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Updated projections of UK heat-related mortality using policy-relevant global warming levels and socio-economic scenarios

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Abstract

High temperatures and heatwaves are associated with significant impacts on human health. With continued global temperature increases, extreme thresholds relevant to health will be exceeded more frequently. This study provides an updated spatial analysis of heat-related mortality for the UK, using the UK Climate Projections (UKCP18) at 1.5 to 4°C global warming levels, and embedding population and demographic data from the recently released UK Shared Socioeconomic Pathways (UK -SSPs). Climate change will lead to an increase in heat-related mortality in the future, exacerbated by increased exposure due to increasing population. We find an increase from ~1,400 average annual deaths in the near-past (1990-2019) (95% CI: 1299 to 1485), to ~2,500 (2304 to 2794), ~3,700 (3280 to 4214), ~8,200 (7376 to 9072) and >18,000 (16,690 to 20,394) average annual deaths at 1.5, 2, 3 and 4°C respectively (assuming no adaptation). This is considered a high-end estimate due to the assumption of high population growth (UK-SSP5). Older populations are shown to be most vulnerable. A large proportion of heat-related deaths (76% (74 to 79%) with 1.5°C global warming) are attributed to more moderate (1-5°C) increases above regional temperature thresholds as opposed to extremes. Our results provide a timely update that can serve as a first step to supporting future UK climate policy and risk assessments. Future research considering nonlinearity in the health response to heat exposure is vital.

1. Introduction

High temperatures and heatwaves are associated with significant impacts on human health. Healthy individuals have efficient heat regulation mechanisms to help cope with increasing temperature, with skin temperature strongly regulated at 35°C or below under normal conditions [1]. However, there are limits to the amount of heat exposure even a healthy and acclimatised individual can tolerate [2]. Exposure to high temperatures can cause heat exhaustion and heat stroke and increase the risk of heat-related mortality [3]. Other consequences can include impacts on mental health, wellbeing, and hospital admissions [e.g. 4]. Risks from high air temperatures are amplified where humidity is higher because evaporative heat-loss is reduced in a humid environment [5]. Older people, babies and young children, and those with underlying health conditions, are particularly at risk from heat stress [6–8].

Globally, 37% of warm-season heat-related deaths during 1991–2018 have been attributed to anthropogenic climate change, with increased heat-related mortality seen on every continent [9]. The IPCC [10] highlights with continued global temperature increases, extreme thresholds relevant to health will be exceeded more frequently by 2050. The ageing global population is also projected to drive an increase in vulnerability to heat [6]. Additionally, the projected increase in urban populations and urban development could increase exposure to heat, given the influence of urban heat island effects, particularly on night-time temperatures [7,11–14].

In the UK, high temperatures and heatwaves are already associated with substantial impacts on society. In England, heatwaves in 2006 were associated with 2,323 excess deaths [8]. In 2020, 2,556 extra deaths were reported for three heatwave events in England [15]. In the future, projections of increasing temperatures across the UK are expected to exacerbate current heat-related impacts, if adaptation is not increased. It is important to assess future heat-related mortality associated with both climate change and socio-economic change.

Numerous heat stress indicators have been developed to guide heat warnings and quantify effects of heat exposure on morbidity, mortality, or productivity [16]. One approach is statistical methods that estimate associations between climate variables and epidemiologic data on morbidity or mortality to create exposure-response functions (ERFs) that are often found to be nonlinear [e.g. 3,6,17,18].

Vardoulakis et al. [19] created linear regional and age specific ERFs for England and Wales based on reported daily counts of all-cause mortality and observed temperature and relative humidity. Future mortality was estimated based on projections of daily mean temperature (TMean) from the UK Climate Projections 2009 (UKCP09), at a resolution of $25km^2$ averaged for 10 regions. Hajat et al., [20] created similar linear ERFs for the UK. Future mortality was estimated based on projections of daily TMean from nine variants of the Met Office Hadley Centre Regional Climate Model (HadRM3-PPE-UK), at a resolution of $25km^2$ averaged across regions.

Jenkins et al., [21] took an average of pre-existing linear ERFs created for London [22–24] to estimate future mortality risk for this region, using high spatial resolution probabilistic projections of urban temperatures from a spatial Weather Generator ($5km^2$, based on UKCP09) that also incorporated the effects of urban land use and anthropogenic heat emissions. The study also considered the role of autonomous or planned adaptation in reducing heat-related mortality by adjusting the regional ERF thresholds by 1 and 2°C. However, limited consideration was given to the types and feasibility of specific adaptation actions this would represent [25].

Recently, Huang et al., [18] applied non-linear ERFs to examine the impact of climate change on all-age temperature-associated mortality in England and Wales relative to degrees of global warming. The study utilised the UK Climate Projections 2018 (UKCP18), using global projections at 60km resolution, averaged for ten geographic regions. Here we include more spatially explicit UKCP18-based projections, considering the effects of population and demographic change, and the potential for natural acclimatisation or adaptation.

