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Projections of heat related mortality under combined climate and socioeconomic adaptation scenarios for England and Wales

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Abstract

This study projects heat-related mortality in England and Wales at Government region level under combined climate and socioeconomic scenarios, focusing on the implications of different pathways on adaptive capacity and resilience. Using UK specific climate projections and socioeconomic narratives, and employing a timeseries regression analysis we estimated the impacts of consistent pairs of Representative Concentration Pathways (RCPs) and Shared Socioeconomic Pathways (SSPs) on future heat-related health burdens. Our findings indicate significant increases in heat-related mortality under high emissions scenarios, with the highest burden observed in the RCP8.5-SSP5 scenario (2050s: 10,317, 2060s: 19,478, 2070s: 34,027), due to combined high temperatures and population growth and ageing in this scenario. Conversely, the lowest burden is seen under RCP2.6-SSP1 (2050s: 3,007, 2060s: 4,004, 2070s: 4,592), reflecting effective adaptation and lower warming levels. These values represent an increases from a baseline of 634 annual heat related deaths (1981–2021). The contribution of individual drivers, regional variations and the impact of potential power outages during heatwaves were also examined. These projections highlight the combined role of mitigation and adaptation, with a focus on resilience, in response to climate change and demonstrate that adaptation beyond the observed bounds will be required to limit heat related mortality to the baseline level even under low emission scenarios.

Introduction

Both heat and cold have been associated with mortality globally [1]. In the UK, periods of extreme heat are associated with excess deaths, with older people and

climate: Chess-Scape https://catalogue.ceda.ac.uk/uuid/8194b416cbee482b89e0df-be17c5786c/ Population and socio-economic variables: UK-SSP https://www.ukclimateresilience.org/products-of-the-uk-ssps-project/ The mortality data is not publicly available as it contains sensitive individual level information. Those wishing to access data of this nature would need to apply for access through ONS and may contact Health.data@ons.gov.uk in the first instance. https://www.ons.gov.uk/aboutus/whatwedo/statistics/requestingstatistics/makingarequest

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those with pre-existing conditions generally being more at risk [2]. Extreme heat is therefore a growing concern in the UK in the context of climate change and an ageing population. The proportion of the population aged 85 years and over is projected to double in the next 25 years [3] and periods of high ambient temperature are expected to increase in prevalence and intensity. For example, 2,139 excess deaths were attributed to the UK 2003 summer heatwave [4] and, under climate change, the summer of 2003 could represent a 'normal' summer by 2040 under RCP8.5 [5]. An estimated 1,928 heatwave deaths have been attributed to the 2018 heatwaves for the UK [6]. The UKCP18 headline report stated summers as warm as 2018 are 25% more likely due to climate change and could occur every other year by 2050 [7]. More recently, the summer of 2022 saw 2,985 excess deaths across the UK [8], and the UK experienced temperatures in excess of 40°C for the first time on record. This extreme temperature is considered to have been extremely unlikely in the absence of anthropogenic climate change and, in some areas in the UK, a statistical impossibility [9]. Under the 1.5°C global mean warming target, in line with the Paris agreement, a study focusing on regional changes found that in Northern Europe, a heatwave with a return period of 30 years under the baseline climate could occur every 5 years [10]. This highlights the impact climate change is already having on heat exposure and so adaptation is crucial even with strong mitigation efforts. Increases in heat related mortality and morbidity have been found under low emission pathways [11–13].

Adaptation to a warming climate is considered to occur through two key pathways, physiological acclimatisation to increased exposure and planned changes in behaviour or infrastructure. Physiological acclimatisation occurs within seasons with greater health effects during early season heat events than comparable events later in the year [14]. Inter-seasonal acclimatisation is expected to occur over longer periods [15]. Studies have reported reductions in heat risk over time [16,17] and between periods [15] in some settings. These were hypothesised to be attributable to the introduction of heat warning systems, increased air conditioning uptake and changes in other socio-economic factors relating to heat risk; the attenuation of risk was considered too significant to be associated with acclimatisation only.

Air conditioning (AC) uptake in domestic settings is currently low in the UK (2% to 5% in England [18]) but it is likely to increase with warmer summers [19] and may play an important role in protecting those most vulnerable to heat. Estimates suggest that up to 32% of English households may have air conditioning by 2050 [20]. The uptake of AC and its distribution across society will depend on socioeconomic development and the adaptation strategies implemented. Inequalities in affordability of both the units and the running and maintenance costs may lead to summer energy poverty in the UK [21] as seen in warmer climates [22–24]. During heatwaves, AC usage can cause power outages (blackouts or brownouts) due to surges in energy demand. Previous studies on the co-occurrence of power outages and heatwaves have found increased mortality on blackout days in the US [25,26]. AC use also contributes to emissions and expelled warm air can exacerbate the Urban Heat Island (UHI) meaning AC could contribute to an increase in heat related mortality [27].

The risk posed to health, wellbeing and productivity by increased exposure to indoor heat was included as one of eight priority areas for adaptation by the UK's Climate Change Committee in their latest risk assessment [28]. As such, work projecting the heat health burden is extensive. Vanos et al. (2020) [29] argue that many projections of the heat health burden neglect three key areas of uncertainty: adaptive capacity, population structure and bioclimate model structure, resulting in projections which do not represent the full range of uncertainty and may therefore be less effective at informing policy.

A systematic review found 55% of papers containing projections of heat related mortality did not include any population changes [30]. Where population changes have been included, these are most often limited to population growth, with some studies including ageing. Neglecting population changes led to an average under-estimation of the health burden of 64% [30].

Where adaptation has been included, the methods used are often oversimplified [31]. Adaptation scenarios are often defined as shifts in the threshold temperature or by applying a constant multiplicative adjustment to the exposure-response function, these rarely have an empirical basis [32]. There is evidence from observed evolutions of risk that health threshold temperatures have changed over time [17] and so understanding these changes may be an effective strategy for modelling risk [33]. Other methods involve using analogue locations and periods to assign an exposure mortality relationship from a similar climate, although this has limitations when considering long-term acclimatisation to one's local climate [32]. Socio-economic factors are likely to act as constraints, limiting adaptation action [34]. A handful of studies have included socioeconomic changes and their impact on vulnerability using composite indices [12,35]. These indices are based on regionalisations of the global Shared Socioeconomic Pathways (SSPs) and include indicators of education/awareness, income, environment, social cohesion and health. Rohat et al. 2019 [12] estimated increases in risk (as a function of vulnerability and exposure) at the national level for Europe but did not produce estimates of the health burden in terms of morbidity or mortality. The study found the proportion of the population at very high heat risk increased from 0.4% up to 20.3% under RCP8.5-SSP5. Wan et al. 2024 [35] used a similar index based on UK-SSPs to project heat-related mortality for Scotland. They explored how the Exposure Response Function (ERF) varies over time across the full temperature range to propose an empirical method for adjusting the ERF under adaptation assumptions. Another approach to modelling adaptation is to calculate directly the level of adaptation required to keep mortality within a given range. Masselot et al. 2025 [36] found risk attenuation of 50% would be insufficient in reducing the net temperature-related mortality burden to zero under a combined scenario of RCP7.0 and SSP3.

Recent heat-related mortality projections for the UK, produced as part of the Health Effects of Climate Change in the UK report (HECC), estimate 10,889 heat related deaths in the 2050s, approximately six times more than the present day [37]. These projections include a single population scenario (Office for National Statistics (ONS) central projection) and do not account for adaptation [38,39]. Another recent UK based study used a single population scenario (SSP5) and included adaptation, modelled as a shift in the mortality-temperature threshold. It was found that adaptation would not entirely mitigate climate changes [40]. A study which looked at changes in the ERF over time suggests that shifting the mortality-temperature threshold poorly represents observed variation in the ERF, with variation characterised by small changes in risk at low temperatures and large changes at high temperatures [35].

Projection studies often use the RCP-SSP framework to define future scenarios. The Representative Concentration Pathways (RCPs) are labelled in relation to the average radiative forcing each scenario represents at the end of the century. The RCPs represent forcings of 2.6, 4.5, 6.0 and 8.5 W/m^2 and more recently 1.9, 3.4 and 7 W/m^2. RCPs 7 and 8.5 assume emissions continue to rise unchecked, with remaining scenarios imposing varying levels of climate change mitigation [41]. The Shared Socioeconomic Pathways (SSPs) are a set of five divergent and plausible socioeconomic development narratives designed for use alongside the RCPs, allowing modellers to consider levels of potential adaptive and mitigative capacity [41]. Each RCP-SSP combination varies in plausibility, with RCPs aligning with multiple SSPs and vice versa, and some pairings being inconsistent [42–44]. Inconsistencies occur when the socioeconomic assumptions underpinning an SSP could not result in a certain level of radiative forcing. A review of heat-health projection studies found 80% of studies using this framework included at least one implausible scenario [30].

A cross-institutional project has sought to regionalise the SSPs for the UK [45]. The underlying assumptions of the global SSPs were used to create storylines for the UK and from these a range of projections were made across a number of indicators. The UK-SSP storylines and their implications for mitigation and adaptation are summarised below.

- **SSP 1: 'Sustainability'. The UK shifts toward environmentally sustainable and egalitarian systems bought on by the negative impacts of environmental degradation.**

  High capacity to mitigate and adapt to climate change.

