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Integrating Shared Socioeconomic Pathway-informed adaptation into temperature-related mortality projections under climate change

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ABSTRACT

The extent to which populations will successfully adapt to continued warming temperatures will be a crucial factor in determining future health burdens. Previous health impact assessments of future temperature-related mortality burdens mostly disregard adaptation or make simplistic assumptions. We apply a novel evidence-based approach to model adaptation that takes into account the fact that adaptation potential is likely to vary at different temperatures. Temporal changes in age-specific mortality risk associated with low and high temperatures were characterised for Scotland between 1974 and 2018 using temperature-specific RR ratios to reflect past changes in adaptive capacity. Three scenarios of future adaption were constructed consistent with the SSPs. These adaptation projections were combined with climate and population projections to estimate the mortality burdens attributable to high (above the 90th percentile of the historical temperature distribution) and low (below the 10th percentile) temperatures up to 2080 under five RCP-SSP scenarios. A decomposition analysis was conducted to attribute the change in the mortality burden into adaptation, climate and population. In 1980–2000, the heat burden (21 deaths/year) was smaller than the colder burden (312 deaths/year). In the 2060–2080 period, the heat burden was projected to be the highest under RCP8.5-SSP5 (1285 deaths/year), and the cold burden was the highest under RCP4.5-SSP4 (320 deaths/year). The net burden was lowest under RCP2.6-SSP1 and highest under RCP8.5-SSP5. Improvements in adaptation was the largest factor reducing the cold burden under RCP2.6-SSP1 whilst temperature increase was the biggest factor contributing to the high heat burdens under RCP8.5-SSP5. Ambient heat will become a more important health determinant than cold in Scotland under all climate change and socio-economic scenarios. Adaptive capacity will not fully counter projected increases in heat deaths, underscoring the need for more ambitious climate mitigation measures for Scotland and elsewhere.

1. Introduction

The adverse health impact of ambient temperatures is one of the most prominent climate change risks (Romanello et al., 2021). Previous studies often estimate future heat burdens focusing on the temperature under climate change while assuming other factors remain static at historical levels (Sanderson et al., 2017). Such methods are useful in exploring the contribution of climate change, whereas they will not reflect realities where socioeconomic conditions strongly influence health burdens, thus limiting their usefulness for policymakers.

There is a gap in projecting future temperature-related mortality burdens not only because of uncertainty in regional temperature change but importantly because of uncertainty in how people will adapt to future temperatures. Among the limited body of literature that explored the effect of vulnerability and adaptation in future temperature-related health burdens, assumptions lacking credible empirical evidence are usually employed (Sanderson et al., 2017). Some studies apply the temperature–mortality I association in analogue cities, however different locations have different demographic and socioeconomic profiles and hence the TM associations are not directly applicable (Gosling et al., 2017).

Other common methods to model acclimatisation include shifting the temperature threshold according to the rate of temperature increase under climate change. Some studies adjust the susceptibility to extreme

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temperatures, represented by the slope of the TM association or the relative risk (RR) of mortality under a certain temperature against a threshold temperature (Huynen and Martens, 2015; Lee et al., 2019; Wang et al., 2022). However, arbitrary levels of change were often employed (Gosling et al., 2017). In addition, the temperature-mortality association has been found to be non-linear, with steeper change in the risks under more extreme temperatures (Gasparrini et al., 2015). The same level of adjustment to the slope under all temperatures does not capture the non-linearity of the temperature-mortality association and may lead to biased estimations of the change in the risks. Furthermore, the effectiveness of different adaptation strategies may vary at different temperatures. For example, public health measures such as heat-health warnings are primarily designed to issue alerts and reduce health impacts associated with extreme high temperatures but not necessary during more moderate heat, so adaptation potential is different at different temperatures. Therefore, a method that captures the effects of adaption on future temperature-related mortality risks by incorporating non-linearity in adaptation potential, and furthermore is based on empirical evidence, is desirable.

Previous studies predominantly assume a decrease in the vulnerability to heat under climate change because of heat acclimatisation (Sanderson et al., 2017). However, vulnerability is influenced by a myriad of socioeconomic conditions that affect the adaptive capacity to extreme temperatures, which may increase or decrease in the future under different socioeconomic scenarios (Lindley et al., 2011; Gosling et al., 2017). Health has been found to deteriorate during recessions because of losses of important services and increased levels of poverty, stress and mental illness (Walsh et al., 2016). In addition to increased acclimatisation and adaptation to heat, decreased adaptive capacities to heat is a possible situation where the vulnerabilities are intensified, yet the future heat burden under this scenario has been rarely explored (Sanderson et al., 2017; Rai et al., 2022).

The Shared Socioeconomic Pathways (SSPs) is a widely used set of scenarios describing five alternative futures of how society, demographics and economics globally might change over the next century (Riahi et al., 2017). National SSPs have been developed in some places such as the UK which include location-specific details consistent with the global SSPs (UK Climate Resilience Programme, n.d.). These SSPs provide a useful framework to explore the health burden considering both future adaptive capacities to extreme temperatures and to demographic change.