1.1. Aims and Objectives

The latest Climate Change Risk Assessment (CCRA3) report for the UK highlighted the urgent need for more action to manage and adapt to risks to health from high temperatures [8]. To do this, high-resolution heat-related mortality projections with consideration of socio-economic changes are needed. Using existing linear ERFs and placing a strong emphasis on the effects of population changes and adaptation, this study builds upon previous assessments for the UK by:

1) Providing up-to-date and spatially explicit projections of heat-related mortality risk in the UK based on the latest UKCP18 regional (12km) data
2) Incorporating the recently released UK-SSP projections [26] to include population and demographic change as key components of exposure and vulnerability [e.g. 6,27].
3) Presenting results at 1.5, 2, 3 and 4°C warming reached in 2020, 2030, 2050 and 2100, to allow risks to be considered in a more policy-relevant manner.
4) Considering the sensitivity of heat-related mortality to additional adaptation in the form of natural acclimatisation to heat represented by 1) spatially explicit adjustments related to modelled temperature distributions and 2) uniform adjustments to the ERF thresholds.

2. Method

2.1 Climate data

Daily mean temperature (TMean) was taken from the UK Met Office's UKCP18 twelve member regional climate model (RCM) ensemble at 12 km resolution [28]. This data was bias corrected using ERA5 reanalysis [29] following the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP) 2b bias correction method [30–32], as applied in Kennedy-Asser et al. [33]. For each global warming level, daily TMean data for each 30-year period, representative of the different levels of global warming above pre-industrial temperatures, were extracted. The 30-year time periods for each global warming level were based on start and end years published in Arnell et al. [34], with the exact years for each global warming level varying slightly between UKCP18 RCM simulations. We note that this approach approximates each global warming level, and that the true climate at an equilibrated global warming level will be different from the transient global warming level presented here. However, the error this introduces may be less significant for UK summer temperatures than other regions of the world [35, Figure 2a]. UKCP18 RCM simulations follow CMIP5 historical climate forcing until 2005 then representative concentration pathway 8.5 (RCP8.5) until 2080.

2.2 Heat Adaptation and Risk Model (HARM)

HARM has been developed to investigate heat-related risk for the UK, building on the earlier ARCADIA Impact Model which provided a probabilistic assessment of heat-related risk in London and the surrounding region [21].

Heat-related mortality (Eq. 1) is calculated using linear ERFs described in Vardoulakis et al., [19] and Hajat et al., [20]. These studies provide estimates of regional temperature thresholds, occurring at the 93rd percentile of daily TMean, and linear exposure-risk relationships, which specify the percentage change in the daily mortality rate for every 1°C increase in temperature above the threshold. The linear ERFs were selected as they provide data for each UK government region[1], for all ages, but also split by age groups (0-64; 65-74; 75-84; 85+) (Table 1). We note that all-age nonlinear ERFs have been developed for the UK in recent literature [e.g. 3,36], and while age-specific ERFs have also now been published [37], they were not available at the time of research. We discuss the limitation of using linear ERFs in Section 4 and Supplementary section 3.

		Exposure-risk relationship (ER) (% change)				
Region	**TMean Threshold (°C)**	**All Ages**	**0-64**	**65-74**	**75-84**	**85+**
North East	16.6	1.2 (0.5, 1.9)	-0.3 (-1.9, 1.3)	2.1 (0.7, 3.6)	2 (0.8, 3.3)	0.2 (-1.3, 1.6)
North West	17.3	1.6 (1.2, 2)	1.4 (0.5, 2.3)	0.6 (-0.3, 1.5)	1 (0.3, 1.8)	3.1 (2.3, 3.9)
Yorkshire and Humber	17.5	2 (1.5, 2.6)	0.5 (-0.8, 1.7)	2.4 (1.3, 3.6)	1.6 (0.8, 2.5)	3.3 (2.3, 4.3)
East Midlands	17.8	2.9 (2.3, 3.4)	1.8 (0.5, 3.1)	1.5 (0.3, 2.7)	3.2 (2.2, 4.1)	4.2 (3.2, 5.2)
West Midlands	17.7	2.5 (2, 3)	1.8 (0.7, 2.8)	2.4 (1.4, 3.4)	2.3 (1.5, 3.1)	3.4 (2.5, 4.3)
East of England	18.5	2.8 (2.3, 3.4)	2.2 (0.9, 3.5)	1.6 (0.5, 2.8)	2.9 (2, 3.8)	3.8 (2.9, 4.7)
London	19.6	4.5 (4, 4.9)	2.8 (1.9, 3.7)	2.5 (1.6, 3.4)	4.8 (4.1, 5.6)	6.4 (5.7, 7.2)
South East	18.3	3 (2.5, 3.4)	1.5 (0.4, 2.5)	2.5 (1.6, 3.5)	2.1 (1.4, 2.8)	4.7 (4, 5.4)
South West	17.6	2.4 (1.8, 2.9)	0.8 (-0.6, 2.2)	2.3 (1, 3.6)	2.6 (1.6, 3.5)	2.9 (1.9, 3.8)
Wales	17.2	2.1 (1.5, 2.7)	0 (-1.5, 1.5)	1.5 (0.2, 2.9)	2.2 (1.2, 3.3)	3.4 (2.2, 4.6)
Scotland	16.6	1.2 (0.5, 1.9)	-0.3 (-1.9, 1.3)	2.1 (0.7, 3.6)	2 (0.8, 3.3)	0.2 (-1.3, 1.6)
Northern Ireland	17.3	1.6 (1.2, 2)	1.4 (0.5, 2.3)	0.6 (-0.3, 1.5)	1 (0.3,1.8)	3.1 (2.3, 3.9)

Table 1: Regional daily TMean thresholds and corresponding exposure-risk relationships for each age group category (95% CI) [19,20].