- **SSP 2:** 'Middle of the road'. Strong public-private partnerships push public service reform and drive technological development. The gap between rich and poor increases despite improvements in the basic standard of quality of life.

  Medium challenges to climate mitigation and adaptation.

- **SSP 3: 'Regional rivalry'. International tensions with increased spending on manufacturing and defence. Natural resources and workers are exploited.**

  Limited capacity for mitigation or adaptation.

- **SSP 4: 'Inequality'. Decentralisation policies favoured to boost economic growth leading to the collapse of the welfare state and high levels of inequality.**

  High capacity to mitigate climate change, low adaptive capacity.

- **SSP 5: 'Fossil-fuelled development'. Reduced support for green policies and continued demand for low-cost fossil fuels. Technological advances counter environmental degradation and population increase leads to huge urban expansion.**

  Mitigation is impossible, high adaptive capacity.

Using the pathways projected above alongside climate projection information, this study projects the heat-related mortality burden for the 9 regions of England and Wales under a range of plausible future scenarios which consider climate, population and socioeconomic changes. Adaptation levels are derived and applied using the methodology of Wan et al. (2024) [35]. This study aimed to give an empirical basis to the inclusion of adaptive capacity for Scotland by characterising the observed change in risk over time and calculating a composite index for adaptative potential created as part of an expert workshop [46]. This extends previous UK projections by accounting for (mal)adaptation and considering a full range of population and climate development under the RCP-SSP framework. This study builds on the work of Wan et al. (2024) [35] by providing projections for England and Wales and by using the quantitative UK-SSP projections, as opposed to the semi-quantitative. These are available at higher spatial resolution meaning we are able to include regional differences in the adaptative capacity index.

Methods

The following methods section is split into three stages which make up the basis of the analysis, an outline of these stages is given below. Fig 1 gives a visual representation of the method.

Stage 1: Observed temperature and mortality data are used to estimate baseline region and age specific ERFs. During this stage, in addition to the overall ERFs for the whole observed period (1981–2020), sub-period (31 overlapping 10 year periods) ERFs are obtained.

Stage 2: The observed ERFs are transformed to obtain projected ERFs using a composite adaptive capacity index based on socioeconomic projections. The sub-period ERFs are used to measure temporal variation in the temperature-mortality

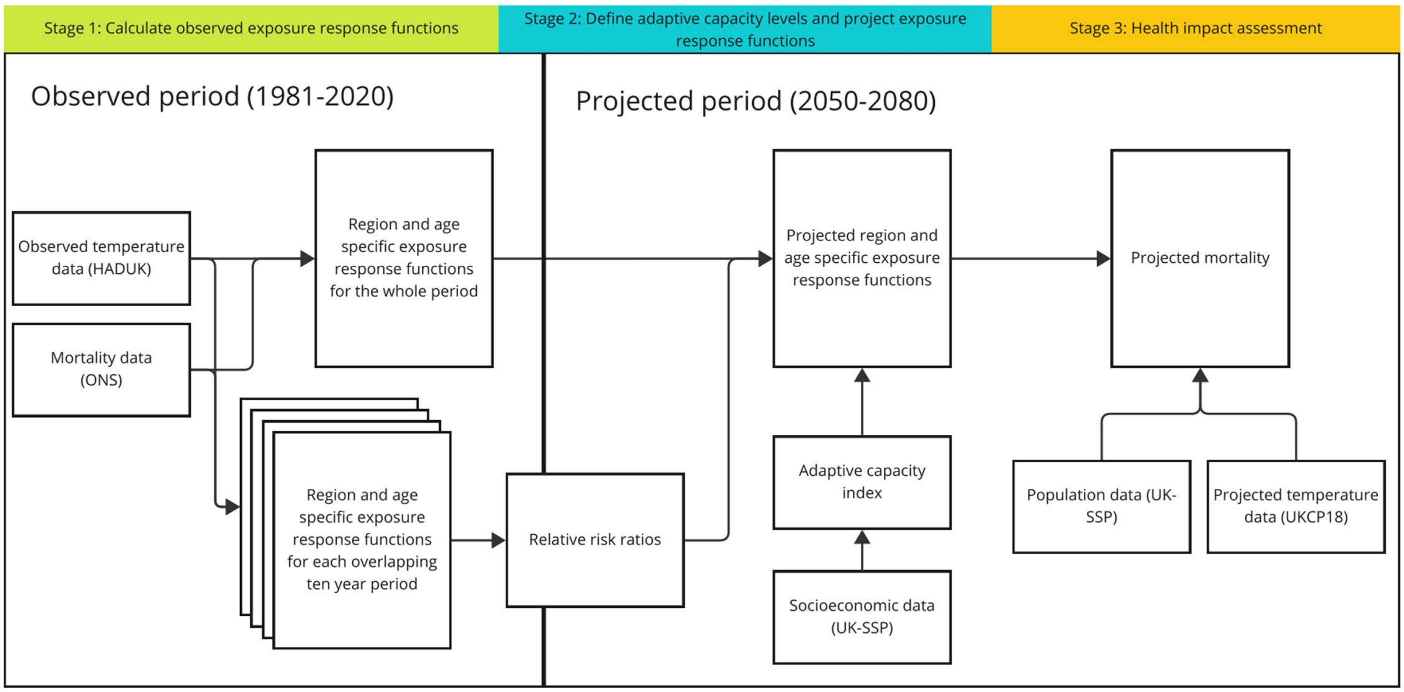

Fig 1. A visual representation of the three main stages which form the methods of this study. Stage one estimates the baseline ERFs, stage two then transforms these functions to obtain projections based on socioeconomic projections, finally stage three combines these with projected population and temperature data within a HIA to obtain estimates of the future heat-related mortality burden.

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relationship. This measure of variation is used to transform the ERFs according to increasing, decreasing and no change in adaptive capacity based on the composite index.

Stage 3: A health impact assessment (HIA) is implemented to estimate the future heat-related mortality burden by combining the projected ERFs with projected temperature and population data.

In addition, the contributions of each driver (climate, population and adaptive capacity) to the mortality burden are disaggregated to separate their relative importance in determining the burden. A power outage scenario is included to illustrate different levels of resilience associated with different adaptation pathways.

All the analysis is conducted at regional level for the 9 regions of England and Wales.

Stage 1: Calculate observed exposure-response functions

Data. To estimate observed ERFs we require daily mortality and temperature time series at regional level.

We use daily all-cause mortality for the period 1981–2020 provided by the UK's Office for National Statistics (ONS). This is stratified into four age bands (0–64, 65–74, 75–84, 85+) to allow for differences in the ERF by age to be captured and so to include population ageing in the projections.

From HAD-UK gridded data [47] we obtain regional temperatures by first using local authority district (LAD) population weighted centroids to assign a temperature time series to each LAD. We then assigned a regional temperature timeseries by calculating the population weighted average across the LADs for each region. We use average ($average = (max + min)/2$) daily temperature for the analysis presented here.

Epidemiological analysis. The ERFs were estimated for average temperature, region, and age group using a time-series quasi-Poisson regression analysis over the summer months (June to September) with distributed lag non-linear models (DLNM) and was implemented in R using the dlnm package [48].

The exposure-response was estimated using a cross basis defined by a natural cubic spline (NS) with two inner knots at the 30th and 70th percentile of the temperature distribution. This knot placement minimised the total deviance in our sensitivity analysis (S1 Table). Natural splines were used to allow for stable extrapolation beyond the observed temperature range, required for incorporating temperature projections under climate change.

Lags of 0–3 days were included to capture the effects of temperature on previous days. The lag-response association was modelled with a NS with 3 degrees of freedom. Long term trends and seasonality were controlled for using a NS with two degrees of freedom per summer. Day of the week was controlled for and entered the model as a factor with seven levels.

We did not control for potential confounding by air pollution or relative humidity, as little effect of confounding has been observed in previous studies for these exposures in relation to heat related mortality in the UK [49,50]. It has been suggested that whilst adjustment for temperature in air pollution studies is necessary the converse is not true [51].

The study period for the epidemiological analysis was 1st January 1981–31st December 2020. Separate models in this form were fitted for each age group and region both for the full period (1981–2020) and for 31 overlapping sub-periods (1981–1990, 1982–1991, etc) to obtain the ERFs.

Obtaining ERFs for the subperiods allows the variation in risk over time to be analysed. The ERFs can be used to define temperature specific Relative Risks (RR), i.e., the value of the ERF at a specific temperature. The degree of variation in risk across the 30-year period (1981–2020) was then estimated by calculating Relative Risk (RR) ratios [35] for each of the subperiods with reference to the RRs estimated for the whole period. The RRs for the whole period were used as reference when calculating RR ratios as a more robust estimate of the ERFs than each of the individual 10-year sub-periods.

Stage 2: Define adaptive capacity levels and project the ERF

To define adaptive capacity levels, we require socioeconomic projections for the future period (2050–2080) and an appropriate index. These adaptive capacity levels will then be combined with the observed ERFs and the corresponding temperature specific RR ratios.

Index definition and data. The UK-SSPs lay out five future pathways for the UK in line with those used in a global context by the IPCC [45]. Several products are available including fact sheets and system diagrams outlining the scenarios alongside semi-quantitative trends and quantified projections.

