

# Climate change: reshaping mortality differences within the United Kingdom?

R. Naqvi\* and M. Hall

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## Abstract

Older people are higher contributors to mortality excess and most sensitive to environmental influences, e.g. temperature. As the population ages, variability in temperature is liable to impact a large proportion of life insurance or pension policies in a portfolio. Climate change is projected to significantly affect future mean temperatures. Moreover, future changes in mean temperature are estimated to vary across different regions of the United Kingdom. Accordingly, the present paper investigates the potential impact of future mean temperature changes on older-age mortality in England & Wales and Scotland. The corresponding effect on older-age mortality differences between England & Wales and Scotland is also investigated.

## Keywords

Older-age mortality; Temperature; Regional variation

## 1. Introduction

Mortality is an unambiguous measure of health. Rapid improvement in mortality has led to a burgeoning older population in the United Kingdom, with over 65s representing, 17.8% of the total population as of mid-2015. The ONS<sup>1</sup> reports that since mid-2005, this age-group has grown by 21%. However, mortality improvements vary substantially across regions. Relative to England & Wales, mortality rates in Scotland (McCartney *et al.*, 2015) were 12% higher in 1981, increasing to 15% higher in 2001, and socio-economic disparity (Wilkinson *et al.*, 2004; McCartney *et al.*, 2015) is increasingly less able to account for regional mortality differences.

Another determinant of regional health and mortality differences relate to environmental influences temperature (a thermal measurement of climate change). There is a sizeable body of evidence that cites clear seasonal patterns in incidence of major causes of death, e.g. coronary heart disease (Fares, 2013); often attributing a temperature association, although the detailed biological mechanisms of this influence are not fully understood. Many studies (Bull & Morton, 1978; Enquselassie *et al.*,

\*Correspondence to: Rabia Naqvi, UCD School of Mathematics and Statistics, University College, Dublin, Belfield, Dublin 4, Ireland. E-mail: [rabia.naqvi@ucdconnect.ie](mailto:rabia.naqvi@ucdconnect.ie)

<sup>1</sup> <https://www.ons.gov.uk/peoplepopulationandcommunity/populationandmigration/populationestimates/bulletins/annualmidyearpopulationestimates/previousReleases>

1993) comment on a parabolic U-shaped relationship between temperature and mortality; mortality being lowest between [15°C, 20°C] and higher on either side of this optimal range. Patterns of increasing mortality effects with age have been observed under both acute heat and cold events (Poumadere *et al.*, 2005; Chung *et al.*, 2015). Unsurprisingly, with climate change has come increasing awareness of potential health and mortality risks associated with temperature variability in the general population, particularly at older ages. Thus, interest for this paper lies in the impact of mean temperature on older-age mortality and on regional mortality differentials in older-age mortality.

UK Climate Projections (Murphy *et al.*, 2009) forecast temperature to change, relative to *standard normals*, by between [0.9°C, 5.0°C] in England & Wales and between [0.7°C, 4.3°C] in Scotland by 2050. Regional temperature disparities are set to widen and it is important to understand how this may impact on relative differences in mortality by region in the future. A common assumption is that warming temperatures augur well for reductions in mortality. However, projections for England & Wales present a scenario whereunder mean temperatures will exceed the optimal range by 2050. Additionally, recent research (Overland *et al.*, 2016) suggests that global warming may lead to an intensification of the effects of the jet stream, causing extreme cold weather in the United Kingdom and United States. Consequently, climate change is a long-term challenge and potential risks presented by climatological hazards is an important consideration, given a transitioning climate with an elevated propensity for acute weather events.

Furthermore, the contract period for a typical life insurance or pension policy is sufficiently long for climate change to have a potential impact. Empirical evidence (Poumadere *et al.*, 2005; Kovats & Kristie, 2006; Jenkins *et al.*, 2009) shows that older people are most severely impacted by acute weather hazards and are higher contributors to mortality excess. Therefore, temperature variability is a risk factor liable to impact a large number of policies in a portfolio. Such considerations can inform product design and the level of risk management undertaken by insurers. Accordingly, the objective of the present analysis is to model the impact of mean temperature on mortality at older ages in England & Wales and Scotland, and to investigate the impact of possible future temperatures on regional mortality differences.

The present paper proceeds as follows. Section 2 describes the data sources and reports summary information. Section 3 provides the modelling framework for present analysis and describes model results. Section 4 presents the impact to regional mortality differences under future temperature scenarios. Section 5 reviews the main conclusions and important caveats to the present analysis.