TMean thresholds and exposure-risk relationships in Table 1 are applied homogenously to all 12km grid cells that fall within the spatial boundary of a given region. This is a necessary simplification given the regional age-specific ERFs applied here will not reflect localised variability in the exposure response within these regions. Daily heat-related mortality (*M*) is calculated for each age group category (*a*), per day (*k*), grid cell (*j*) and time-period (*t*), where daily TMean > Regional TMean Threshold:

$$M_{akjt} = P_{ajt}\left(\frac{ER_{aj} \cdot i_{kjt}}{100} \cdot r_{aj}\right)$$

Equation 1

Where:

r = the baseline (2011) daily mortality rate (*r*)
a = age group category
j = grid cell
t = time-period
ER = the Exposure-risk Relationship for each age group (*a*) in grid cell *j*

[1]In [24] estimates for Scotland and Northern Ireland were based on exposure-risk relationships for North West and North East England respectively, as underlying mortality data was not available in the same format as for England and Wales.

i = the increment by which TMean exceeds the threshold per day (k) grid cell (j) and time-period (t)
P = the population per age group (a), in each grid cell (j) and time-period (t)

12km gridded datasets for present population (total and per age group) and the baseline (2011) daily mortality rate (total and per age group) were created from existing sources (see Supplementary section 1). Future population and demographic projections from the UK-SSP database, for the single year 2020, 2030, 2050 and 2100 under the UK-SSP5 scenario are used, which are UK specific but align with the global SSPs [38]. UK-SSP5 is characterised by high fossil fuel development, with large increases in population resulting in rapidly expanding cities and massive urban sprawl [26,38]. This scenario is applied here as it relates to a high radiative forcing pathway most closely aligned to RCP8.5. Full details on creating 12km gridded population, demographic and mortality data, and links to datasets, are included in Supplementary section 1.

In Section 3 population is first kept constant at the 2011 baseline level, to assess the impacts of projected climate change only on heat-related mortality. UK-SSP5 population projections are then applied to consider the implications of both climate change and population change on heat-related mortality. Hence, while the climate change scenarios reflect changes in terms of the hazard, the population data reflects potential changes in the exposure, as the number of people potentially at risk increases from 63 million in 2011 to 128 million in 2100 (Supplementary table 1).

Daily mortality (M_{akjt}) (Eq. 1) is summed across the year to provide gridded estimates of annual mortality per age group and summed across all grid cells to provide aggregate results of annual heat-related deaths in the UK and per 100,000 population. Estimates are made for all ages and for each of the age groups separately. The demographic component reflects potential changes in vulnerability associated with an ageing population in the future, with the proportion of total population over 85 increasing from 2.2% in 2011 to 12.1% in 2100 under UK-SSP5 [38,39]. In addition, as daily mortality is calculated in relation to the increment (i) above which TMean exceeds the threshold per day (k) grid cell (j) and time period (t), daily mortality data are summed across the year for each increment i to provide an estimate of annual heat-related deaths in the UK per each 1°C increment above regional TMean thresholds.

The study also considers the sensitivity of results to the role of adaptation through population acclimatisation. As in previous work, the 'no adaptation' scenario assumes communities will not adjust to the higher temperatures in the future [21,40], providing a baseline from which to assess potential benefits of additional adaptation. To represent acclimatisation, TMean threshold values are adjusted by 1°C and 2°C respectively under future global warming levels, while the slope of the ERF remains unchanged. Similar modifications have been applied in previous studies [21,41–43] as a reasonable approximation of the range of acclimatisation that could be achieved due to increased personal resilience and/or behavioural change. Secondly, the potential for communities to naturally acclimatise over time, on -pace with incremental climate change, is explored. The approach follows similar studies [e.g. 40,44] in assuming that future TMean thresholds will change in line with the rate of local warming, in this case equivalent to the 93rd percentile of daily TMean for each grid cell per global warming level.

3. Results

Assuming no population change or additional adaptation, average annual heat-related deaths are projected to increase under future global warming levels (Figure 1). At 1.5°C 2386 (95% CI: 2157 to 2616) deaths per year are estimated, an increase of 71% (66 to 76%) above the 1393 (1299 to 1486) deaths per year estimated for the period 1990-2019. At 2°C warming, 3136 (2745 to 3527) average annual deaths are estimated, equivalent to a 125% (111 to 137%) increase from the recent past. Under 4°C warming, 8949 (8054 to 9845) deaths per year are projected, an increase of 542% (520 to 562%) compared to the near-past. If population change is also accounted for then projected heat-related deaths are further amplified, with 2549 (2304 to 2794) deaths per year with 1.5°C warming in 2020 (+ 83% (77 to 88%)), 3747 (3280 to 4214) deaths per year with 2°C warming in 2030 (+ 169% (153 to 184%)), and 18,542 (16,690 to 20,394) deaths per year with 4°C warming in 2100 (+ 1232% (1185 to 1272%)) (Supplementary table 2.1).

At lower global warming levels climate change is responsible for a greater proportion of heat-related deaths than population change; 86% (85.3 to 86.4%) of average annual heat-related deaths are associated with climate change under 1.5°C of global warming. However, over time socio-economic change becomes an increasingly important factor. At 4°C, under the SSP5 scenario, population change is the dominant factor, accounting for 56% (55.8 to 56.1%) of average annual heat-related deaths.