Some recent studies assume a positive association between Gross Domestic Product (GDP) and the adaptive capacity to extreme temperatures, and estimate future temperature-related mortality burdens based on adjusted TM associations according to projected GDP under the SSPs (Wang et al., 2019; Rai et al., 2022). However, GDP is not the only factor affecting the adaptation to extreme temperatures (Lindley et al., 2011). For example, global GDP is projected to increase rapidly under SSP5—a fossil fuel-dominated pathway, whereas the natural environment may deteriorate under this pathway, counteracting the benefits of high GDP (UK Climate Resilience Programme, n.d.). Therefore, there is a need to assess the effect of the composite socioeconomic adaptive capacity level on the projection of mortality burden attributable to extreme temperatures considering climate change and socioeconomic scenarios.

This study investigates future mortality burdens associated with low and high temperatures in Scotland integrating changes in climate, adaptive capacity and demography. An innovative evidence-based method is utilised to take into account the changes in the susceptibility to extreme temperatures under scenarios of changing adaptive capacities. It fills the research gap in assessing the effect of adaptation on temperature-related mortality burdens under scenarios of increased and decreased adaptive capacities supported by empirical evidence and informed by the SSPs. Scotland was chosen as the study location because it has been experiencing poorer health compared to other western European countries since the 1950s due to socioeconomic vulnerabilities (Walsh et al., 2016), which may contribute to increased susceptibility to cold and heat. In addition, Scotland has a relatively cool climate and few actions have been taken to reduce heat risks to date, so there may be a low adaptive capacity to heat-health risks under climate change (Wan et al., 2022a). Therefore, there is a need to investigate future temperature-related mortality burdens in Scotland and assess its adaptive capacity.

2. Data and methods

2.1. Data

2.1.1. Mortality

The National Records of Scotland provided daily all-cause mortality counts in the whole of Scotland between 1974 and 2018, which is separated into the four biggest cities (Aberdeen, Dundee, Edinburgh and Glasgow) and three regions (East, West and North excluding the four cities). The mortality count was provided for two age groups (0–74 and 75 and above years old) to investigate the different risks among the younger and older age groups.

2.1.2. Population and socioeconomic adaptive capacity

Historical populations in 1981, 1991, 2001 and 2011 were obtained for the two age groups from the PopChange dataset (Lloyd et al., 2017). Population projection data under each SSP was attained from the UK-SSP project for each decade from 2020 to 2080 (UK Climate Resilience Programme, n.d.). Both the historical and projected population data and are on a 1 km-by-1km grid.

The socioeconomic adaptive capacity levels were determined by the composite change in key socioeconomic factors based on from the method and result from a previous study in Wan et al. (2022b), which is an unweighted average of income, income inequality, social cohesion, health care, public awareness, urban population for both the heat and cold adaptive capacity. Additionally, the adaptive capacity index to heat also included green space and the adaptive capacity to cold included energy efficiency. The projection of these indicators was obtained from the UK-SSP project (UK Climate Resilience Programme, n.d.). Three scenarios of adaptive capacity were adopted: increase under SSP1, no change under SSP2 and 5, and decrease under SSP3 and 4.

2.1.3. Temperature

The HadUK-Grid Gridded Climate Observation dataset was used for daily maximum and minimum temperatures on a 1 km-by-1km grid in Scotland between 1974 and 2018 (Hollis et al., 2019) from which daily mean temperature (T_{daily}) was calculated. Population-weighted average temperatures were calculated for the four cities and three regions by weighing the temperature in each 1 km grid-cell with the proportion of the population in that grid-cell against the total population in individual cities/regions. This temperature series, combined with daily mortality counts between 1974 and 2018, was used to investigate the exposure–response function (ERF) between temperature and mortality in Scotland.

T_{daily} in Scotland between 1980 and 2080 were obtained from the CHESS-SCAPE dataset (Robinson et al., 2022), which is bias-corrected and downscaled to a 1 km by 1 km grid using climate model outputs of the UK Climate Projections 2018 (UKCP18) under Representative Concentration Pathway (RCP) 8.5. This dataset was selected because of its extended outputs under RCP 2.6 and 4.5 (Robinson et al., 2022). The dataset contains climate projections from four perturbed-physics ensembles (PPE) to sample the uncertainties arising from Global Climate Model (GCM) parameters (Robinson et al., 2022), providing four temperature series for each RCP. The historical simulation period is for 1980–2010, which was merged with RCP4.5 for 2010–2020 to obtain two 20-year historical periods (1980–2000 and 2000–2020). Population-weighted temperatures using CHESS-SCAPE outputs were used to estimate temperature-related mortality burden in both historical and future periods for consistency.