An adaptive capacity index for heat has been proposed by a previous study which drew on evidence from literature review and an expert workshop and uses the semi-quantitative trends which cover the whole of the UK as a single unit [46]. We adapt this index to allow calculations for each region using the UK-SSP quantitative projections, which contain a different set of indicators. The resulting index is as follows:

$$\begin{aligned} \textit{Adaptive capacity to heat} = \textit{Average}\ (&\textit{Income} - \textit{Income inequality} + \textit{Social cohesion} + \textit{Health care} \\ &+ \textit{Education} - \textit{Urban population} + \textit{Natural cover}). \end{aligned}$$

Indicators of income (average household income), income inequality (P80/P20), social cohesion (% of neighbours willing to help) and health care (GPs per capita) were available in the quantitative projections at LAD (Local Authority District), NUTS2 and NUTS3 (Nomenclature of territorial units for statistics 2 and 3) level. These were aggregated to region using population information from the UK-SSP projections to calculate weighted averages.

The semi quantitative trends have an indicator representing the level of public awareness of health-related, environmental and sustainability issues. This indicator is not present in the quantitative projections. Education was used as a proxy and aggregate to region through calculation of a population weighted average. Education was used by Wan et al. (2022) [46] in a sensitivity analysis for indicator selection in place of public awareness and did not alter the resulting adaptation level.

To calculate urban population, we used the European commission definition to identify urban centres both in the present and projected futures, that is '*urban centres (cities) must have a minimum of 50,000 inhabitants plus a population density of at least 1,500 people per square kilometre or density of built-up area greater than 50%'* [52]. The UK-SSP quantitative projections contain headcounts and a binary measure of land use (natural or artificial) on a 1km square grid [53]. We defined any 1km grid square with a headcount of over 1,500 as potentially urban. A 1km square buffer was added to these grid points and the dissolve function was used to combine neighbouring grid points into a single polygon. These polygons were then cleaned with any holes removed. For each of the resulting polygons we calculated the population and built-up area (based on the proportion of artificial land cover). Where the population was greater than 50,000 and the built-up area was greater than 50% we defined a city and counted the urban population. This is a conservative method of defining the urban population as all cities identified will have a population density over 1,500 when averaged over the total area. However, as we are interested in the trend (whether the urban population increases or decreases and by what magnitude) the main concern is to identify cities in a way that is consistent for each period and allows for urban expansion to be considered.

Each of the indicators above was expressed as a change from the observed period. These were normalised on a scale of {-1,1} before entering the index calculation. First the magnitudes where normalised between 0 and 1 and then signs where assigned based on whether an increase of decrease was observed.

Projecting the exposure response functions. Three adaptative capacity scenarios were defined by the behaviour of the adaptative capacity index: high, low and no change. Under the no change scenario, the 1981–2020 ERF was used directly for the HIA. Under the high and low adaptative capacity scenarios, the 1981–2020 ERF was modified using a set of RR ratios [35].

A linear approximation of each of the sets of RR ratios (one set for each sub-period and age group) is calculated, and the slopes compared. The set of RR ratios with the highest slope was applied under the low adaptative capacity scenario and the RR ratios with the lowest slope was applied under the high adaptative capacity scenario. When calculating the linear approximation, the RR ratios were calculated across the observed temperature range. The result is three sets of temperature and age specific ERFs for each region for use in the future period (2050–2080), representing low, high and no change in adaptative capacity.

The use of the temperature specific RR ratios results in an adjustment in the ERF more aligned to what is observed across different periods than when a constant adaptative capacity factor is applied across all temperatures. This is characterised by larger differences between ERFs at higher temperatures. Fig 2 illustrates the transformation of the ERF under a linear approximation of a set of RR ratios and a constant adaptation factor. Applying a constant adaptation factor results in an overestimation of risk at low exposures and an underestimation at high exposures.

Stage 3: Health impact assessment

For the HIA, the projected ERFs are combined with climate and population projections to estimate the future heat-related mortality burden. This requires a set of future scenarios with corresponding projection data. To disaggregate the effects of each driver (climate, population, and adaptive capacity) we also require the same information for the observed period.

Data. For the projected temperature data, we used the bias-corrected chess-scape project data, which extends the UKCP18 projections to include multiple RCPs [54]. This allows us to complete the HIA under RCP2.6, 4.5, 6.0 and 8.5 for the period 2050–2080 and for each of 4 model runs. Results are presented for the 2050s, 2060s and 2070s. The data is available at 1km grid and is aggregated to region in the same way as the observed temperature series to give a population weighted average.

We use the UK-SSP quantitative projections for population projections for each SSP [53]. The UK-SSP data gives headcounts for each Local Authority District (LAD) grouped by age. We aggregate this to regional level for the 9 regions of England and Wales (S1 Fig).

Population data for the observed period was obtained from the ONS census data for the years 1981, 1991, 2001, 2011 and 2021 [55]. The 1981 census population was used for the period 1981–1985, the 1991 census for 1986–1995 and

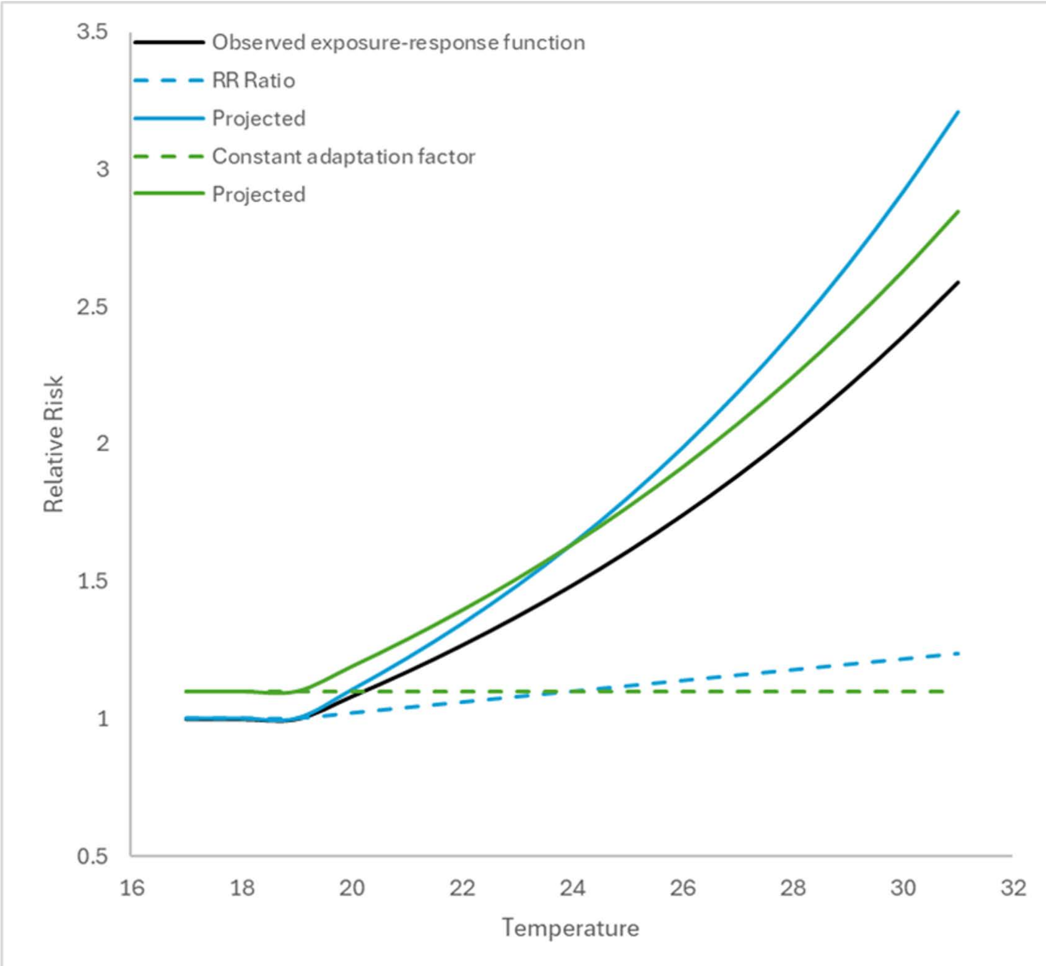

Fig 2. Illustration of projecting the ERF with an RR ratio (blue) versus a constant adaptation factor (green). Constant adaptation factors tend to overestimate differences in ERFs at low exposure and underestimate differences at high exposures compared to RR ratios derived from observed differences in ERFs. Note: this figure is a sketch and is not based on real data.

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so on. The observed temperature data is as described in stage 1. Observed adaptive capacity is equivalent to the 'no change' scenario, i.e., using the ERF for the 1981–2020 period.

Scenarios. In the HIA, we used the RCP-SSP framework to define a set of scenarios, this resulted in fifteen plausible pairings [44]. Table 1 shows the RCPs used alongside each SSP.

In addition to the quantitative index calculated in stage 2 we include a power outage scenario which represents the degree to which the heat adaptation pathway may be resilient to outages caused by power surges during heatwave events. Table 1 outlines how the UK-SSP storylines were used to inform heat adaptation storylines and resilience levels. For the power outage scenario, an extreme hot period (RCP8.5, model run 1, 08/08/2079-18/08/2079) was selected from the projected temperature data to represent a severe heatwave which could result in power outages. This period included 10 consecutive days exceeding the 95th percentile of the observed temperature series. Heat related mortality during this period was calculated under the ERF corresponding to the adaptive capacity index for each SSP and for either the high or low adaptative capacity scenario depending on the resilience to power outages based on the storylines presented in Table 1. This simulates the excess mortality due to a power outage under each scenario.