Under UK-SSP5 (assuming no adaptation), limiting global warming to 1.5°C compared to 4°C avoids 86% of heat-related deaths, whilst limiting global warming to 2°C compared to 4°C avoids 80% of heat-related deaths.

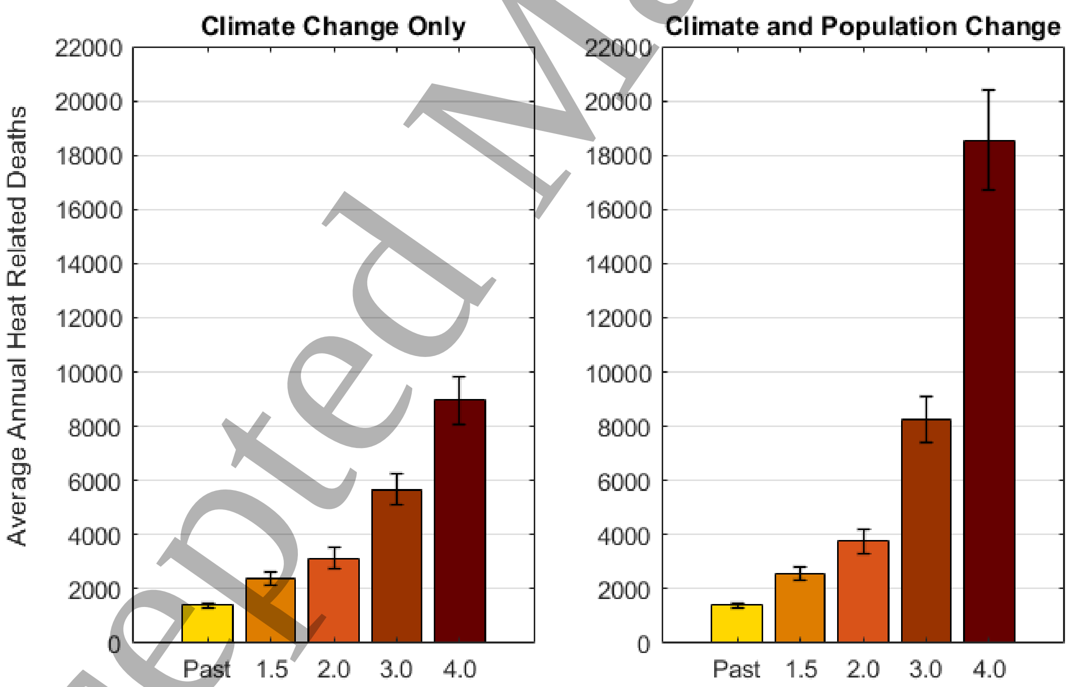

Figure 1: Average annual heat-related deaths in the UK. Left panel assumes constant population (climate change only) and right panel assumes future population (UK-SSP5 2020, 2030, 2050 and 2100 population projections for 1.5 to 4°C respectively) with no adaptation. Bars reflect ensemble average annual heat-related deaths for the past and global warming levels. The black lines represent 95% CIs.

Figure 2 illustrates the potential role of adaptation by 1) increasing the regional heat-related TMean threshold by 1°C and 2°C respectively, and 2) by assuming acclimatisation occurs naturally over time, on-pace with global warming. Both adaptation scenarios result in a reduction in average annual heat-related deaths compared to no adaptation (Supplementary table 2.2). At 1.5 and 2°C, increasing the regional heat-related TMean threshold by fixed values of 2°C reduces average annual heat-related mortality by 44% (48 to 24%) and 13% (24 to 3%) respectively, compared to the near-past. On-pace acclimatisation also minimises the change in heat-related mortality at lower global warming levels (similar to findings in [40]). However, for 3 and 4°C global warming levels heat-related mortality is projected to increase from the near-past, given changes in population exposure, even with assumptions of adaptation.