2.2. *Epidemiological analysis*

The ERF between temperature and all-cause mortality in Scotland was modelled using a two-stage approach. In the first stage, time series quasi-Poisson regression with distributed lag non-linear models (DLNM) (Gasparrini, 2011) was used to model the ERF in individual age groups and cities/regions for every annual rolling 20-year period between 1974 and 2018, i.e. 1974-1993, 1975–1994, …,1999–2018 (26 overlapping periods in total). This approach was utilised to capture the continuous change in the ERF over time while ensuring a sufficient sample size. Separate analyses were conducted for May to September (MtS) and October to April (OtA) to capture the different lengths of lagged effects of cold and heat respectively (Wan et al., 2022a). Maximum lags of 1 and 14 days were used to model the lagged effects of heat and cold respectively. Separate models were used to investigate the cold and heat effects because high temperatures are very sparse in the time series due to the cool climate in Scotland, so full-year model may yield an unstable estimation of the heat effect. Additionally, previous studies have found that using a longer lag to model the heat effect may reduce the precision of the effect estimation, and hence different models for cold and heat were used to better handle the different lag structures of cold and heat effects (Gasparrini, 2016). The lag-response association was modelled with indicators of lag 0 and 1 in MtS and a natural cubic spline (NS) with two knots on the log scale of 14 in OtA. NS with two inner knots at the 30th and 70th percentiles of the temperature series were used to model the TM association (Wan et al., 2022a). Sensitivity analyses on the location of knots were conducted in a previous study of the team which found the risk function remained largely unaffected by the knots (Wan et al., 2022a). Long-term trend and medium-term variation in the mortality series were controlled using an interaction term of year indicators and the day of MtS/OtA. Day-of-week and public holidays were controlled for.

In the second stage, the ERFs in individual age groups, periods and locations from the first stage analysis were aggregated using multivariate meta-regression to generate a mean estimate for Scotland. Age and period were predictors and location was a random-effects predictor of the meta-regression. The 26 periods are overlapped, so an NS with 3 degrees of freedom was used to model the effect of period on the ERF.

The 10th and 90th percentiles of population-weighted T_{daily} in Scotland in 1974–2018 (i.e. 2.6 and 15.0 °C) were used as the temperature thresholds for cold and heat extremes respectively. These thresholds were selected to calculate the RRs and estimate the mortality burden attributable to temperatures beyond the thresholds in this study. A previous study found an average threshold of 2.6 °C for cold and 14.5 °C for heat in Scotland (Dimitriadou et al., 2022), which are similar to the thresholds used in this study. In addition, the use of the 10th and 90th percentile of temperature distribution enables the estimation of the mortality burden attributable to low and high temperatures at the same extreme level during the historical period. The threshold temperatures were kept constant in each period, which allowed the comparison of the RR under the same temperature exposures.

The analyses were conducted in R/RStudio using packages dlnm (Gasparrini, 2011) and mixmeta (Sera et al., 2019).

2.3. *Modification of the risk function under adaptation scenarios*

The ratio of temperature-specific RRs in individual historical periods against the latest historical period of 1999–2018 was calculated in this study to reflect temporal changes in temperature-specific effects. Linear regression of temperature on RR ratio in each historical period was performed for heat and cold separately to represent the association between temperature and RR ratio. As mentioned in the Introduction section, the temperature-specific RR ratios reflect adaptation at different temperatures. A hypothetical illustration of the heat effect in two periods and RR ratio is given in Fig. 1. The blue and black lines are hypothetical RRs in two periods with a larger difference at more extreme temperatures, which is captured by the increase in the RR ratio (blue dashed line) at higher temperatures. In comparison, the RRs (orange line) derived using a hypothetical increase of 20% of the RR in period 1, equivalent to a RR ratio of 1.2 across all temperatures (orange dashed line) results in a uniform upward shift in the RR in period 2 without changing its shape, which may lead to an overestimation of the RR at moderately high temperatures and underestimation of the RR at more extreme temperatures.

The temperature-specific RRs in the most recent period 1999–2018 was adjusted based on linear approximation of the RR ratio under scenarios of adaptive capacities. Three scenarios of changes in adaptive capacity were constructed in line with the SSP storylines. Under SSP2 and 5, there is little change in the adaptive capacity and hence the RRs in 1999–2018 was applied to the future directly. Under SSP1, the lowest RR ratio slope found in the historical period was applied to the RRs in 1999–2018 to reflect the increase in adaptative capacity. Under SSP 3 and 4, the highest RR ratio slope found in the historical period was applied to reflect the decrease in the adaptative capacity. When 1999–2018 has the lowest or highest historical risk, an RR ratio slope of 0.01 and −0.01 is applied to the scenarios of an increase and decrease in the adaptive capacity respectively to explore the change in mortality risk beyond historical ranges. This corresponds to a 10% change in the RRs at the temperature that is 10 °C lower or higher than the cold/heat threshold and a 20% change in the RRs at the temperature that is 20 °C lower/higher than the cold/heat threshold. Adjusting the RRs of 10%–30% has been used in previous studies (Huynen and Martens, 2015; Aboubakri et al., 2020; Rai et al., 2022).