## 2. Data

### 2.1. Mortality Data

Population estimates of England & Wales and Scotland are sourced from The Human Mortality Database (Wilmoth & Shkolnikov, 2008) and refer to (civilian) population size, by single year of age, on 1 January each year. Monthly population death data for the period 1974–2014 was made available by the National Records of Scotland (NRS). The Office of National Statistics (ONS) supplied corresponding data for the period 1993–2014 in respect of England & Wales. Death data are classified according to year, month, sex, and single year of age (from 60 to 95 years). This paper models older-age mortality variation over decadal time intervals, that is, 1995–2004 and 2005–2014

respectively. “Over 75s” represent the group that tends to be jointly and severely impacted by acute weather developments (Jenkins *et al.*, 2009). On this basis, older-age mortality is investigated with respect to ages 75–90 years.

In this age range, female population estimates in England & Wales and Scotland are very consistent over the whole period of investigation, growing by 242,000 approx. (or 0.5% per annum) and 31,000 approx. (or 0.7% per annum), respectively. Correspondingly, in this age range, male population estimates in England & Wales and Scotland exhibit growth in population size of 611,000 approx. (or 2.0% per annum) and 60,000 approx. (or 2.3% per annum), respectively.

## 2.2. Temperature Data

The central England temperature (CET) data series (Parker *et al.*, 1992) is produced and maintained by the Met Office Hadley Centre. It constitutes the longest monthly series in the world, with records beginning from 1659; it is widely used as a measure of thermal conditions representative of a roughly triangular area of the United Kingdom enclosed by Lancashire, London, and Bristol. Here, monthly mean temperature data from CET dataset are used to analyse the contribution of temperature on older-age mortality trends in England & Wales.

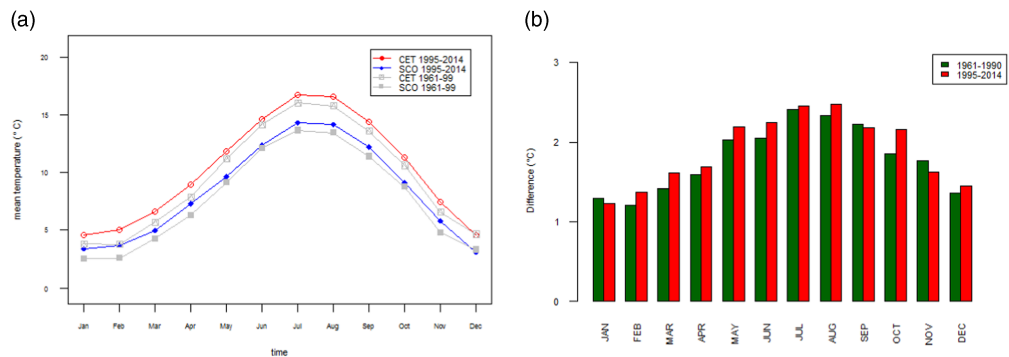
Based on paper by Jones & Lister (2004), for “mainland” Scotland (SMT), monthly data recorded by selection of long-running historic weather stations are used to construct a corresponding monthly mean temperature time series; data from island stations (Lerwick and Stornoway) are ignored for purposes of variance reduction and comparability with neighbouring site (i.e. CET). The resulting temperature data are used to analyse its role in older-age mortality trends of Scotland. Climatological conditions in Scotland do not differ drastically from other regions in the United Kingdom. However, Scotland tends to be cloudier, wetter, windier and average temperatures are lower relative to CET.

The United Kingdom Climate Impacts Program’s *UK Climate Projections* (so-called UKCP09 (Murphy *et al.*, 2009)), developed in 2009, is the leading source of climate change information for the whole of the United Kingdom. Using sophisticated global climate models, UKCP09 projections provide probabilistic representations of monthly, seasonal or annual changes in a number of climate variables relative to latest *standard normals*.<sup>2</sup> The present analysis uses UKCP09 scenarios of (summer and winter) mean temperature change, up to 2050, to investigate possible impact of future temperature change on relative mortality between England & Wales and Scotland.

Subsequent sections model the temperature–mortality relationship in England & Wales and Scotland, respectively. Relative impact of possible future temperatures on this relationship in each region is assessed. In this context, it is notable that all regions of the United Kingdom have experienced an increase in mean temperatures between 1961 and 2006 annually and for all seasons (Jenkins *et al.*, 2009). Increases in annual average temperature, relative to standard normals, are typically between 1.0°C and 1.7°C, tending to be largest in the south and east of England and smallest in Scotland (Jenkins, 2009).

Figure 1a highlights rising temperatures, on average, in both CET and SMT, relative to corresponding *standard normals*. It can also be seen that historical temperature disparity between regions

<sup>2</sup> Climatological standard normals are defined by the World Meteorological Organisation (WMO) as “averages of climatological data computed for consecutive periods of 30 years...”. The present global standard normals period is 1961–1990.



