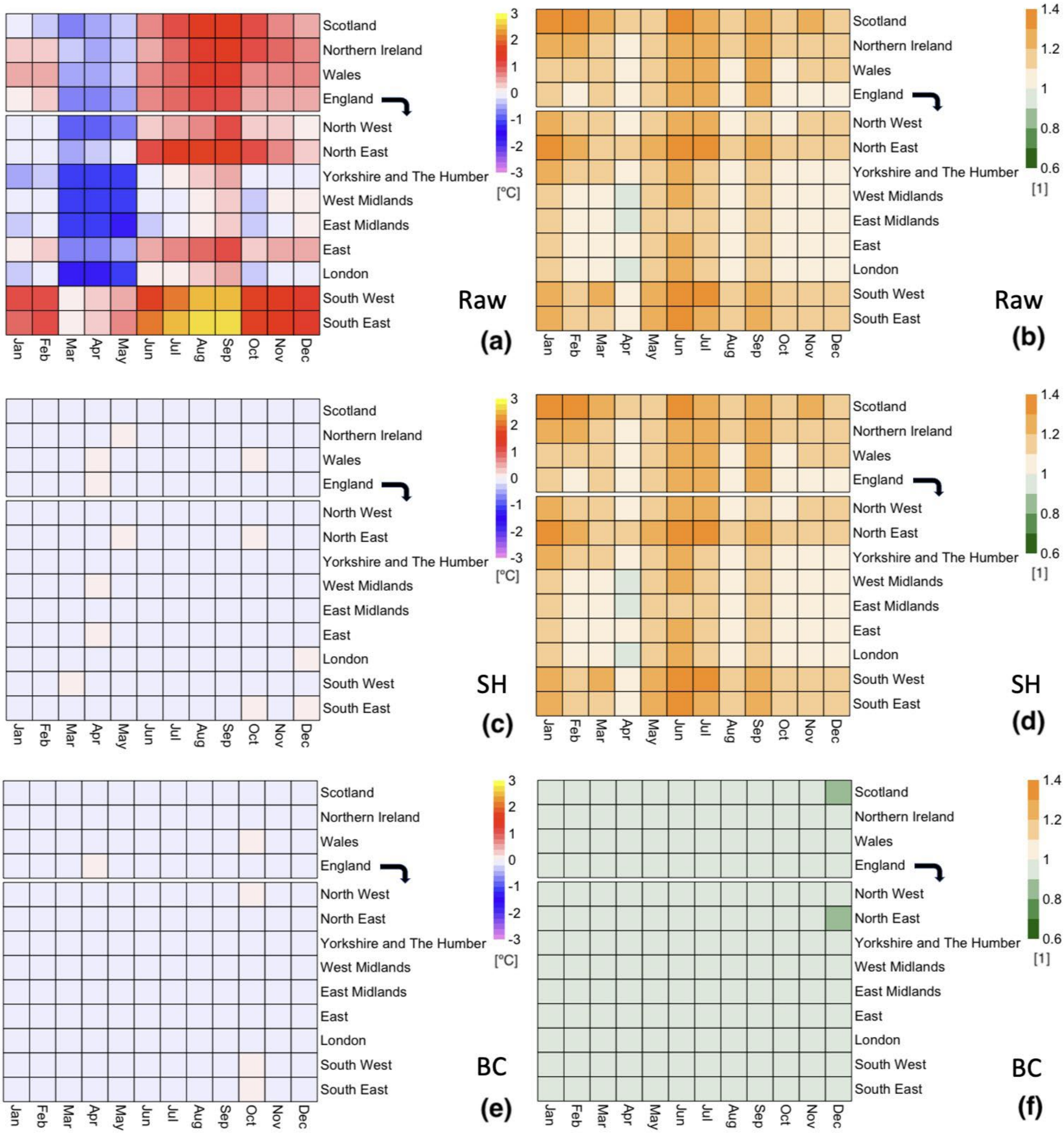
Overheating in indoor environments is covered in detail in Chapter 5, with priorities for housing and buildings policy covered in that chapter. There has been more evidence in recent years on overheating in buildings, and the effectiveness and limitations of strategies for passive and space cooling. Housing policies to achieve net zero (for example through planning or retrofit) may increase the risk of overheating if adequate measures to offset this risk (such as additional ventilation) are not provided (see Chapter 14). It can therefore be beneficial if the full range of housing interventions are considered in an integrated manner and include consideration for health (for example, energy demand, dampness, flood damage, indoor air quality, and overheating). It is important to note that many adaptation interventions in the built environment (for example, improved thermal insulation) are likely to strengthen resilience to both heat and cold; unintended consequences of retrofit can be minimised through careful design.