Table 1. Summary of the UK-SSP storyline with reference to their implications to heat adaptation and the RCPs consistent with each SSP.

SSP	Heat adaptation storyline	RCPs
SSP1	Improvements in health and healthcare and lower health inequalities reduce vulnerability to heat and improve access to care during heat events. Greater social cohesion allows mobilisation within the community to support vulnerable individuals. A rise in environmentalist attitudes and fall in consumption mean nature-based solutions and home improvements such as shading, shutters and green/cool roofs are favoured over air conditioning. High adaptation and resilience.	RCP2.6 RCP4.5 RCP6.0
SSP2	The collapse of the welfare state under this scenario increases inequalities in health and healthcare provision. Increased urbanisation moving towards city-states increases heat exposure due to the Urban Heat Island (UHI). Large inequalities and individualistic public attitudes mean some individuals have access to air conditioning with summer fuel poverty an emerging inequality. Medium adaptation and low resilience.	RCP2.6 RCP4.5 RCP6.0
SSP3	Falls in education and health spending and declines in health increase vulnerability. Urban sprawl and slums increase heat exposure as homes are not adaptable to high temperatures. Low adaptation and resilience.	RCP4.5 RCP6.0
SSP4	Overall decline in access to education and healthcare due to privatisation and income inequality increase vulnerability for most the population. Reduction in social cohesion means little support for vulnerable individuals within the community. Large inequalities and individualistic public attitudes mean some individuals have access to air conditioning with summer fuel poverty an emerging inequality. Low adaptation and resilience.	RCP2.6 RCP4.5 RCP6.0
SSP5	Increased urbanisation and continued use of fossil fuels mean greater exposure. However, technological advances and prosperity in the North of England reduce inequalities and most individuals have access to air conditioning. This may mean the population is vulnerable to power outages due to surges in demand during heatwaves especially under the sprawling development projected as a result of weak spatial planning policy and high population increase. Medium adaptation and low resilience.	RCP2.6 RCP4.5 RCP6.0 RCP8.5

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Analysis. For each of the identified plausible pairs of RCPs and SSPs (15 scenarios) we calculate the projected burden (M_T) via:

$$BMR = \frac{DMR}{RR_{tmean}}, \tag{1}$$

$$M_T = BMR * P * (RR_{tmean} * RR\ Ratio_{tmean} - 1)\,. \tag{2}$$

The calculation is performed for each day to obtain daily heat related mortality, with results then summed to give annual totals for each year in each model run. DMR is the daily mortality rate, calculated using the mortality and population time series for the observed period. BMR the baseline mortality rate, excluding heat related deaths. RR_{tmean} is the temperature specific relative risk, in the calculation of mortality this is first modified by the corresponding $RR\ Ratio$. The temperature specific RR and $RR\ Ratio$ are selected for each day using the value of $tmean$ extracted from the temperature time series. P is the population under each SSP at the middle of each decade.

The calculation is only implemented for 'hot days', where a temperature threshold is exceeded, this threshold was placed at the 95th percentile of the observed range and was selected as an approximate average minimum mortality temperature (MMT) across the 9 regions (S2 Table and S1 Text). This MMT percentile is within the range used across similar studies [56].

The calculation is also implemented for each of temperature change, population change and socioeconomic development in isolation with the remaining factors kept at the observed values to explore how estimated burdens respond to both overall and disaggregated changes.

Results

Throughout the results section the following region abbreviations are used to refer to the UK regions: North West (NW), North East (NE), West Midlands (WM) Yorkshire and the Humber (YH), Wales (WA), West Midlands (WM), East Midlands (EM), East England (EE), London (LN), South East (SE) and South West (SW). A reference map is included in S1 Fig.

Projected changes in climate, population and adaptive capacity

The number of hot days, i.e., days above the 95th percentile of the regional baseline (1981–2021) temperature series is projected to increase under all RCPs (Fig 3). For RCP2.6 this will mean an additional 21–32 hot days each year throughout the 2060s. For RCP8.5 an additional 64–73 hot days are projected for the same period.

Each SSP has implications for population change in terms of size and structure (Fig 4). Under SSPs 1, 2 and 5, population growth occurs across all regions and age groups. These SSPs also see population ageing, with the greatest increase in population size for those aged 65 and over. Under SSPs 3 and 4, a decline in the population aged 64 and under is projected (for the 2060s) and the population of adults aged 65 and over is projected to increase. Similar patterns are seen across all regions with differences in the size of these changes.

The referenced plots show the projections for the 2060s. Similar patterns are observed for the 2050s and 2070s and equivalent plots are provided in S2 Text.

Adaptive capacity, as described by the compound index outlined in the methods, is projected to increase under SSP1, remain constant for SSP2 and decrease for SSPs 3 and 4, these changes are consistent for all regions. Under SSP5 regional differences in the index are observed, with several regions exhibiting an increase in adaptive capacity and the remaining regions no change (Fig 5). The behaviour seen in the index for London under SSP5 is due to an initial decrease in education funding, followed by an increase in the following decades.

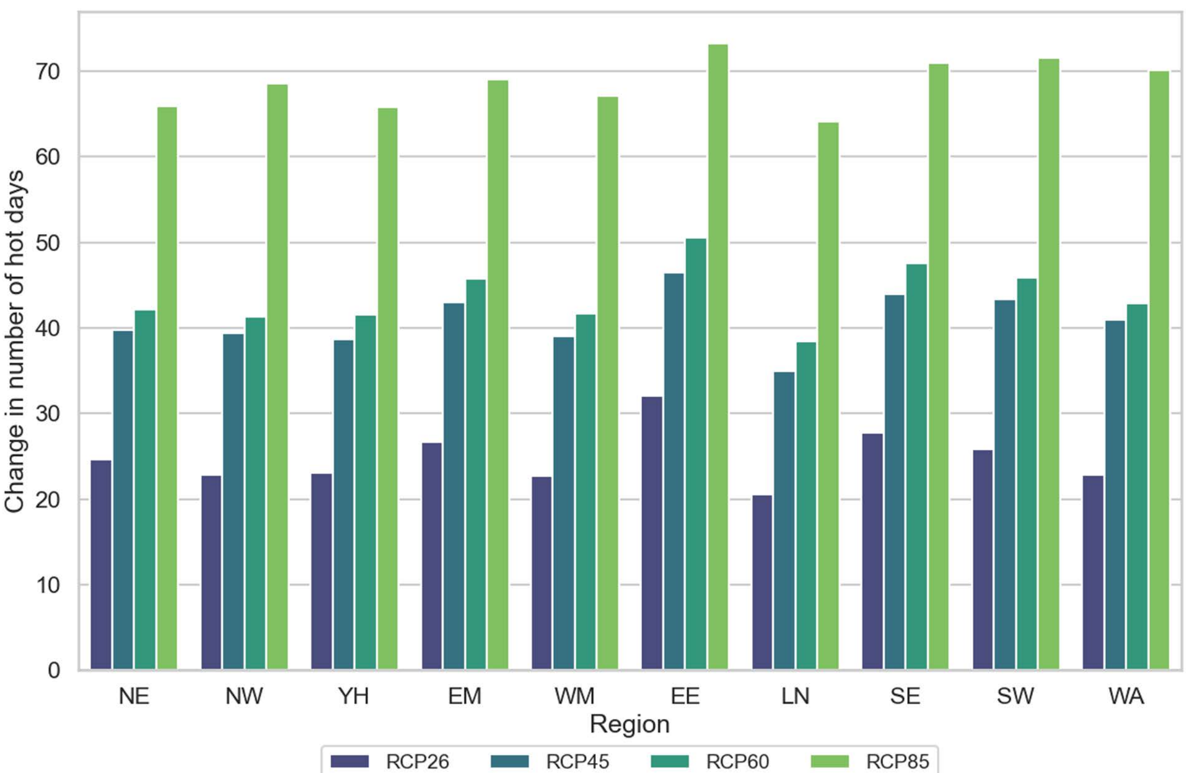

Fig 3. Descriptive plot showing the change in the number of hot days compared to the baseline period for each of the regions of England and Wales under the four RCPs for the 2060s.