**Figure 1.** Comparative changes in mean temperature between CET and SMT, decomposed by month

**Table 1.** Incidence of Acute Heat and Cold Events in CET by Quinquennial Periods 1995–2014

Month	(a) Heat					(b) Cold				
	Expected No. (5years)	1995– 1999	2000– 2004	2005– 2009	2010– 2014	Expected No. (5 years)	1995– 1999	2000– 2004	2005– 2009	2010– 2014
January						2.3	2	2	1	2
February						2.5				2
March						0.2				1
April										
May					1					1
June	0.7	1		2			1		2	
July	0.7	2		4	1		2		4	1
August	0.5	4	1				4	1		
September		1			1		1			1
October					1					1
November										1
December						1.8	1	1	2	2
Subtotal	1.8	8	1	6	4	6.8	3	3	3	8

is subject to change. Figure 1b compares disparity in mean monthly temperatures between England & Wales and Scotland over time. Generally, regional disparity in mean monthly temperature is higher in 1995–2014 relative to standard normal period, due to CET experiencing, on average, larger temperature increases than SMT. Table 1 evidences an increase in incidence of acute heat<sup>3</sup> and cold<sup>4</sup> events in CET relative to expected, based on *standard normals* period. The timing of acute events supports evidence of warming and of some alteration to traditional seasonal timings.

<sup>3</sup> An acute heat event is so defined when the daily maximum temperature of more than 5 consecutive days exceeds the *standard normals* average maximum temperature by 5°C and of those runs, periods where maximum daily temperatures >24°C (assuming relative humidity 82%) each day.

<sup>4</sup> An acute cold event is so defined when the daily maximum temperature of more than 3 consecutive days is under the *standard normals* average maximum temperature and of those runs, periods where maximum daily temperatures <3°C (assuming relative humidity 82%) each day.

### 3. Modelling Impact of Temperature on Current Mortality

In this section, generalised additive models (GAMs) (Hastie & Tibshirani, 1990; Wood, 2006) are used to model the impact of temperature on mortality in England & Wales and Scotland over the periods 1995–2004, 2005–2014, respectively. GAMs are widely used in exploratory data analysis as an effective means of capturing more subtle non-linear patterns in data. GAMs extend the power of conventional regression techniques, by fitting non-parametric functions to estimate relationships between the response variable and explanatory variables, as necessary. In particular, the response variable is assumed to be affected by the explanatory variables through additive unspecified smooth functions and, the underlying probability distribution for the data can be any distribution from the exponential family. Therefore, in time-series studies of pollution/temperature-related mortality, GAMs are a widely applied method (Schwartz, 1994; Schwartz, 2000; Zanobetti *et al.*, 2000; Pattenden *et al.*, 2003; Cheng *et al.*, 2014). When the response variable represents counts (e.g. number of deaths), as is the case here, Poisson GAMs (with log link) are well suited to examining the effects of various explanatory variables on mortality rates. With R (R Core Team, 2015) statistical software and implementation in R package mgcv, the present analysis is conducted using an over-dispersed Poisson GAM model.

The model is fit separately by gender (i.e. male/female), region (i.e. England & Wales/Scotland) and decadal period (i.e. 1995–2004/2005–2014), as follows:

$$\log(m_{ijkl}) = \beta_0 + s_1(\text{Age}_i) + s_2(\text{Mean monthly temperature}_j) + s_3(\text{Month}_k) + s_4(\text{Year}_l) + \log([\text{Population}_{il}]) \quad (1)$$

where  $\text{Deaths}_{ijkl} \sim \text{Poisson}(E_{il}^c m_{ijkl})$ , population estimates on 1 January are used to approximate central exposed to risk and  $s_i$  are smooth functions implemented using cubic regression splines.

As previously noted, the model is fit to ages 75–90 years. The inclusion of explanatory factors, apart from mean temperature, serves to ensure that deviance in mortality is not confounded by other factors/proxies. Explanatory variable *Month* is a marker for seasonality, i.e. the presence of common characteristics in months that permit grouping into distinguishable seasons. To date, mortality has been higher in winter<sup>5</sup> months due mainly to prevalence of circulatory and respiratory diseases (Wilkinson *et al.*, 2004). Explanatory variable *Year* captures general improvements in mortality over time.