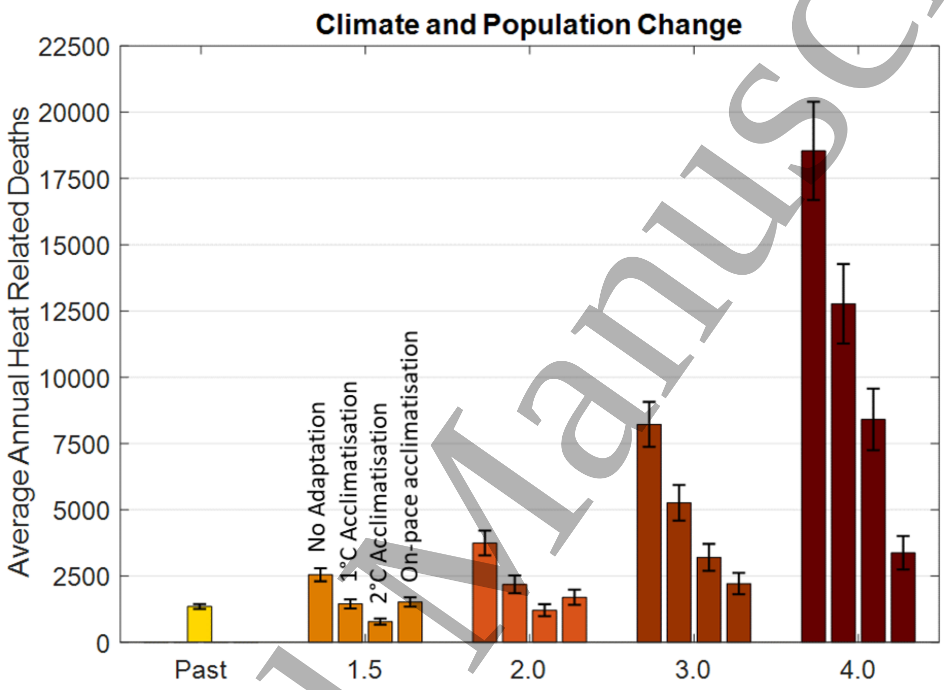

Figure 2: Average annual heat-related deaths in the UK assuming future population (UK-SSP5 2020, 2030, 2050 and 2100 projections. Bars reflect ensemble average annual heat-related deaths for the past and given global warming levels. The black lines represent 95% CIs. For each global warming level, the bars represent average annual heat-related deaths assuming no adaptation; acclimatisation represented by adjusting threshold values adjust by 1°C and 2°C; and on-pace acclimatisation equivalent to the 93rd percentile.

Figure 3 presents UK average annual heat-related deaths, broken down by deaths for each 1°C interval above regional temperature thresholds, and highlights that with global warming of 1.5°C, 76% (74 to 79%) of heat-related deaths can be attributed to moderate (1-5°C) increases above temperature thresholds. With global warming of 4°C, 54% (52 to 57%) of heat-related deaths can be attributed to moderate (1-5°C) increases above temperature thresholds. Whilst the impacts of moderate threshold exceedances on heat-related mortality are lower, since they occur more frequently, they account for larger aggregated impacts overall.

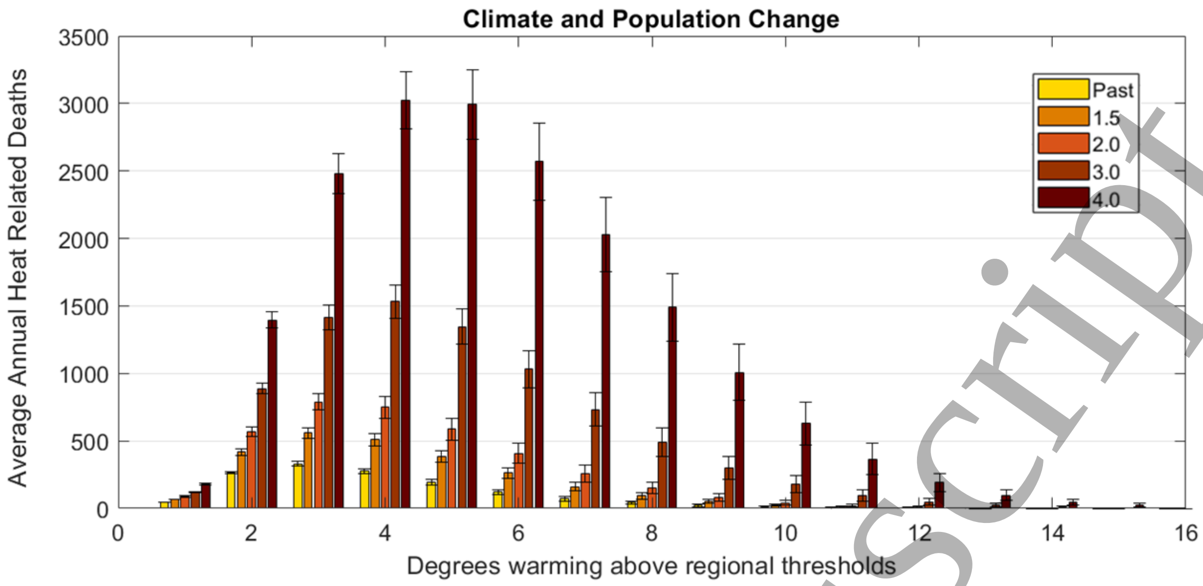

Figure 3: Average annual heat-related deaths in the UK per each 1°C increment above regional TMean thresholds, assuming future population change (UK-SSP5 2020, 2030, 2050 and 2100 population projections for 1.5 to 4°C respectively) with no adaptation. Bars reflect ensemble average annual heat-related deaths for the past and given global warming levels. The black lines represent 95% CIs.

Figure 4 presents average annual heat-related deaths normalised per 100,000 population per age group (assuming no adaptation) (Supplementary table 1). Older populations, particularly those in the 85+ category, are most vulnerable and, in relative terms, the benefits of limiting global warming to 1.5°C or 2°C compared to 4°C will be largest for elderly populations who are most at risk at higher global warming levels.