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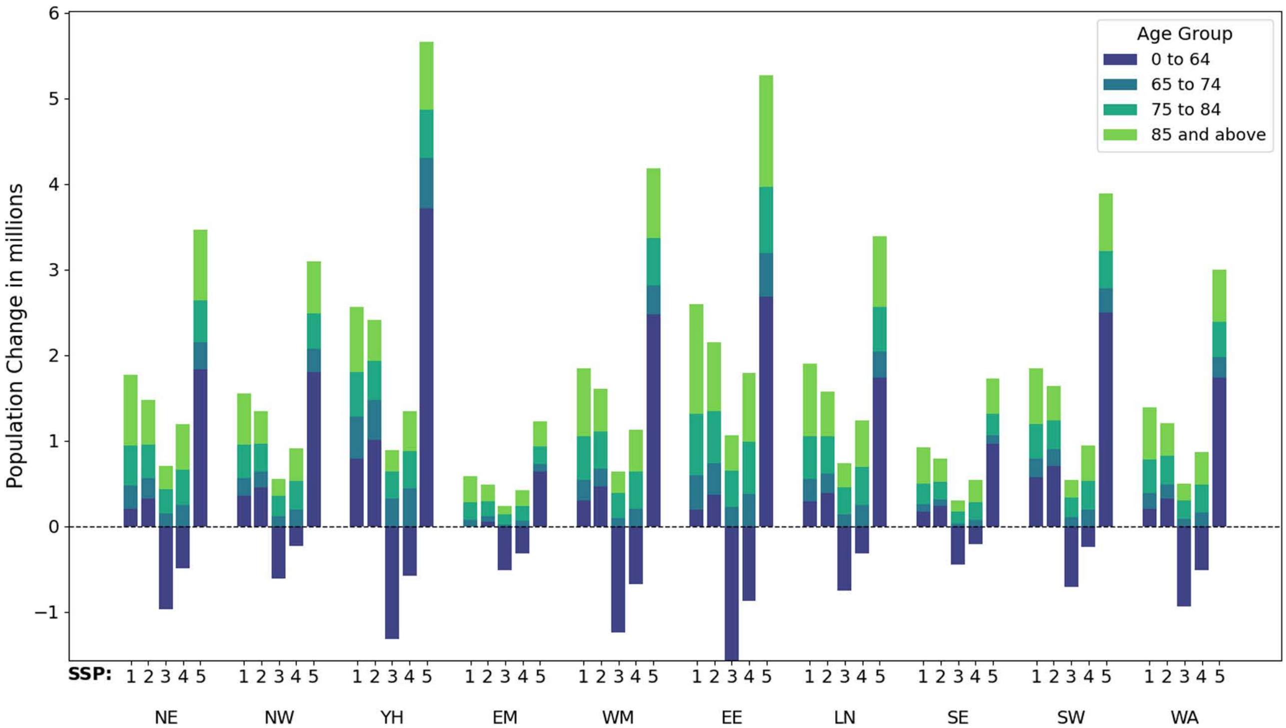

Fig 4. Descriptive plot showing the change in the population compared to the baseline period for each of the regions of England and Wales under the 5 SSPs for the 2060s.

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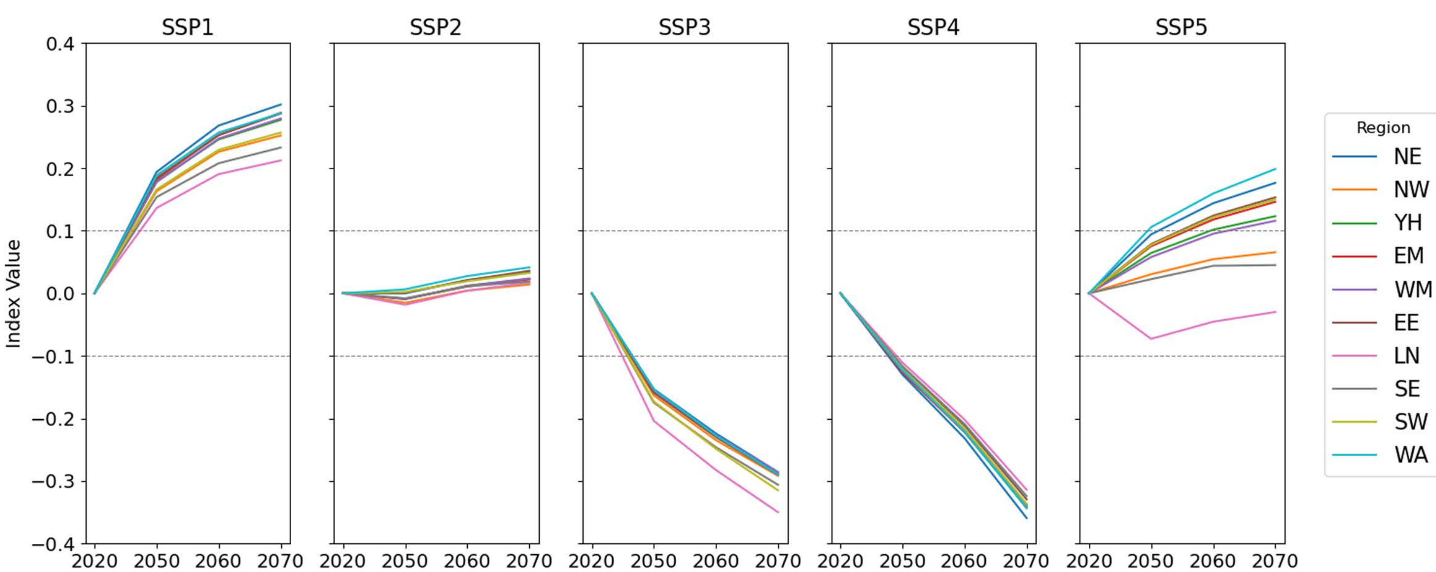

Fig 5. Descriptive plot showing the change is broken down into the four age categories. C: The adaptive capacity index plotted for each decade and region for the 5 SSPs.

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Projected relative risks

The RRs for the observed period, RR ratios, and the modified ERF are shown in Fig 6 for a single region (West Midlands) to illustrate the projection of the ERF. Equivalent plots for the remaining regions and all age-groups are included in S3 Text. The RRs over the observed period show a general decline over time for the West Midlands (Fig 6A). Across all regions there is no clear trend observed over time (S3 Text). Generally, the older age groups have higher associated risks, although this is not a universal observation and is likely due to low counts for some regions and periods, for instance in the more northern regions and earlier in the study period. The RR ratios give a plausible set of adaptation levels (Fig 6B and Fig 6D) with the highest and lowest slope being used to model low and high adaptative capacity respectively. The resulting ERF for 'high', 'low' and 'no change' in adaptive capacity are shown in Fig 6C and Fig 6E. Greater differences in RR are observed at higher temperatures.

Projected heat health burden

Fig 7 shows a matrix of plots containing the projected annual heat-related mortality for each period aggregated to England and Wales. Burdens generally increase from RCP2.6 to RCP8.5. SSP1 and SSP3 have the lowest associated burdens due to increases in adaptive capacity (SSP1) and population decline (SSP3). SSP2 and SSP4 have similar burdens, with SSP4 having a larger burden for the oldest age group (S2 Fig) due to higher population growth in this group.

Under the lowest emission scenario (RCP2.6), population changes are the largest driver of the heat health burden (Fig 8). As emissions increase, climate changes begin to dominate. Generally, adaptation has a comparatively small impact compared to these drivers. Also observed is an interaction effect, with the net effect being greater than the sum of the individual contributions. This occurs due to simultaneous increases in the vulnerable population and number of hot days.

The largest heat-related mortality burdens are observed under RCP8.5-SSP5 (2050s: 10,317, 2060s: 19,478, 2070s: 34,027) equivalent to approximately 50 times more heat-related deaths in the 2070s compared to 634 in the baseline period (1981–2021). The smallest heat-related mortality burdens are observed under RCP2.6-SSP1(2050s: 3,007, 2060s: 4,004, 2070s: 4,592), equivalent to approximately 6 times the observed heat-related deaths by the 2070s. Despite a relatively low level of global warming and high adaptive capacity across all regions, an increase in hot days combined with a significant increases in population size (in particular in those older than 65) results in significant increases in the burden compared to the observed period (Fig 7).

Regional variations. Fig 9 shows regional variation in heat-related mortality rate across a set of key scenarios, RCP2.6-SSP1 (low), RCP4.5-SSP2 (middle), and RCP8.5-SSP5 (high). For scenario RCP2.6-SSP1, the East Midlands, East of England, London, and the South East show markedly higher heat-related mortality rates compared to the other regions. The North East, North West, and Yorkshire and the Humber have relatively low heat-related mortality rates (below 5 deaths per 100,000 population). Little difference is seen across the decades studied as the climate and population remain relatively stable.

There is less variation between regions for RCP4.5-SSP2, with the lowest rates again in the North East, North West, and Yorkshire and the Humber, and marginally higher rates in the East Midlands, East of England, and the South East. For RCP8.5-SSP5, greater variation between regions is seen. Low heat-related mortality rates are observed in the North East and Yorkshire and the Humber, and high rates in the North West, East Midlands, London, and the South East. For both of these scenarios there are significant increases across the decades.

Power outage scenario. A power outage scenario was simulated for a period of 10 consecutive days which exceeded the threshold temperature (95th percentile of the baseline climate) for each region. The results for SSP1, SSP2 and SSP5 are presented here (SSP3 and SSP4 are not included as they already exhibit low adaptive capacity under the composite index).