For the limited age range and time periods considered, interactions between explanatory variables are not included in the model. This results in a simple, easily interpretable model suitable for an initial investigation into the potential temperature-related effects on older-age mortality. Further, cubic regression splines are used in the primary model because they are computationally simplest and have sufficient flexibility for most purposes. Results are presented in proceeding (sub)sections as follows:

- Model results outlining effects of explanatory variables on male mortality, compared on a regional basis
- Model results outlining effects of explanatory variables on female mortality, compared on a regional basis
- Expected impact on regional mortality variation under projected temperature scenarios, by gender

<sup>5</sup> According to the Met Office, winter is defined as months December, January, February.

3.1. Model Results – Males

Model results confirm that explanatory variables included in the model are highly significant (see Tables A1 and A2) in respect of both regions and both decadal periods (i.e. 1995–2004, 2005–2014, respectively). Table 2 summarises fit of models for England & Wales and Scotland, respectively.

Figures 2 and 3 present the partial effects of explanatory variables on mortality for the periods 1995–2004 and 2005–2014. In both regions, the partial effect of *Age* on mortality increases linearly and the partial effect of *Year* on mortality is decreasing. The downward trajectory of *Year* partial effect is more pronounced in England & Wales than Scotland (especially in decade ending 2004) and then appears to level off from 2010. In both regions, the partial effect of *Month* on mortality (i.e. seasonal mortality) is curved for period 1995–2004; this curve tends to flatten in period 2005–2014.

In Figure 3a, the partial effect of mean temperature on mortality for England & Wales exhibits an upwardly tending curve at higher mean temperatures. This tendency has been recorded in other studies(Bull & Morton, 1978; Enquselassie *et al.*, 1993) that suggest a U-shaped temperature-

Table 2. Summary of GAM Models, by Region and Period\*

(a) England & Wales				(b) Scotland			
Period	R <sup>2</sup>	Deviance Explained	Deviance Explained by Temp	Period	R <sup>2</sup>	Deviance Explained	Deviance Explained by Temp
1995–2004	0.853	0.956	0.001678018	1995–2004	0.783	0.882	0.001526
2005–2014	0.835	0.978	0.00164315	2005–2014	0.661	0.916	0.0021863

\*GAM, generalised additive model.

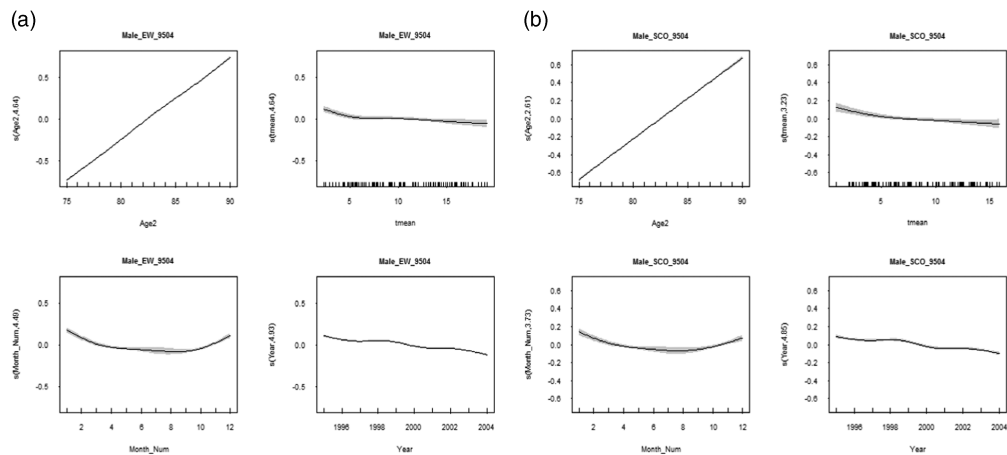
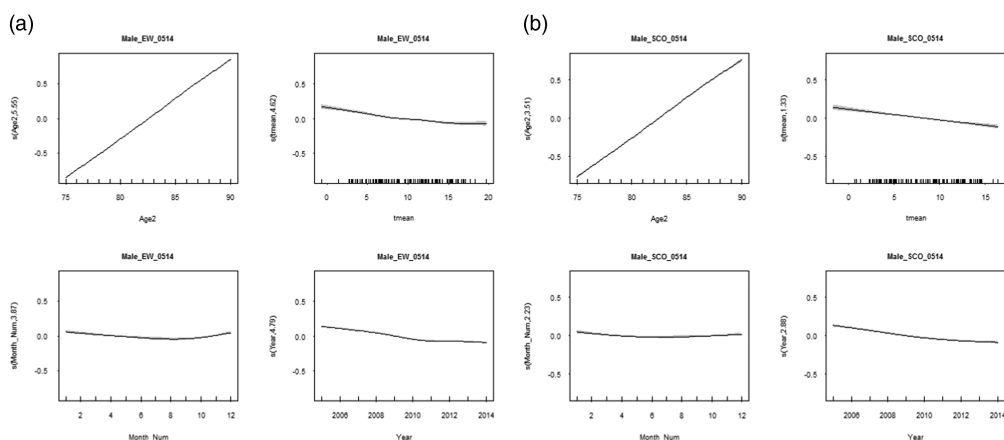