2.4. *Mortality burden estimation*

Daily temperature-related mortality ($M_{temperature}$) was calculated for the two age groups using the functions below (Hajat et al., 2014).

$$M_{temperature} = BMR * P * (RR - 1)$$

$$BMR = \frac{DMR}{RR}$$

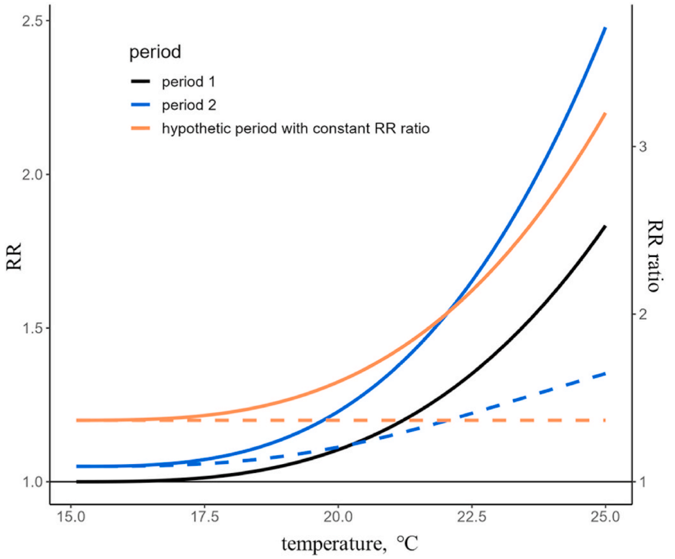

Fig. 1. Illustration of RR and RR ratio in relation to temperature: hypothetical RR in two periods (black and blue solid lines), the temperature-specific RR ratio in period 2 against period 1 (blue dashed line), a hypothetical RR ratio of 1.2 across all temperatures (orange dashed line) and the derived RRs (orange solid line) by transforming the RRs in period 1 with an RR ratio of 1.2. The left and right y-axis show the value of RR and RR ratio respectively.

$M_{temperature}$ is the multiplication of the baseline daily all-cause mortality rate (BMR), the population across Scotland (P) and the temperature-specific RRs. The BMR was calculated from the daily mortality rate (DMR) for the two age groups excluding deaths attributed to cold or heat. Daily $M_{temperature}$ was summed for each year in two historical and two future periods under each scenario.

Three components determining the mortality burdens attributable to extreme temperatures: temperature, adaptation as reflected by RRs and population are compared. The daily deaths between 2010 and 2018 was modelled using a cubic spline of day of year with 3 degrees of freedom to obtain the annual cycle of daily mortality, which is divided by the population in 2011 to obtain the DMR. The DMR in 2010–2018 was applied to the estimation of mortality burdens in all periods to enable the attribution of the estimated mortality burden to the three individual components. The time and scenario of the data for the three components used for estimating $M_{temperature}$ is shown in Table 1.

Future $M_{temperature}$ were estimated under five SSP-RCP scenarios: SSP1-RCP2.6, SSP2-RCP4.5, SSP4-4.5, SSP3-RCP8.5, and SSP5-RCP8.5. These scenarios were selected as being the most typical and important scenarios (O'Neill et al., 2016; Riahi et al., 2017). Although RCP8.5 could not be achieved under SSP3 from most integrated assessment models, it can be elicited under additional assumptions such as higher economic growth (Riahi et al., 2017). This makes SSP3-RCP8.5, a combination of both high emission and vulnerability, a useful scenario for climate change impacts, adaptation and vulnerability research relating to extremes, which has been utilised in several previous studies (Liu et al., 2017; Ren et al., 2018). The five scenarios and their corresponding combination of changes in temperature, adaptive capacity, population size and ageing are illustrated in Fig. A1. The changes in the mean annual burden from 1980 to 2000 to 2000–2020 and 2060–2080 were decomposed into the three components using the Das Gupta method (Das Gupta, 1993).

3. Results

There were 4.9 and 0.3 million people for those below and above 75 years old respectively in Scotland in 2011, with an average of 20.8 and 34.9 thousand annual deaths respectively between 2010 and 2018. Daily mortality and temperature in 1974–2018 are summarised in Table A1. The older population is projected to increase under all SSPs with a lower increase under SSP3 (increase by 165%), medium increase under SSP2 (265%) and SSP4 (263%) and the largest increase under SSP1 (355%) and SSP5 (357%) between 1991 and 2070 (Fig. 2A). In the same period, the younger population is projected to decrease under SSP3 (21%) and SSP4 (10%), and increase under SSP1 (5%), SSP2 (7%) and SSP5 (35%).

The annual average population-weighted T_{daily} increases from 8.4 °C to 9.1 °C between 1980-2000 and 2000–2020 in Scotland, and is projected to increase by 1.5 °C (RCP2.6), 2.2 °C (RCP4.5) and 3.3 °C (RCP8.5) on average in 2060–2080 compared to 1980–2000 (Fig. 2B). Under climate change, the increase in the number of hot days is double to triple the decrease in the cold days (Fig. 2C and Fig. A2).