For SSP1 the high adaptative capacity scenario was used for both the initial and power outage run, this results in no change in mortality attributable to the power outage. For SSPs 2 and 5 the initial run used the adaptive capacity level as

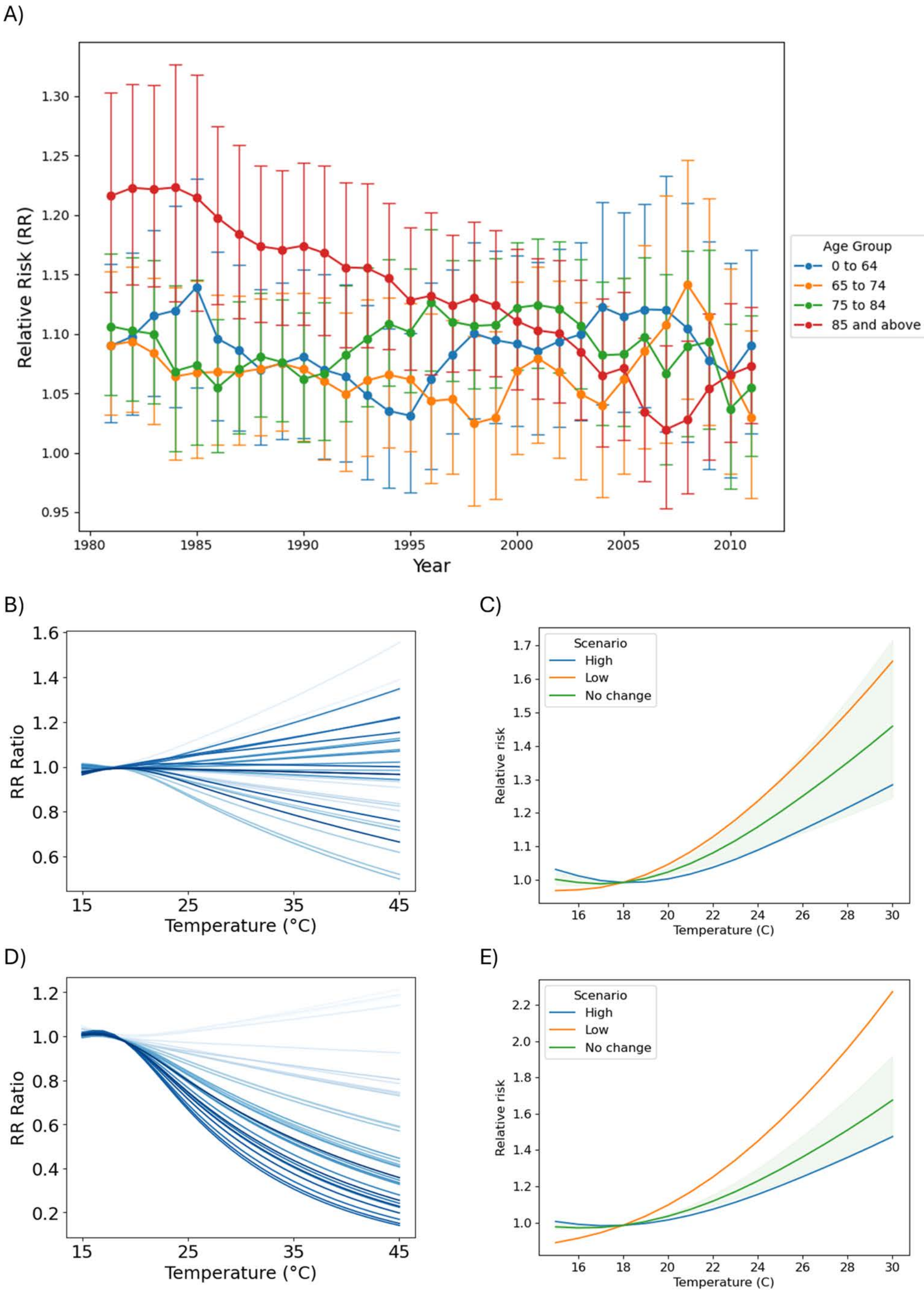

Fig 6. Collection of plots showing the modification of the RRs by the risk ratios extracted from the observed period, an illustration for the West Midlands region, similar plots for the remaining regions are included in. S3 Text. A: Plot showing the variation of the RRs over the observed period for the West Midland region. This is a snapshot of the temperature specific RRs at 24ºC. Points are plotted at the beginning of each 10-year period. B: The RR ratios for the West Midland region for the 0–64 age group. Each line represents one of the 31 overlapping 10-year time periods compared to the ERF for 1981–2021. Darker blues are more recent. C: The resulting RRs for the high, low and no change adaptive capacity scenarios for the West Midland and 0–64 age group. D: The RR ratios for the West Midland region for the 85 + age group. Each line represents one of the 31 overlapping 10-year time periods compared to the ERF for 1981–2021. Darker blues are more recent. E: The resulting RRs for the high, low and no change adaptive capacity scenarios for the West Midland and 85 + age group.

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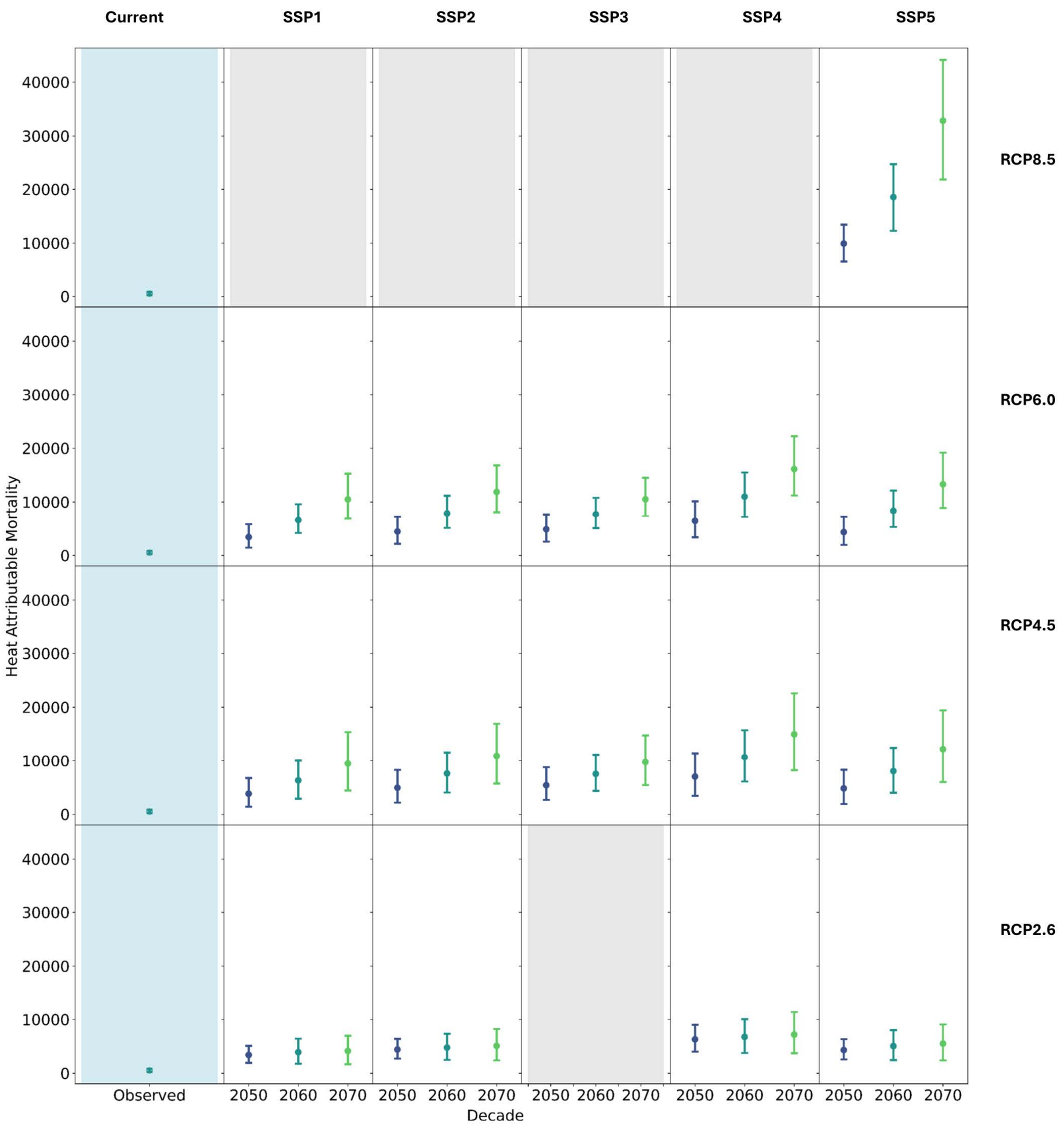

Fig 7. RCP-SSP matrix containing the estimated annual mortality for each scenario for England and Wales for each decade and the baseline period. The points are plotted at the median result and the bands represent the full range of values across the years in each decade and each of the four climate model runs. Reading along a single row can be interpreted as the difference in projected heat-related mortality due to changes in population and adaptive capacity (as these plots are for a single RCP). Reading down a single column can be interpreted as the difference in projected heat related mortality due to changes in climate (as these plots are for a single SSP). A similar matrix with disaggregation by age can be found in S2 Fig. RCP-SSP matrix plots for each region with the addition of age disaggregation can be found in S3 Text.

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defined by the index. The power outage run used the low adaptive capacity ERFs. These decisions are in line with the composite index and the adaptive capacity storylines presented in Table 1.

Table 2 shows the percentage of the heat-related mortality burden attributable to a power outage caused by a surge in power demand for AC over the 10-day period. For England and Wales, 16% (SSP2) and 27% (SSP5) of the heat related deaths over the heatwave period are attributable to the power outage.