Figure 2. GAM-derived partial effects of explanatory variables on male mortality, by region 1995–2004 (a) 1995–2004: England & Wales and (b) 1995–2004: Scotland



**Figure 3.** GAM-derived partial effects of explanatory variables on male mortality, by region 2005–2014 (a) 2005–2014: England & Wales and (b) 2005–2014: Scotland

**Table 3.** Summary of GAM Models, by Region and Period\*

(a) England & Wales				(b) Scotland			
Period	$R^2$	Deviance Explained	Deviance Explained by Temp	Period	$R^2$	Deviance Explained	Deviance Explained by Temp
1995–2004	0.816	0.969	0.001522296	1995–2004	0.564	0.921	0.0008856989
2005–2014	0.893	0.977	0.00170192	2005–2014	0.643	0.937	0.0003346171

\*GAM, generalised additive model.

mortality relationship. That is, at marginal temperatures (e.g. over 20°C for the United Kingdom) mortality can re-accelerate.

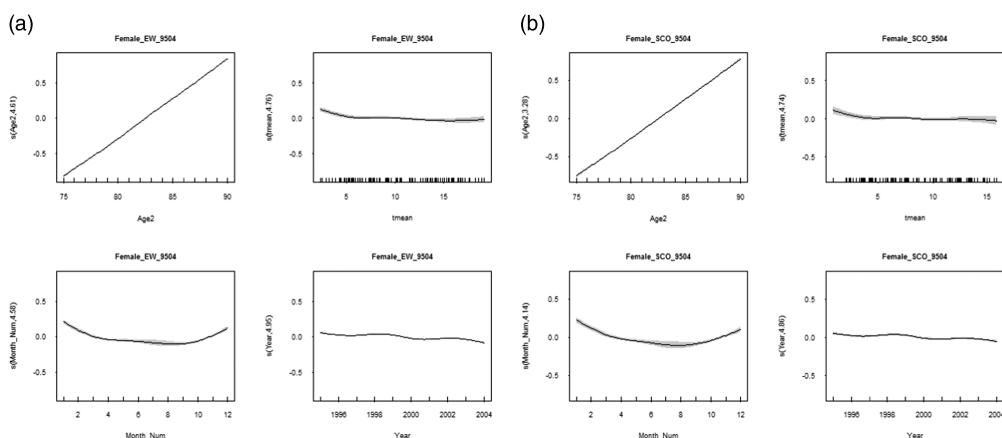
### 3.2. Model Results – Females

Model results confirm that explanatory variables included in the model are highly significant (see Tables A3 and A4) in respect of both regions and in both periods. Table 3 summarises fit of models for England & Wales and Scotland, respectively.

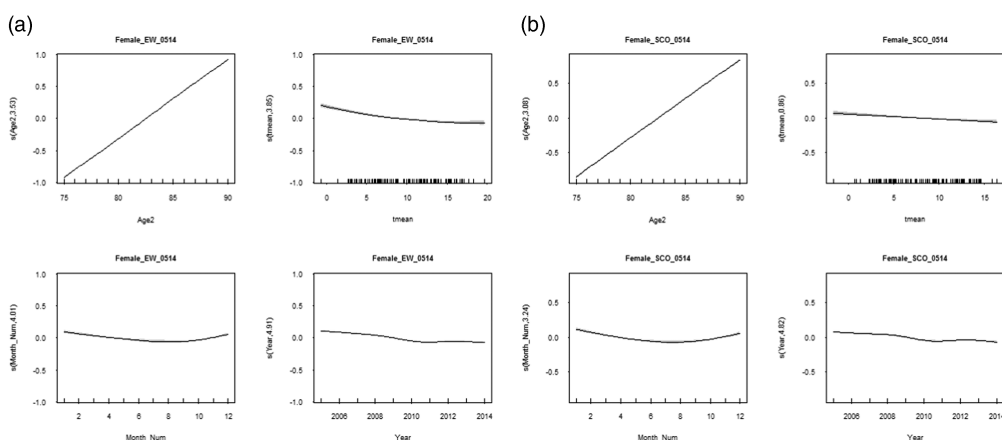
Figures 4 and 5 present the partial effects of explanatory variables on mortality for the periods 1995–2004 and 2005–2014. As seen for males, in both regions, the partial effect of *Age* on mortality increases linearly. Relative to males, differences in partial effects emerge as follows:

- partial effect of *Month* on mortality does not flatten to the same extent in period 2005–2014
- partial effect of *Year* on mortality is not as well defined in each decadal period

In concordance with males, Figure 5a exhibits an upwardly curving mean temperature partial effect, for England & Wales, at higher mean temperatures. Mean temperatures in England & Wales appear, over time, to increasingly approach threshold levels at which older-age mortality increases. Mean



**Figure 4.** GAM-derived partial effects of explanatory variables on female mortality, by region 1995–2004 (a) 1995–2004: England & Wales and (b) 1995–2004: Scotland



**Figure 5.** GAM-derived partial effects of explanatory variables on female mortality, by region 2005–2014 (a) 2005–2014: England & Wales and (b) 2005–2014: Scotland

temperatures in SMT are lower relative to CET, hence this type of curvature is not evident in Figure 5b.

#### 4. Future Temperature Scenarios

Changes in mean temperature are expected to vary by region, with expanding regional climatological disparities. Using models fitted to the most recent decadal period, 2005–2014, the potential impact of possible future mean temperature change on mortality differences between England & Wales and Scotland is assessed.

With January and July being used as seasonal proxies for winter and summer respectively, current seasonal mean temperatures are calculated as the average of monthly mean temperatures pertaining to proxy months, in the period 2005–2014 inclusive. Further assuming no change in contribution of *Age*, *Month*, *Year* to older-age mortality, relative mortality differences between regions are predicted

**Table 4.** Summary of UKCP09 Seasonal Mean Temperature Projection (Under a Medium Emissions Scenario) by 2050 According to Region\*

<i>(a) England &amp; Wales</i>				
	Current Mean Temperature	Standard Normals Mean Temperature	Projected Change Range	2050 Projected Mean Temperature Range
Winter	4.7°C	3.8°C	[0.9°C, 3.7°C]	[4.7°C, 7.5°C]
Summer	16.8°C	16.1°C	[1.1°C, 5.0°C]	[17.2°C, 21.1°C]
<i>(b) Scotland</i>				
	Current Mean Temperature	Standard Normals Mean Temperature	Projected Change Range	2050 Projected Mean Temperature Range
Winter	3.4°C	2.5°C	[0.7°C, 3.1°C]	[3.2°C, 5.6°C]
Summer	14.4°C	13.6°C	[1.0°C, 4.3°C]	[14.6°C, 17.9°C]

\*Standard normal mean temperature refers to average of monthly mean temperature for January or July in global standard normals period 1961–1990. Projected change range refers to average change relative to standard normal with respect to following areas: East Midlands, London, South East England, South West England, West Midlands (England & Wales) and Scotland East, Scotland North, Scotland West (Scotland).

at current<sup>6</sup> and projected seasonal mean temperatures (assuming a medium emissions scenario), as shown in Table 4. Predictions assume an individual aged 80 years, *Month* is set to January or July, as appropriate, and *Year* is fixed at 2014.

That is, expected relative difference is calculated using central death probabilities as follows:

$$100 \times \left( \frac{m_{80}^{\text{Scotland; Year} = 2014; \text{Sex; Month; Temp}}}{m_{80}^{\text{England \& Wales; Year} = 2014; \text{Sex; Month; Temp}}} - 1 \right) \quad (2)$$

Tables 5 and 6 present the expected relative differences in mortality for males and females at mean seasonal temperature scenarios, drawn from UKCP09 climate change projections for 2050s. Scenario 1 represents the minimum mean temperature in the range projected by 2050 (as shown in Table 4), for England & Wales and Scotland respectively. Scenario 2 represents the maximum mean temperature in the range projected by 2050, for England & Wales and Scotland, respectively.

These simple results (based on selected proxies for “winter”, “summer”, and “old-age”) indicate that, in winter, increasing regional temperatures and increasing regional mean temperature difference are expected to result in a wider mortality gap between England & Wales and Scotland. However, in summer, the mortality gap is expected to improve, precipitated by potential re-acceleration of mortality at marginal mean temperature levels (i.e. over 20°C) in England & Wales. The degree of improvement in regional mortality differences varies by gender.

#### 4.1. Acute Temperatures

One limitation of the UKCP09 projections is its focus on central probabilistic estimates of potential future climate change. This results in low probability but high impact climatological hazards, e.g.

<sup>6</sup> Refers to average of monthly mean temperatures for January or July in period 2005–2014 inclusive.