Impacts that burden the public health system are important during hot weather. There are several factors that can influence mortality during heatwaves, including peak daytime and night-time temperatures, duration of event, geographical extent of hot weather, the timing of the heatwave (the first heatwave of the year often can have higher mortality than subsequent heatwaves), and the relative change from pre-heatwave conditions. The CCRA3 identified that there is better understanding of the effectiveness of health protection strategies, particularly for actions linked to heat alerts (103). Strengthening the climate resiliency of health systems will protect and promote human health and wellbeing. There are multiple opportunities for targeted investments and finance to protect against exposure to climate hazards, particularly for those at highest risk. Heat-health action plans that include early warning and response systems are effective adaptation options for extreme heat (104). The 'Third Adaptation Report for the Health and Care Sector' assessed the current state of climate adaptation and laid out recommendations and next steps related to health information systems, service delivery, and leadership, workforce development and resourcing (105). Key recommendations include increasing access to information on climate risk, implementation of the AWHP, and increasing capacity and resilience of health and social care services to anticipate and respond to climate impacts, through long-term adaptation planning.

Appendix A

The panels (a), (c) and (e) in the left column show differences between population-weighted monthly means of daily means of various model outputs and observations. The panels (b), (d) and (f) in the right column show ratios between population-weighted monthly standard deviations of various model outputs and observations (also based on daily means).

The top (panels (a) and (b)), middle (panels (c) and (d)), and bottom (panels (e) and (f)) rows show the results using raw (original, unprocessed), SH-method processed and BC-method processed UKCP18 simulations, respectively, for our regions of interest over the reference period from December 1980 to November 2019. Raw (unadjusted) UKCP18 simulations over the used historical period show monthly mean biases with significant regional and temporal heterogeneity (left column). For example, we can see in the top left panel that most of the UK shows cooling (warming) bias in spring (summer). Additionally, raw UKCP18 monthly variability is mostly inflated with respect to observed variability (right column). The BC method appropriately adjusts raw UKCP18 projects to essentially corrects for biases in monthly means and variability (the bottom row).



Appendix B

UK and regional relative risks (95% CI) for heat-related mortality and cold-related mortality (using moderate (higher) and extreme (lower) thresholds for cold) for all ages and by age groups

Region (age group)	Heat: RR	Heat: upper limit	Heat: lower limit	Cold low threshold: RR	Cold low threshold: upper limit	Cold low threshold: lower limit	Cold high threshold: RR	Cold high threshold: upper limit	Cold high threshold: lower limit
London (all)	1.106	1.084	1.128	1.213	1.145	1.286	1.451	1.361	1.548
London (0 to 64)	1.062	1.018	1.108	1.194	1.053	1.354	1.332	1.159	1.531
London (65 to 74	1.075	1.026	1.127	1.136	0.989	1.305	1.370	1.175	1.597
London (75 to 84)	1.117	1.078	1.157	1.225	1.107	1.357	1.484	1.325	1.663
London (85 years and older)	1.137	1.100	1.175	1.245	1.132	1.368	1.536	1.383	1.706
North East (all)	1.025	1.001	1.049	1.084	1.015	1.158	1.171	1.072	1.279
North East (0 to 64)	1.040	0.987	1.095	1.075	0.925	1.250	1.176	0.958	1.443
North East (65 to 74)	1.034	0.980	1.090	1.059	0.904	1.239	1.040	0.843	1.283
North East (75 to 84)	1.022	0.982	1.064	1.123	1.003	1.256	1.184	1.018	1.378
North East (85 years and older)	0.998	0.960	1.038	1.065	0.955	1.188	1.166	1.009	1.346
North West (all)	1.037	1.022	1.052	1.164	1.116	1.214	1.303	1.231	1.380
North West (0 to 64)	1.011	0.978	1.044	1.198	1.090	1.316	1.136	0.998	1.294
North West (65 to 74)	1.026	0.993	1.060	1.157	1.052	1.273	1.258	1.105	1.432
North West (75 to 84)	1.048	1.022	1.075	1.150	1.069	1.237	1.309	1.184	1.446
North West (85 years and older)	1.047	1.021	1.074	1.159	1.080	1.244	1.412	1.283	1.554
South East (all)	1.066	1.049	1.083	1.159	1.105	1.215	1.290	1.224	1.360
South East (0 to 64)	1.021	0.982	1.061	1.037	0.925	1.163	1.088	0.957	1.236
South East (65 to 74)	1.030	0.992	1.069	1.082	0.965	1.213	1.261	1.111	1.431
South East (75 to 84)	1.066	1.036	1.096	1.248	1.150	1.354	1.357	1.238	1.487
South East (85 years and older)	1.095	1.069	1.121	1.166	1.088	1.250	1.326	1.228	1.432
South West (all)	1.048	1.031	1.066	1.161	1.092	1.234	1.329	1.241	1.422
South West (0 to 64)	0.995	0.953	1.040	1.042	0.887	1.224	1.145	0.956	1.370
South West (65 to 74)	1.033	0.991	1.077	1.076	0.922	1.255	1.332	1.124	1.580
South West (75 to 84)	1.055	1.023	1.088	1.163	1.043	1.297	1.435	1.269	1.622
South West (85 years and older)	1.068	1.041	1.095	1.227	1.121	1.342	1.323	1.197	1.462
East Midlands (all)	1.054	1.035	1.074	1.095	1.038	1.154	1.239	1.157	1.327
East Midlands (0 to 64)	1.029	0.985	1.075	1.087	0.961	1.230	1.243	1.057	1.462
East Midlands (65 to 74)	1.042	1.000	1.087	1.015	0.899	1.145	1.207	1.033	1.411