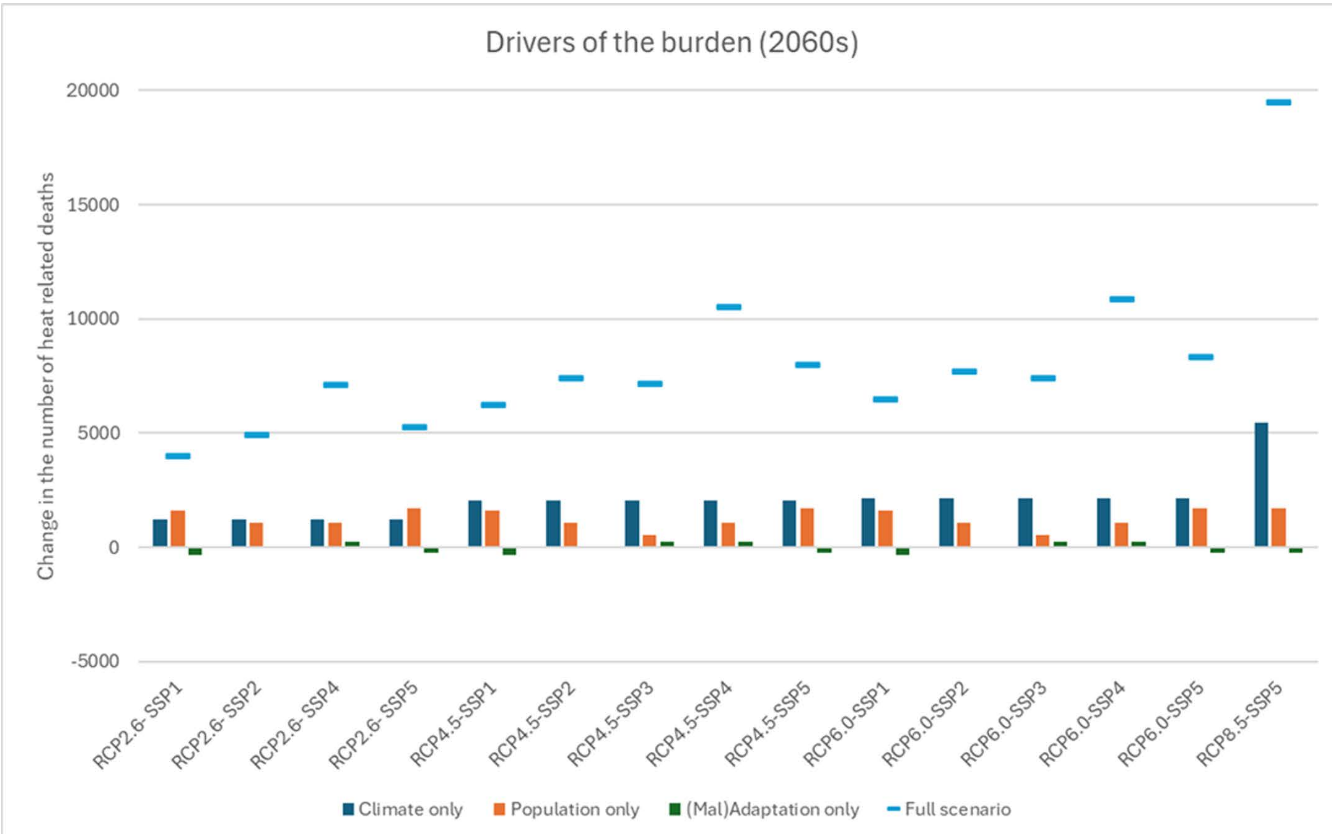

Fig 8. Plot showing the disaggregation of the estimated mortality burden by the three key drivers, adaptation, population and climate for each RCP-SSP pairing for the 2060s (the 2050s and 2070s show similar results and are included in S3 Fig). The x-axis is the difference in mortality from the observered period under each driver. The burden under the full scenario is given by the blue marker.

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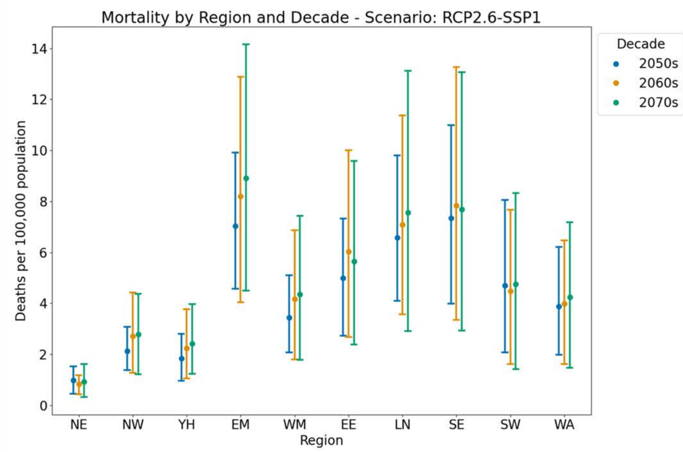
Discussion

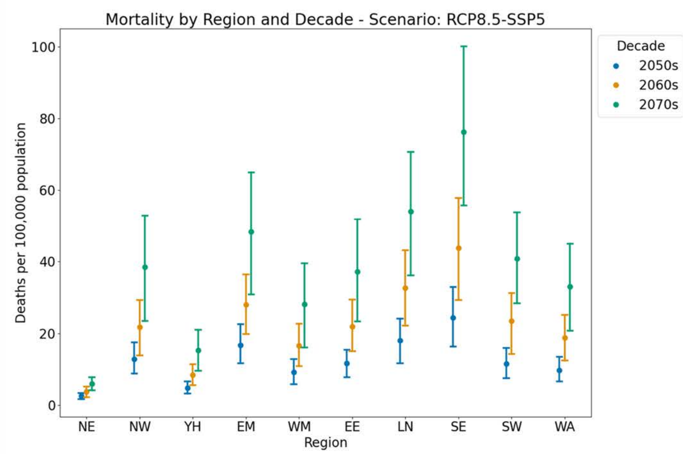
The future heat-related mortality burdens for England and Wales were projected for fifteen plausible RCP-SSP combinations at regional level, incorporating projected climate, population, and adaptive capacity changes. This extends previous projection work by providing projections for a more comprehensive set of scenarios and drivers and by improving spatial coverage and resolution. The adaptive capacity index has been adapted to use the quantitative UK-SSP projections to allow for its calculation at regional level, allowing differential development across regions to be captured. A novel power outage scenario is simulated in addition to the use of the adaptive capacity index to illustrate the potential implications of adaptation pathways relying on AC. By transforming the ERFs using RR ratios, developed by Wan et al. (2024) [35], adaptation in this study has a more empirical basis than studies where the ERF is either transformed by a single multiplier across all temperatures or by a change in threshold temperature [32]. We observe larger changes in risk at higher temperatures, with little change around the MMT, in line with the previous application for Scotland [35].

The highest estimated change in the heat-related mortality burden was under RCP8.5-SSP5, the combination of high temperatures alongside significant population growth and ageing do not appear to be mediated by the increased adaptive capacity projected in several regions. The lowest burden is predicted under RCP2.6-SSP1. Despite both having high population growth, in particular for those aged 65 and above, this is mediated in RCP2.6-SSP1 by lower temperatures and high adaptive capacity across all regions. The increase in mortality under this scenario is still significant and highlights

A)



B)



C)

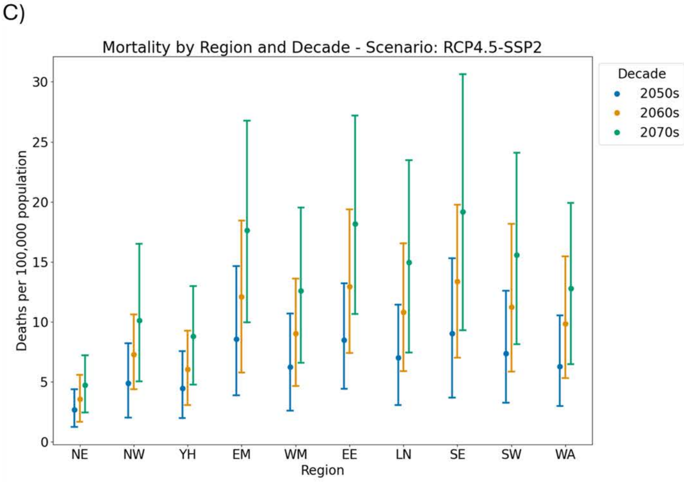


Fig 9. Collection of plots showing regional variation in heat-related mortality rate under three key (a: RCP2.5-SSP1, b: RCP4.5-SSP2 and c: RCP8.5-SSP5) scenarios for each decade. Note the vertical scales are different in each plot. The points are plotted at the median result and the bands represent the range of values across the years in each decade and each of the four climate model runs. The mortality is given as a rate per 100,000 population to allow differences beyond population size to be seen.

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Table 2. Percentage of heat-related deaths attributable to a power outage during a future heatwave period (RCP8.5, model run 1, 08/08/2079-18/08/2079) under adaptation assumptions for SSP1, SSP2 and SSP5.