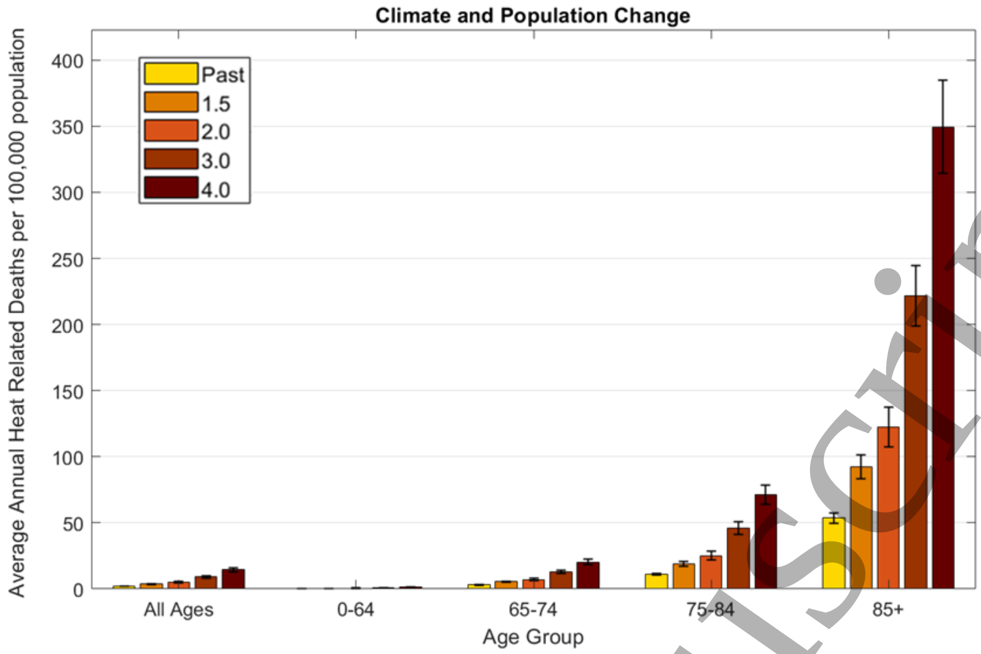

Figure 4: Average annual heat-related deaths per 100,000 population per age group assuming future population change (UK-SSP5 2020, 2030, 2050 and 2100 population projections for 1.5 to 4°C respectively) with no adaptation. Bars reflect ensemble average annual heat-related deaths for the past and given global warming levels. The black lines represent 95% CIs.

Figure 5 shows the spatial pattern of average annual heat-related deaths for the near-past, 2°C in 2030 and 4°C in 2100. Spatial distributions of heat-related mortality reflect the projected changes in daily TMean as well as the underlying regional population, temperature thresholds and exposure-risk relationships (whilst noting the regional scale of the ERFs applied to individual grid cells).

Figure 5a highlights that the regions at greatest projected risk include Greater London and the Southeast, as well as a band of regions stretching from the West Midlands, including Birmingham, up to Yorkshire including Leeds, and around Greater Manchester in the Northwest. Most heat-related deaths occur in England compared to other UK countries under all scenarios. A north south divide is evident across the UK, with limited (17.6%) heat related mortality projected for Northern England, Northern Ireland, and Scotland. Under future global warming, the number of heat-related deaths are projected to increase across these Northern areas as well as expand spatially. Expansion of projected heat-related deaths in the UK is most apparent at 4°C due to high levels of regional warming and projected patterns of urban sprawl under UK-SSP5 (see Supplementary figure 2 for maps assuming climate change only). Compared to the near-past, under 4°C regions in Southern and Central England are projected to experience large increases in average annual heat-related deaths (+13,420 (11974 to 14868)), as well as smaller increases across higher population regions of Wales (+712 (628-796)), Scotland (+415 (367-464)) and Northern Ireland (+108 (91-124)).