The TM association in Scotland in the 26 20-year historical periods between 1974 and 2018 is shown in Fig. 3A. The RRs were higher among the older than the younger age group. The cold effect increased slightly between 1974-1993 and 1982–2001, with an abrupt increase in 1983–2002 and remained largely unchanged until 1987–2008 followed by a steady decrease thereafter. The variation in the heat susceptibility is smaller than cold. The cold and heat effect were found to be the highest in 1987–2006 and 1974–1993 respectively. The lowest cold and heat effects were observed in 1999–2018 and 1987–2006 respectively.

RR ratio and temperature roughly follow a linear relationship for the heat effect (Fig. 3B). The association of RR ratio and low temperature appears to be non-linear, especially in periods with high cold effects. Nevertheless, the linear regression of RR ratio on temperature was obtained to represent temporal changes in temperature-specific RRs for simplicity. The minimum and maximum slope of the temperature-RR ratio regression line for heat is −0.002 and 0.008 respectively (dashed lines in Fig. 3B). It indicates a decrease in the RR of 0.2% and an increase in the RR of 0.8% for each degree Celsius above the heat threshold of 15 °C. For example, when the temperature is 25 °C, the RR is 2% lower and 8% higher in the period with the lowest and higher heat risks respectively compared to in 1999–2018. The maximum slope of the temperature—RR ratio regression line for cold is 0.056.1999–2018 has the lowest cold risk. Therefore, as introduced in the Methods section, a temperature-RR ratio slope of −0.001 is assumed for cold to explore a further decrease in the cold effect under SSP1. The transformed RRs under each SSPs are illustrated in Fig. 3C.

The annual mortality burdens attributed to cold and heat estimated for 1980–2000, 2000–2020 and 2060–2080 are shown in Fig. 4 (and for 2040–2060 in Table A2). The mortality burdens estimated using temperature outputs from individual PPEs are shown in Fig. A3 to isolate the year-to-year variation from model uncertainty. There were 312 and 21 deaths/year attributable to extreme cold and heat respectively between 1980 and 2000. In 2000–2020, the cold burden decreased by 90% and the heat burden increased by 295% compared to 1980–2000. The heat burden is projected to be larger than cold in the future under all scenarios. No mortality associated with extreme cold was projected under RCP2.6-SSP1 in 2040–2060 and 2060–2080 due to the high adaptive capacity. In 2060–2080, the cold burden was projected to be the highest under RCP4.5-SSP4 (320 deaths/year). In the same period, the heat burden was projected to be the lowest under RCP2.6-SSP1 (343 deaths/year) and the highest under RCP8.5-SSP5 (1285 deaths/year).

The mortality rate per 1 million total population is presented in Fig. 4B (values in Table A2). The mortality rate decreased from 62 to 6 for cold and increased from 4 to 16 for heat from 1980 to 2000 to 2000–2020. In 2060–2080, RCP2.6-SSP1 observed the lowest mortality rate attributable to both extreme cold (no deaths/million population) and heat (53 deaths/million population). The highest cold-related mortality rate was projected to be 58 deaths/million population under

Table 1
The time of the data for the three components in estimating the mortality burden attributable to extreme temperatures in four periods.

Period of mortality burden	Temperature	Relative risks (RRs)			Population
Historical: 1980–2000	01/12/1980–30/11/2000	1981–2000			1991
Historical: 2000–2020	01/12/2000–30/11/2010 & 01/12/2010–30/11/2020 (RCP4.5)	1999–2018			2011
		Three adaptation scenarios			
		No change (SSP2&5)	Low adaptation (SSP3&4)	High adaptation (SSP1)	
Future: 2040–2060	01/12/2040–30/11/2060 (RCP2.6, 4.5 & 8.5)	Baseline period 1981–2000	The RRs in the baseline period transformed by the largest RR ratio	The RRs in baseline period transformed by the smallest RR ratio	2050 (SSP1-5)
Future: 2060–2080	01/12/2060–30/11/2080 (RCP2.6, 4.5 & 8.5)				2070 (SSP1-5)