Regions	Attributable Fraction		
	SSP1	SSP2	SSP5
NE	0%	37%	75%
NW	0%	10%	9%
YH	0%	20%	49%
EM	0%	14%	24%
WM	0%	29%	47%
EE	0%	5%	28%
LN	0%	19%	19%
SE	0%	11%	10%
SW	0%	20%	37%
WA	0%	9%	29%
England and Wales	0%	16%	27%

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the need for concerted mitigation and adaptation efforts to protect health in a changing climate. Maladaptation in some regions and population growth in excess of the ONS central projection explain the larger burdens (34,027 in the 2070s under RCP8.5-SSP5) estimated here than in previous work [38,39] which estimated the burden to be around 21,000 under RCP8.5 in the 2070s. The projections from this study are in line with previous studies incorporating climate, population and adaptation under the RCP-SSP framework within Europe. Under RCP8.5-SSP5 we project 53 times more heat-related deaths, for this scenario Wan et al. (2024) [35] projected an increase of 61 times and Rohat et al. (2019) [12] an increase in the at risk population of 40 times.

The combination of warming, population change and adaptation is greater than the sum of the individual components, with net changes in mortality much higher than those predicted under a single driver. This finding is consistent with the literature and is discussed in detail in Liu et al. (2027) [57]. This interaction demonstrates the importance of considering each of these drivers together when projecting temperature related mortality, excluding a driver will likely result in large underestimations of the burden [30].

We do not look at cold-related mortality in this study as the health mechanisms and policy implications of these two exposures are different. It has been suggested a 'net benefit' to climate change could occur due to a decrease in temperature-related mortality, driven by a reduction on cold days. Observed annual cold-related mortality in the UK is estimated to be in the order of 50,000 excess deaths each year [2,58,59]. This would require a reduction of 8% under RCP2.6-SSP1 and 67% under RCP8.5-SSP5 to maintain a constant temperature-related mortality burden. Studies for the UK have projected declines in cold related mortality as high as 31% (without population ageing) [58] and as low as 2% (with population ageing) [60]. Wan et al. (2024) [35] found that, for Scotland, heat would become a more important health determinant than cold across all scenarios by 2080.

Regional difference in rates of heat-related mortality were observed. Generally, the Northern regions have lower heat-related mortality rates, likely due to their cooler climates. High rates in London and the East of England may occur due to greater urbanisation (leading to a larger UHI effect) in these areas and warmer climates in the south of the country. London also showed no change in adaptive capacity and so may experience greater vulnerability within the population than other regions where adaptive capacity improved. The higher levels of mortality seen in the East Midlands are likely due to population ageing, with very little increase in the younger age group, and a relatively large increase in hot days (Fig 3). The greatest regional variation is observed for RCP8.5-SSP5, likely due to variation in adaptive capacity under SSP5, which is not seen in the other scenarios.

The power-outage scenario is used to stress-test the heat adaptation storylines. This back of the envelope calculation highlights the importance of considering the narratives behind the SSPs when using these to model adaptive capacity. Different pathways may result in similar index values but have varied implications for resilience and equity. For example the SSP1 and SSP5 pathways both see improved adaptive capacity in a number of regions. Under SSP5 this is solely driven by higher incomes and access to healthcare, with modest improvements in access to education. Under SSP1 these institutional factors are bolstered by greater social cohesion, reduced inequalities and significantly lower environmental degradation (compared to SSP5). Our findings from the blackout scenario are broadly in line with observational studies on the impact of multiday power-outages during heatwaves. During the 2003 power outage in New York City an increase in mortality of 28% was observed [25]. Another study of historical heatwaves and power outages across three US cities found the outage over doubled the heatwave attributable mortality [26].

Strength and limitations

A key strength of this study is the use of RR Ratios to modify ERFs in a way that reflects the temporal variation observed in these functions, this results in more realistic projected ERFs. The inclusion of climate, population and adaptive capacity changes across a comprehensive set of plausible RCP-SSP pairings gives a range of projections to capture uncertainty and represent the potential pathways and their implications for heat related mortality. The power outage scenario is a novel approach which begins to incorporate the concept of resilience into the HIA framework. Conducting analysis at regional level is important for policy prioritisation and reduces the potential for spatial inequalities in risk to be masked under national aggregations.

The nature of projection studies means they are subject to uncertainties from several different sources. Rather than attempt to quantify these unknowns, this study addresses uncertainty in the future burden by including a range of drivers (climate, demographic and socio-economic) across a set of divergent future scenarios to provide a range for the projections. Bespoke datasets for the UK context are chosen to best represent the impact under RCPs (chess-scape) and SSPs (UK-SSP project) for this setting at high spatial resolution and for a full set of scenarios. A sensitivity analysis under different data choices is not possible as these are the only sets available which enable the analysis presented. We do, however, put our results in the context of the wider literature and find the projections are consistent in magnitude to similar work.

Extrapolation of the ERF beyond the observed temperature range is required to produce projections of climate change impacts. This introduces uncertainty as it is not given that the observed trend will continue. Using natural cubic splines to model the ERF enables more stable estimations and avoids overfitting because the data around the extreme is very sparse. This assumes a log-linear relationship beyond the boundary knot. It is likely that the extrapolated heat effect is an underestimation of the actual effect [61].

By considering relative risk ratios within the observed range, high adaptation is likely to be underestimated in this study as adaptation measures for heat in the coming years may be greater than the observed period. As the climate warms, the UK may begin to develop a 'heat culture', more commonly associated with warmer countries. This concept, which contains many of the aspects included in our index, describes the elements that explain the heat adaptation process [62]. Currently the UK lacks a heat culture and so the development of this would accelerate the adaptation process beyond the observed variation. However, our results highlight the importance of such measures and developments as adaptation within the observed ranges has little impact on the heat health burden. The index includes indicators of risk established in the literature [12,35,46], however, it is not certain that these are the key indicators of risk, how each should be weighted or how these map to changes in the ERF. By including a range of adaptation levels we give a range of estimates which better capture the uncertainty in the projections than by not including this element. In addition to this we include estimates for each of the drivers in isolation to give projections under the counterfactual, whereby the current population is exposed to the future climate.

Future work would seek to estimate the mortality burden under more explicit adaptation pathways. Work has been done to formalise these pathways in the case of urban greening, building improvement or air conditioning use [27]. Integrating these and behaviour change into HIAs is an important aspect of future work to better inform policy.

Misallocation of the exposure is likely as this was allocated at a regional level and so does not reflect the differences in temperature experienced due to local climates. Regional temperature timeseries were obtained from population weighting of the 1km grid. This improves the representativeness of this exposure allocation compared to geographical centroid temperatures or an unweighted average.

We use the same threshold percentile (different absolute temperature threshold) across all regions and do not alter the absolute temperature threshold for the future period. This may reduce the regional differences observed in heat risk and mortality. The threshold was placed based on the observed MMTs and threshold values used in the existing literature [56]. Threshold placement does not affect RR but does impact the number of hot days included in the analysis [63] and so keeping the threshold constant allows for more direct comparisons of the health burden.

Conclusion

This study highlights the impact of combined climate, population and socioeconomic factors on future heat-related mortality across the 9 regions of England and Wales. Our projections show that under scenarios with high emissions and ongoing socioeconomic inequalities (RCP8.5-SSP5), the heat health burden could increase significantly (~50 times) due to higher temperatures and substantial population growth, especially among the elderly. On the other hand, scenarios with effective mitigation and high adaptive capacity (RCP2.6-SSP1) exhibit much lower increases in heat-related deaths despite population growth. These lower increases are still significant (~6 times) and so adaptation beyond the observed variation in risk is required to mitigate the health risks. The study also revealed regional differences in mortality rates and estimated up to 27% of the heat-related mortality burden during a severe heatwave may be induced by power outages, illustrating the need for comprehensive adaptation strategies which prioritise both resilience and equity.

Supporting information

S1 Fig: Reference map of the regions of England and Wales.
(TIF)

S1 Table: Sensitivity analysis altering the positioning of the knots (k1 and k2) in the exposure response dimension and the number of degrees of freedom for the NS representing the lag response function (df1) and per year for seasonality (df2). The estimated attributable mortality (attr) and an upper (ub) and lower (lb) bound (derived from monte-carlo simulations) are given for each model and the model deviation (summed across the regions). The model with the lowest deviance is highlighted and is the model selected.
(XLSX)

S2 Table: Minimum mortality temperatures for each region and the corresponding percentile. These were calculated by minimising the exposure-response function for the model as described in the methods but without stratification by age.
(XLSX)

S1 Text: Exposure response function for each region for the whole period not stratified by age. These are used to extract the minimum mortality temperature.
(DOCX)

S2 Text: Projections for changes in hot days and population for 2050 and 2070 as presented for 2060 in the text.
(DOCX)

S2 Fig: RCP-SSP matrix for England and Wales containing the estimated annual mortality for each scenario, region, age group and decade as well as the baseline period. The points are plotted at the median result and the bands represent the range of values across the years in each decade and each of the four climate model runs.
(TIF)

S3 Text: The following pages contain a collection of figures corresponding to figure 6 and figure 7 in the main text for each region and age group. To avoid duplication of captions a single set of descriptions is included.
(DOCX)

S3 Fig: Disaggregation of the drivers of the heat health burden for the 2050s and 2070s as presented in the main text for the 2060s.
(TIF)

Author contributions

Conceptualization: Rebecca Cole, Kai Wan.

Formal analysis: Rebecca Cole.

Funding acquisition: Shakoor Hajat, Clare Heaviside.

Supervision: Peninah Murage, Helen L. Macintyre, Shakoor Hajat, Clare Heaviside.

Writing – original draft: Rebecca Cole.

Writing – review & editing: Rebecca Cole, Kai Wan, Peninah Murage, Helen L. Macintyre, Shakoor Hajat, Clare Heaviside.

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