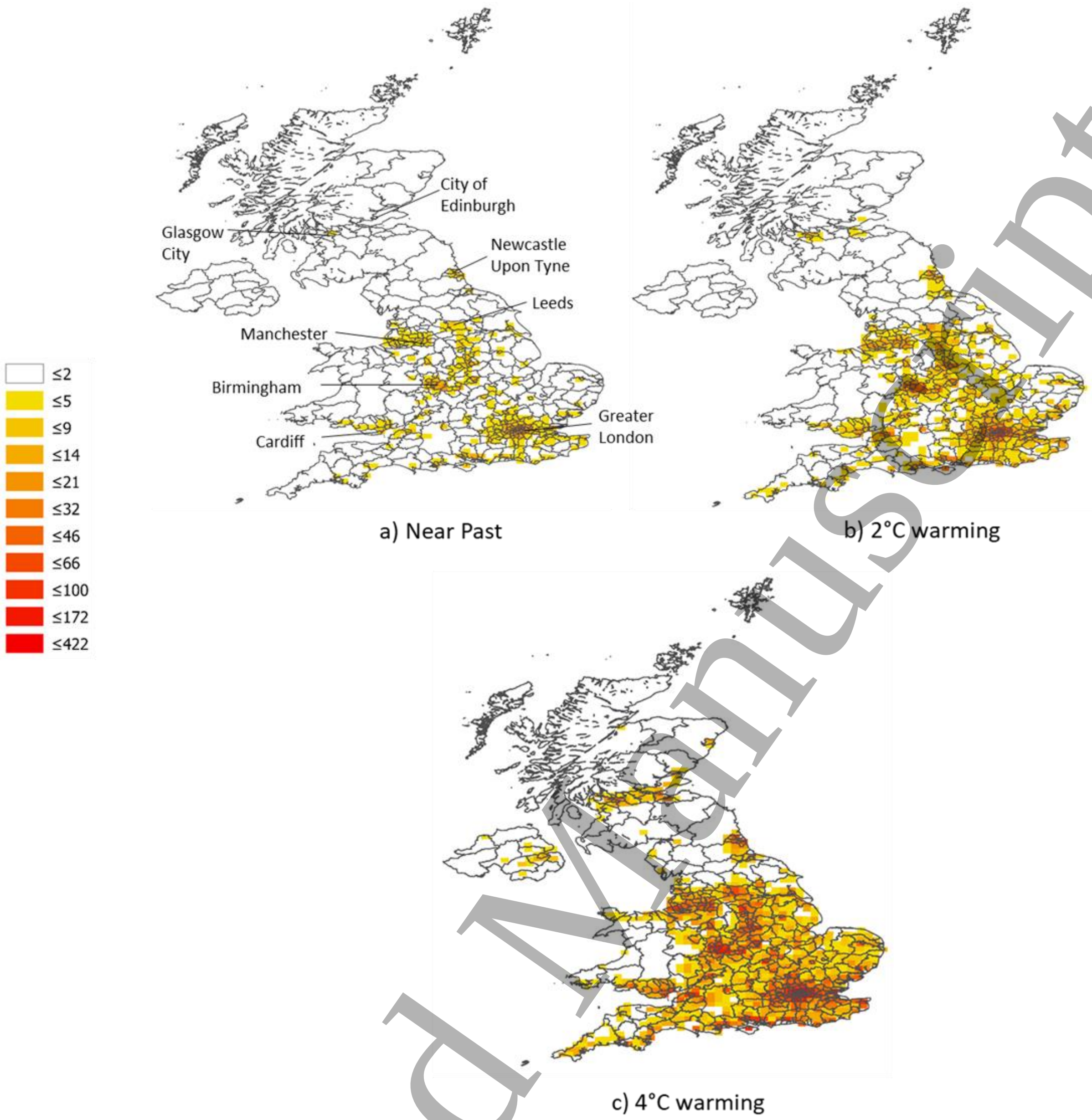

Figure 5: Spatial pattern of average annual heat-related deaths in the UK for all ages based on an ensemble of 12 RCM simulations (mean estimates across the 12 RCMs are shown) at 12km for a) near-past; b) 2°C global warming in 2030 and c) 4°C global warming in 2100. These results consider both climate change and population change but not adaptation. Boundaries represent Local Authority Districts (LADs) for geographical context.

4. Discussion and Conclusions

This study provides an updated analysis of heat-related mortality in the UK, using UKCP18 data and, importantly, embedding UK-SSP5 population and demographic data, for a range of future global warming levels. As results are generated using the UK-SSP5, which projects the largest population (~128 million by 2100 compared to a range of ~49-85 million for UK-SSPs 1-4) [26,38], they may be considered a high-end estimate. In agreement with previous studies the results illustrate that older populations are most vulnerable to heat-related mortality, particularly those in the 85+ category. Further, a large proportion of heat-related deaths (76% (74 to 79%) with global warming of 1.5°C and

54% (52 to 57%) with global warming of 4°C) can be attributed to more moderate (1-5°C) increases in temperature above regional thresholds as opposed to extremes. This is similar to findings of Gasparinni et al. [3] and Williams et al. [45]. This is of relevance in the UK when considering the thresholds upon which Heat Health Alerts (designed to support health care professionals and as early warning systems for the public) will be issued, and the role of such actions, given they will only be triggered on days that represent a small fraction of total annual heat-related deaths [45]. This highlights the need for year-round adaptation to heat stress as well as emergency responses during heatwaves or extreme temperatures.

When considering adaptation, at 4°C results illustrate that the greatest benefits occur where natural acclimatisation is assumed to be on-pace with regional climate change. However, given natural acclimatisation would likely occur gradually over time this represents a best-case adaptation outcome. In this example on-pace acclimatisation was assumed to remain constant over time, at the 93rd percentile. Other studies highlight that heat mortality can occur at higher or lower percentiles when considering different time periods [46] and for different countries with different climates and adapted populations [e.g. 3,40,47].

While both approaches to represent adaptation included here result in benefits in terms of reduced heat-related deaths under future global warming, methods are based on a simple and homogenous representation of how populations could adapt through natural acclimatisation, housing and/or behavioural changes. The study by Kingsborough et al., [25] for Greater London assessed the role of long-term adaptation pathways for managing heat-risk, incorporating scenarios of urban greening and green roofs, which can reduce ambient temperatures, and the role of air conditioning which can reduce internal temperatures whilst also having negative feedback on anthropogenic heat emissions. Future research could embed these methods within a heat risk framework for the UK. For example, adaptation actions can be implemented by coupling heat-related mortality estimates with models of urban development and land use change to help represent a shift from modelling shorter-term autonomous to longer-term planned adaptation actions.