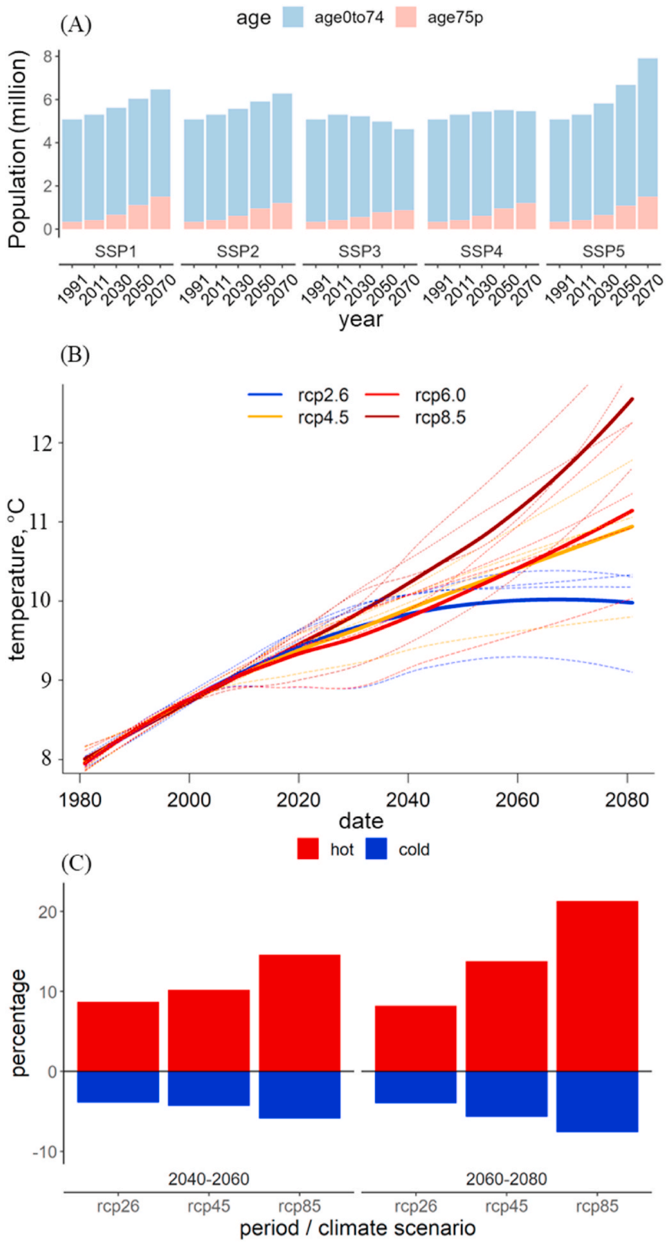

Fig. 2. (A) Population in Scotland under the five UK-SSPs. (B) population-weighted daily mean temperatures under four RCPs. (Dashed line: output from individual PPEs; solid line: PPE mean.) (C) Change in the percentage of hot and cold days in two future periods under three RCPs compared to 1974–2018 during which there were 10% days below and above the cold and heat thresholds respectively.

RCP4.5-SSP4, and the highest heat-related mortality rate was projected to be 275 deaths/million population under RCP8.5-SSP3.

The contribution of the three components: temperature, RR and population to the change in the mortality burden in 2000–2020 and 2060–2080 (under five scenarios) compared to 1980–2000 is shown in Fig. 4C and Table A3. RR contributed to most of the change in the cold burden in 2000–2020 and 2060–2080 under RCP2.6-SSP1. The temperature increase drove a decrease in the cold burden; however, this effect was largely counteracted by the increase in population among the older population.

The temperature increase drove the largest proportion of the elevated heat burden in 2000–2020 and in 2060–2080 compared to 1980–2000. The most notable effect of adaptive capacity was observed under RCP4.5-SSP4 and RCP8.5-SSP3 among the younger population, under which the lower adaptive capacity contributed to 42% and 36% of the increase in heat burden respectively from 1980 to 2000 to 2060–2080.

4. Discussion

This study utilised 45 years of historical evidence from the TM association in Scotland to project the future mortality burden until 2060–2080. It takes into account changes in temperature, adaptive capacities, and population under a consistent RCP-SSP framework. Future scenarios of an increase and decrease in adaptive capacities to extreme temperatures were informed by the SSPs and historical variations in the susceptibilities to extreme temperatures captured by temperature-specific RR ratios. A larger variation in the cold susceptibility than heat in the historical period was found in this study. The cold burden decreased by 90% between 1980-2000 and 2000–2020, mainly due to the sharp decrease in the susceptibility to cold. In 2060–2080, the projected cold burden is the highest under RCP4.5-SSP4 (320 deaths/year) and the lowest under RCP2.6-SSP1 with no deaths associated with extreme cold due to a high adaptive capacity, even though the latter has a cooler climate and a larger population. In comparison, the annual mortality burden attributable to heat increased from 21 in 1980–2000 to 83 in 2000–2020, which was projected to increase to 343 and 1285 in 2060–2080 under RCP2.6-SSP1 and RCP8.5-SSP5 respectively.

Historical policy actions in reducing the cold impact and fuel poverty may have contributed to the historical variation in the cold susceptibility (Scottish Government, 2017). There was an increase in the UK energy price between 2002 and 2010, a reverse of the previous decreasing trend between the 1970s–1990s (Fouquet, 2014). Between 2011 and 2017, there was a general improvement in energy efficiency and fuel poverty (Scottish Government, 2017), corresponding to a steady decrease in cold susceptibility. Generally, the opposite trend was observed for heat susceptibility compared to cold. This may be associated with elevated indoor overheating risk due to measures of increasing energy efficiency such as internal wall insulation, and an increase in airtightness and reduction in ventilation (Fosas et al., 2018). A similar reversed trend in the cold and heat susceptibilities has also been found in a study in the Czech Republic (Janoš et al., 2023).