Region (age group)	Heat: RR	Heat: upper limit	Heat: lower limit	Cold low threshold: RR	Cold low threshold: upper limit	Cold low threshold: lower limit	Cold high threshold: RR	Cold high threshold: upper limit	Cold high threshold: lower limit
East Midlands (75 to 84)	1.051	1.017	1.087	1.143	1.041	1.254	1.222	1.083	1.378
East Midlands (85 years and older)	1.072	1.041	1.105	1.091	1.004	1.186	1.265	1.136	1.409
West Midlands (all)	1.048	1.031	1.066	1.145	1.093	1.200	1.310	1.230	1.395
West Midlands (0 to 64)	1.053	1.015	1.094	1.215	1.090	1.354	1.347	1.162	1.561
West Midlands (65 to 74)	1.062	1.022	1.103	1.140	1.019	1.275	1.294	1.114	1.503
West Midlands (75 to 84)	1.054	1.023	1.085	1.102	1.015	1.198	1.310	1.171	1.464
West Midlands (85 years and older)	1.035	1.008	1.063	1.147	1.065	1.237	1.298	1.173	1.435
Yorkshire and the Humber (all)	1.032	1.013	1.050	1.095	1.047	1.146	1.206	1.133	1.283
Yorkshire and the Humber (0 to 64)	1.009	0.968	1.052	1.107	0.996	1.230	1.096	0.946	1.271
Yorkshire and the Humber (65 to 74)	1.040	0.998	1.083	1.058	0.951	1.176	1.143	0.987	1.323
Yorkshire and the Humber (75 to 84)	1.054	1.022	1.088	1.103	1.019	1.195	1.209	1.083	1.350
Yorkshire and the Humber (85 years and older)	1.018	0.989	1.049	1.099	1.022	1.182	1.286	1.164	1.421
East of England (all)	1.069	1.050	1.087	1.131	1.075	1.191	1.292	1.218	1.370
East of England (0 to 64)	1.026	0.983	1.071	1.009	0.887	1.148	1.172	1.010	1.359
East of England (65 to 74)	1.050	1.007	1.095	1.009	0.886	1.149	1.153	0.994	1.336
East of England (75 to 84)	1.057	1.024	1.091	1.132	1.034	1.239	1.349	1.215	1.497
East of England (85 years and older)	1.099	1.070	1.128	1.220	1.129	1.317	1.351	1.236	1.477
Wales (all)	1.058	1.035	1.082	1.127	1.065	1.194	1.285	1.188	1.390
Wales (0 to 64)	1.065	1.011	1.122	1.077	0.941	1.233	1.257	1.041	1.518
Wales (65 to 74)	1.011	0.960	1.064	1.015	0.885	1.164	1.125	0.935	1.355
Wales (75 to 84)	1.056	1.014	1.101	1.131	1.019	1.254	1.411	1.222	1.628
Wales (85 years and older)	1.087	1.048	1.127	1.202	1.096	1.318	1.275	1.123	1.447
Scotland (all)	1.022	1.006	1.038	1.076	1.033	1.121	1.159	1.089	1.234
Scotland (0 to 64)	1.018	0.983	1.053	0.957	0.877	1.045	1.023	0.892	1.173
Scotland (65 to 74)	1.007	0.972	1.044	1.011	0.921	1.110	1.076	0.933	1.241
Scotland (75 to 84)	1.014	0.986	1.043	1.139	1.061	1.222	1.281	1.148	1.428
Scotland (85 years and older)	1.040	1.012	1.069	1.135	1.058	1.218	1.193	1.072	1.327
Northern Ireland (all)	1.023	1.010	1.035	1.112	1.075	1.152	1.249	1.175	1.327
Northern Ireland (0 to 64)	1.004	0.977	1.031	1.062	0.981	1.149	1.022	0.889	1.175
Northern Ireland (65 to 74)	1.007	0.981	1.034	1.037	0.958	1.121	1.144	0.996	1.315
Northern Ireland (75 to 84)	1.032	1.011	1.054	1.155	1.087	1.227	1.323	1.189	1.471
Northern Ireland (85 years and older)	1.032	1.011	1.054	1.138	1.073	1.206	1.369	1.236	1.517

Acronyms and abbreviations

Abbreviation	Meaning
AWHP	Adverse Weather and Health Plan
BC	bias correction method
CCRA	Climate Change Risk Assessment
DfE	Department for Education
dlnm	distributed lag non-linear model
EWD	excess winter deaths
HECC	Health Effects of Climate Change in the UK report
HIA	Health impact assessment
ONS	Office for National Statistics
RCP	representative concentration pathways
RR	relative risk
SH	shift method to adjust population data
UKCP	UK Climate Projections
YLL	years of life lost

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