**Table 5.** Regional Male Mortality Differences (%) at Age 80 Years – Seasonal Mean Temperature Scenario Results

<i>(a) Winter (January)</i>				
	England & Wales	Scotland	$\Delta_{\text{Temp}}$	Relative Difference in Mortality (%)
Current	4.7°C	3.4°C	1.3°C	15.29
Scenario 1	4.7°C	3.2°C	1.5°C	15.71
Scenario 2	7.5°C	5.6°C	1.9°C	18.38

<i>(b) Summer (July)</i>				
	England & Wales	Scotland	$\Delta_{\text{Temp}}$	Relative Difference in Mortality (%)
Current	16.8°C	14.4°C	2.4°C	17.94
Scenario 1	17.2°C	14.6°C	2.6°C	17.67
Scenario 2	21.1°C	17.9°C	3.2°C	11.66

**Table 6.** Regional Female Mortality Differences(%) at Age 80 Years – Seasonal Mean Temperature Scenario Results

<i>(a) Winter (January)</i>				
	England & Wales	Scotland	$\Delta_{\text{Temp}}$	Relative Difference in Mortality (%)
Current	4.7°C	3.4°C	1.3°C	21.37
Scenario 1	4.7°C	3.2°C	1.5°C	21.65
Scenario 2	7.5°C	5.6°C	1.9°C	25.70

<i>(b) Summer (July)</i>				
	England & Wales	Scotland	$\Delta_{\text{Temp}}$	Relative Difference in Mortality (%)
Current	16.8°C	14.4°C	2.4°C	24.21
Scenario 1	17.2°C	14.6°C	2.6°C	24.11
Scenario 2	21.1°C	17.9°C	3.2°C	21.08

acute heat and cold events, often being overlooked. Acute climatological events represent hazards that may occur at some point in the future and may or may not, be tied to a specific time frame (e.g. 2020s, 2050s, or 2080s). Table 1 indicates that incidence of such acute weather events, as defined, has increased in recent years and prospective warming does not exclude the possibility of acute cold events (Overland *et al.*, 2016).

In 2015, the Adaptation Sub-Committee of the Committee for Climate Change commissioned a project to investigate the development of plausible “high-end” climate change scenarios, including heatwaves and coldwaves (Wade *et al.*, 2015). Table 7 summarises the *hypothetical* temperature scenarios created on an evidential basis for this report that are typically extreme, that is, on the margins or outside of the 10th to 90th percentile range presented in UKCP09 projections.

**Table 7.** Summary of Acute Scenarios Presented in Report (Event Based or Annual Average Scenarios)

<b>Acute heat scenario description</b> ("H++ scenario")	Average summer maximum temperatures would exceed 30°C over most of the UK, and would exceed 34°C over much of central and southern England
<b>Acute cold scenario description</b> ("L- scenario")	In the 2020s, UK average winter temperatures: 0.3°C In the 2080s, UK average winter temperatures: -4°C

Future research should consider the impact on older-age mortality of acute temperature scenarios, to fully appreciate the development of relative differences in mortality between regions within the United Kingdom.

## 5. Conclusions

Additive models applied in the present analysis find mean temperature to be a significant factor in older-age mortality. Generally, increasing temperatures imply decreasing mortality rates. However, results also suggest that a U-shaped temperature–mortality relationship operates at older ages, i.e. there is a temperature range such that mortality is higher on either side of this optimal range; thus having implications for insurers in the medium term.

Relative to England & Wales, Scotland currently has a more unfavourable climate and mortality rates in Scotland are substantially higher. With warming temperatures, regional temperature (and climate) disparities are anticipated to change. England & Wales is expected to warm faster than Scotland. Generally, this means

- in summer, mortality differences between England & Wales and Scotland are expected to improve
- in winter, mortality differences between England & Wales and Scotland are not expected to improve

However, overall climate is also expected to become more unpredictable; acute weather events more likely. During these periods, the present analysis suggests, in presence of U-shaped temperature–mortality relationship, the direction of change in regional mortality differences depends strongly on which region is subject to more unfavourable conditions.

Importantly, this is a simple analysis to highlight the potential impact that climate change, as measured by mean temperature, may have on older-age mortality differences between England & Wales and Scotland. However, the relationship between temperature and mortality is not a *static* one, but is subject to change over time and across regions, e.g. evidence (Momiya & Katayama, 1972; Kunst *et al.*, 1993) indicates that “adaptation” moderates temperature effects, and persistent exposure (Eurowinter Group, 1997) to a particular climate can mitigate or accentuate the impact of unusual climatological hazards, when they occur. That is, the relationship has many interdependencies. Thus, further work is required to fully develop the temperature–mortality relationship in the United Kingdom in order to fully quantify the implications for future mortality development and regional mortality disparity at older ages, e.g. inclusion of higher order terms in models.