The annual cold-related deaths in 1980–2000 and 2000–2020 in Scotland found in this study are smaller than cold-related mortalities estimated in other parts of the UK (Vardoulakis et al., 2014). In addition to the difference in the risk function in different locations, one reason for this difference is that a milder temperature was adopted for the cold threshold in these studies as Scotland has a cooler climate than the rest of the UK (Hajat et al., 2014; Vardoulakis et al., 2014). Previous research has revealed that the cold burden is highly sensitive to the cold threshold, and a substantial portion of cold-related mortalities is attributed to days with moderate cold temperatures, which are more prevalent compared to extremely cold days (Arbuthnott et al., 2018). However, the excess mortality under extreme cold is more likely to be directly caused by low temperatures compared to moderate temperatures (Arbuthnott et al., 2018).

There are some limitations of this study. The historical variations in the cold and heat susceptibilities were assumed to reflect changes in adaptive capacity. However, the specific adaptation mechanisms are not investigated. The effect of adaptive capacity on the heat burden estimated in this study may be conservative under any climate change and adaptation scenarios due to the small variation in the heat susceptibility observed in the historical period. On the contrary, this study may overestimate the projected cold burden under the scenario with low adaptive capacity because the effect of existing interventions in reducing cold risks, such as building insulation and increasing energy efficiency have long-lasting effects and hence the likelihood that the cold susceptibility deteriorates to the highest historical level may be small. In addition, the change in the adaptive capacities to cold and heat was in the same direction within individual SSPs in this study. This assumption

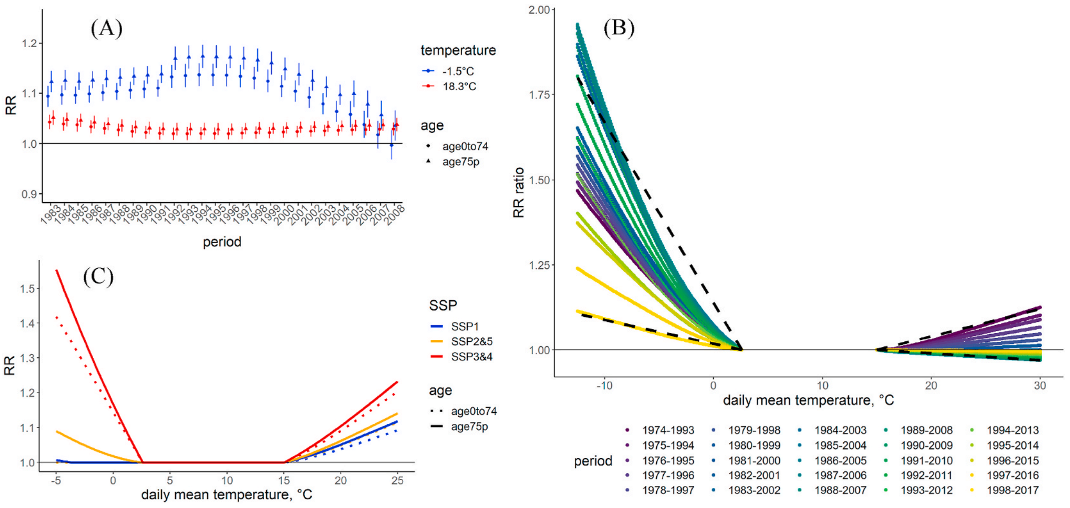

Fig. 3. (A) The RR at −1.5 °C and 18.3 °C (the 1st and 99th percentile of population-weighted daily mean temperature between 1974 and 2018) in Scotland in 26 20-year historical periods indicated by the central year of each period, e.g. 1983 for 1974–1993. (B) The ratio of temperature-specific RRs in each historical period against 1999–2018. (C)The transformed RRs under each SSPs.