Projected changes in heat-related mortality without adaptation are generally consistent with earlier studies (e.g. Vardoulakis et al., [19] and Hajat et al., [20]), and while this study differs in that it focuses on global warming levels, results are compared here with the time-periods of the 2000s, 2020s and 2050s from earlier studies. This study suggests average annual deaths in the near-past would be 29% (25 to 34%) lower than estimates for the 2000s reported in Hajat et al., [20] (1,393 average annual deaths versus 1,974), 22% (15 to 30%) lower comparing results from this study for 2020 to the 2020s, but 17% (5 to 29%) higher when comparing results from this study for 2050 to the 2050s (8,224 average annual deaths versus 7,040). These discrepancies reflect the different underlying climate and population data and methods. This study uses UKCP18 climate data, which succeeds UKCP09, and includes updated climate models with increased spatial resolution [see 48 for full discussion]. Results were estimated based on 30-year daily TMean timeseries for each 12km grid cell (1,694 grid cells in the UK) and RCM ensemble member. In contrast, Hajat et al., [20] used 9-year daily TMean data at 25km, and then averaged gridded data within each of 12 UK administrative regions to create a regional TMean timeseries. This study uses RCP8.5, a high-end scenario compared to the A1B medium emission scenario used in Hajat et al., [20], however it samples global warming levels as opposed to time-periods. Here, global warming levels are associated with time by combining them with the spatially explicit UK-SSP5 population and demographic scenarios for given years. Differences in UK population between this study and that of Hajat et al. [20] were limited for the near-past (1.4%) and 2030 versus 2030s (-0.6%) given different data sources and methods, however larger deviations occur when comparing data for 2050 versus the 2050s (14.1%), with UK-SSP5 projections assuming much higher population growth than the 2010-based ONS UK principal projections, including more vulnerable elderly people. In the future results can be generated for the full range of UK-SSPs, including those with lower population growth trajectories. This will be important as the study highlighted that over time projected changes in population begin to dominate.

The ERF method used here has also been compared with a nonlinear modelling method for heat-related mortality during historical heatwave events in England [36]. As shown in Supplementary section 3, noting methodological differences such as use of gridded versus regional climate data; higher TMean thresholds; and linear ERFs used in this study, total heatwave deaths in England are on average similar (+5.8%) [34]. We emphasise that nonlinearity in climate, combined with nonlinearity in the health response to heat exposure is extremely important [49], the latter component of which is not considered in this study. Therefore, while our study serves as a first step towards a new UK heat-mortality risk assessment using the latest generation UKCP18 and UK-SSP data as well as adaptation changes, future work needs to incorporate age-specific nonlinear ERFs to fully examine the extreme effects of heat to health.

Uncertainty in the estimates presented reflect uncertainty in the UKCP18 regional climate model projections. However, as the ERFs were assumed to remain constant in the future, uncertainty related to the extrapolation of the ERFs to future time-periods that go beyond the present-day temperature range is not considered. While this may be realistic, at least in the shorter-term, given findings from studies that have calculated ERFs for different historical time-periods and found no significant difference [35,44,49], in the longer-term the scale and shape of ERFs could change given the sharp increase in risk at high temperatures , potential for natural acclimatisation and behavioural change, or improvements in infrastructure that could reduce risks [17].

Another source of uncertainty related to the ERFs are that they have been developed based on epidemiological data aggregated across large geographical areas, whereas the underlying spatial pattern in mortality is likely to be heterogenous [51]. In this regard, Figure 5 is only illustrative of broad scale distributions of mortality across the UK, showing deaths distributed by population density. At a local level other vulnerability or infrastructure conditions could alter spatial patterns of risk for particular groups, including access to green space; underlying health conditions; quality of accommodation; and level of air pollution [33,44,51].

The consideration of socioeconomic and demographic inequalities will also be important when considering heat-related adaptation planning and those that would benefit, or be disadvantaged, by interventions. The integration of additional projections of socio-economic factors, such as indicators of health and inequality from the UK-SSPs, will form an important component of future modelling effort and research. This will be particularly relevant alongside the aim to produce heat-related mortality risk maps at a higher spatial resolution in the future, for example by using 2.2km UKCP18 Local data. UKCP18 Local has also been shown to resolve the land surface atmosphere exchange more accurately than in the UKCP18 regional simulations, allowing better representation of the urban heat island effect in cities [52]. Such updates, alongside the presentation of outputs that enable policy makers to directly assess the benefits of different mitigation policies via estimates of avoided damages at lower versus higher global warming levels will be key to support future policy and the next UK CCRA due in 5-years. This study provides a platform for further research to assess the role of specific types of adaptation, including nature-based solutions such as urban greening, in reducing projections of heat-related mortality.

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Data availability statement

The data that underpin this study are cited in the references and Supplementary information. This data is freely available online: UKCP18 Regional Projections on a 12km grid over the UK for 1980-2080: https://catalogue.ceda.ac.uk/uuid/589211abeb844070a95d061c8cc7f604; HadUK-Grid gridded and regional average climate observations for the UK: http://catalogue.ceda.ac.uk/uuid/4dc8450d889a491ebb20e724debe2dfb; UK-SSPs: https://www.ukclimateresilience.org/products-of-the-uk-ssps-project/; UK gridded population based on Census 2011 and Land Cover Map 2007: https://doi.org/10.5285/61f10c74-8c2c-4637-a274-5fa9b2e5ce44; UK Population, 2011 census: https://www.ons.gov.uk/peoplepopulationandcommunity/populationandmigration/populationestimates/datasets/2011censuspopulationandhouseholdestimatesfortheunitedkingdom; Mortality statistics (England and Wales): https://www.ons.gov.uk/peoplepopulationandcommunity/birthsdeathsandmarriages/deaths/datasets/deathsregisteredbyareaofusualresidenceenglandandwales; Mortality statistics (Scotland): https://www.nrscotland.gov.uk/statistics-and-data/statistics/statistics-by-theme/vital-events/deaths/deaths-time-series-data; Mortality statistics (Norther Ireland): https://www.nisra.gov.uk/publications/death-statistics and https://www.nisra.gov.uk/publications/death-statistics. The resultant 12km gridded population and baseline mortality datasets created are available to download via: https://osf.io/eyf3b/?view_only=32057e9182654b63b05f1a58fc5fbf6b.

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