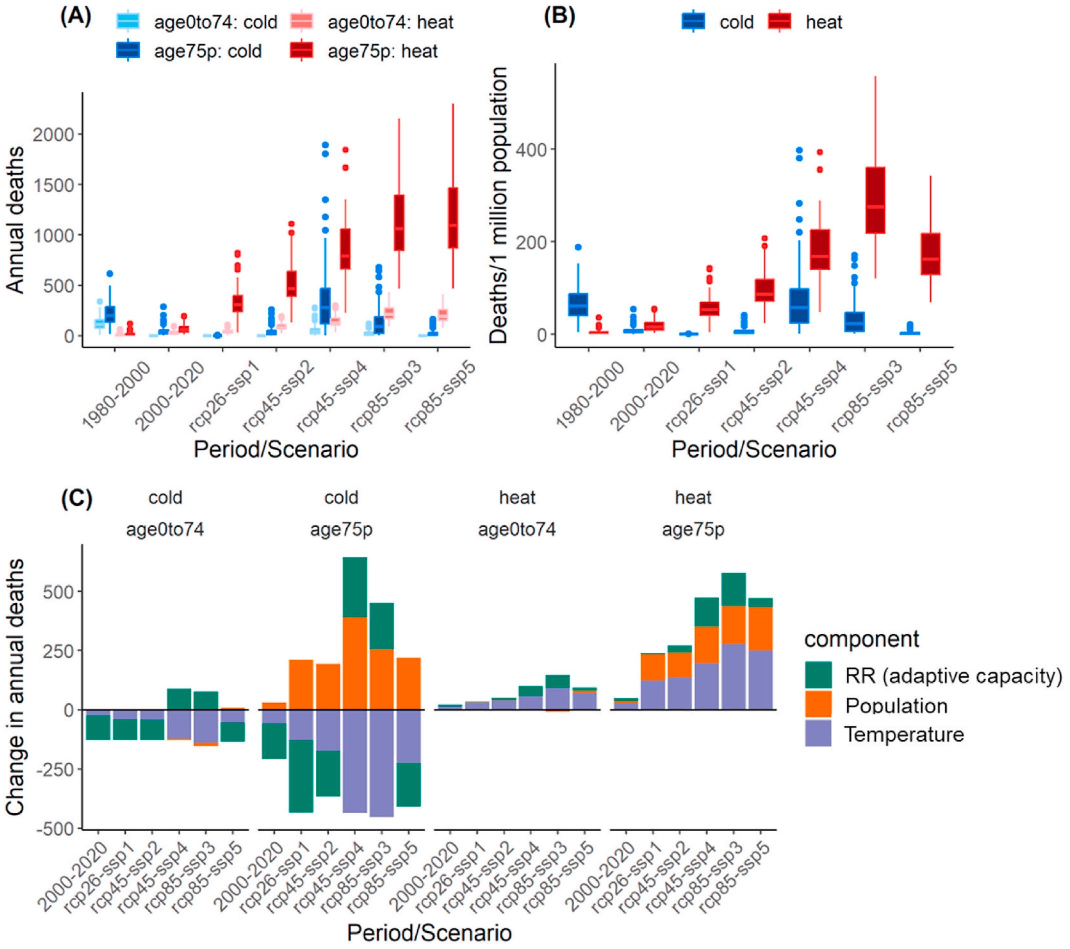

Fig. 4. (A) Annual mortality burden for two age groups and (B) annual mortality burden per 1 million population attributed to cold and heat in Scotland in two historical periods (1980–2000 and 2000–2020) and 2060–2080 under five RCP-SSP scenarios. (C) The change in mean annual mortality burden in 2000–2020 and 2060–2080 under five scenarios compared to 1980–2000 and the decomposition of the change into three components.

was made based on compatibility with the projected change in the key socioeconomic factors affecting the adaptive capacities, utilising the output from the UK-SSP project (Wan et al., 2022b). However, there may be the possibility that the adaptive capacities to cold and heat change in opposite directions (e.g. an increase in the adaptive capacity to heat and a decrease in the adaptive capacity to cold), which could be explored in future studies. Similarly, only one adaptation level was investigated under RCP2.6-SSP1 based on the projections on the socioeconomic indicators of the UK-SSP project. However, different levels of adaptation may occur under RCP2.6-SSP1, which can be explored in future research. Another limitation is that the annual cycle of mortality rate in the future by 2080 was assumed to remain constant as in 2010–2018 for this study because of the absence of robust data on this. Although this is an assumption commonly made in previous studies in estimating temperature-related mortality burdens (Gasparrini et al., 2017), the baseline mortality rate is likely to change in the future as affected by various socioeconomic factors that are interconnected with the adaptive capacity to cold and heat, which is an area requiring further research (Lloyd et al., 2023).

Nonetheless, this study used a novel approach with the adaptation assumptions informed by both the SSPs and observed historical RR ratios that capture the difference in RR under different temperatures. The slope of the linear approximation of RR ratio can be used to quantify the difference in the non-linear temperature-mortality associations across locations or periods in other studies, which is an advancement of the current prevalent methods of simplifying the association using a linear threshold model or comparing the heat effect at a certain temperature. The results of this study of the cold/heat burdens under five future RCP-SSPs reflect a wide range of probable future risks. This method is applicable to the estimation of climate change health risks in any locations that have historical risk functions or historical data from which the risk function can be derived and similar SSP frameworks.

In conclusion, the increase in the hot days and associated mortality burden surpasses the decrease in cold days under all scenarios of climate change, indicating heat is a significant health concern even in a cool place like Scotland and the net increase in health risks related to extreme temperatures due to climate change. More than half of the increase in the heat burden between 1980-2000 and 2060–2080 could be prevented if there were no global warming, corresponding to 193 (RCP2.6-SSP1) and 724 (RCP8.5-SSP5) deaths/year. The cold and heat mortality rate and the combined mortality burden are both the lowest under RCP2.6-SSP1, which is a low future emissions pathway with high adaptive capacity, emphasising the health benefits of adaptation and climate change mitigation.

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CRediT authorship contribution statement

Kai Wan: Writing – review & editing, Writing – original draft, Visualization, Project administration, Methodology, Investigation, Formal analysis, Conceptualization. **Shakoor Hajat:** Writing – review & editing, Validation, Supervision, Methodology, Investigation, Conceptualization. **Ruth M. Doherty:** Writing – review & editing, Supervision. **Zhiqiang Feng:** Writing – review & editing, Validation, Supervision, Methodology, Investigation, Conceptualization.

Declaration of competing interest

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

Data availability

The authors do not have permission to share data.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envres.2024.118731.

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