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## References

- Bull, G.M. & Morton, J. (1978). Environment, temperature and death rates. *Age and Ageing*, 7(4), 210–224.
- Cheng, J., Xu, Z., Zhu, R., Wang, X., Jin, L., Song, J. & Su, H. (2014). Impact of diurnal temperature range on human health: a systematic review. *International Journal of Biometeorology*, 58(9), 2011–2024.
- Chung, Y., Lim, Y.H., Honda, Y., Guo, Y.L.L., Hashizume, M., Bell, M.L., Chen, B.Y. & Kim, H. (2015). Mortality related to extreme temperature for 15 cities in northeast Asia. *Epidemiology*, 26(2), 255–262.
- Enquesselassie, F., Dobson, A.J., Alexander, H.M. & Steele, P.L. (1993). Seasons, temperature and coronary disease. *International Journal of Epidemiology*, 22(4), 632–636.
- Eurowinter Group (1997). Cold exposure and winter mortality from ischaemic heart disease, cerebrovascular disease, respiratory disease, and all causes in warm and cold regions of Europe. *The Lancet*, 349(9062), 1341–1346.
- Fares, A. (2013). Winter cardiovascular diseases phenomenon. *North American Journal of Medical Sciences*, 5(4), 266.
- Hastie, T.J. & Tibshirani, R.J. (1990). Generalized Additive Models. Volume 43 of Monographs on Statistics and Applied Probability, Chapman & Hall, London.
- Jenkins, G.J. (2009). UK Climate Projections: Briefing Report. Exeter: Met Office Hadley Centre.
- Jenkins, G.J., Perry, M., Prior, J., UKCIP09 & UK Climate Impacts Programme. (2009). The climate of the United Kingdom and recent trends. Exeter: Met Office Hadley Centre.
- Jones, P.D. & Lister, D. (2004). The development of monthly temperature series for Scotland and Northern Ireland. *International Journal of Climatology*, 24(5), 569–590.
- Kovats, R.S. & Kristie, L.E. (2006). Heatwaves and public health in Europe. *The European Journal of Public Health*, 16(6), 592–599.
- Kunst, A.E., Looman, C.W. & Mackenbach, J.P. (1993). Outdoor air temperature and mortality in the Netherlands: a time-series analysis. *American Journal of Epidemiology*, 137(3), 331–341.
- McCartney, G., Russ, T.C., Walsh, D., Lewsey, J., Smith, M., Smith, G.D., Stamatakis, E. & Batty, G.D. (2015). Explaining the excess mortality in Scotland compared with England: pooling of 18 cohort studies. *Journal of Epidemiology and Community Health*, 69(1), 20–27.

- Momiyama, M. & Katayama, K. (1972). Deseasonalization of mortality in the world. *International Journal of Biometeorology*, 16(4), 329–342.
- Murphy, J.M., Sexton, D.M., Jenkins, G.J., Booth, B.B., Brown, C.C., Clark, R.T., Collins, M., Harris, G.R., Kendon, E.J., Betts, R.A. & Brown, S.J. (2009). UK Climate Projections Science Report: Climate Change Projections. Exeter: Met Office Hadley Centre.
- Overland, J., Dethloff, K., Francis, J., Hall, R., Hanna, E., Kim, S.J., Screen, J., Shepherd, T.G. & Vihma, T. (2016). Nonlinear response of mid-latitude weather to the changing Arctic. *Nature Climate Change*, 6, 992–999.
- Parker, D.E., Legg, T.P. & Folland, C.K. (1992). A new daily central England temperature series, 1772–1991. *International Journal of Climatology*, 12(4), 317–342.
- Pattenden, S., Nikiforov, B. & Armstrong, B.G. (2003). Mortality and temperature in Sofia and London. *Journal of Epidemiology and Community Health*, 57(8), 628–633.
- Poumadere, M., Mays, C., Le Mer, S. & Blong, R. (2005). The 2003 heat wave in France: dangerous climate change here and now. *Risk Analysis*, 25(6), 1483–1494.
- R Core Team (2015). R: A Language and Environment for Statistical Computing [Computer software]. R Foundation for Statistical Computing, Vienna, Austria.
- Schwartz, J. (1994). Nonparametric smoothing in the analysis of air pollution and respiratory illness. *Canadian Journal of Statistics*, 22(4), 471–487.
- Schwartz, J. (2000). Assessing confounding, effect modification, and thresholds in the association between ambient particles and daily deaths. *Environmental Health Perspectives*, 108(6), 563.
- Wade, S., Sanderson, M., Golding, N., Lowe, J., Betts, R., Reynard, N., Kay, A., Stewart, L., Prudhomme, C., Shaffrey, L. & Lloyd-Hughes, B. (2015). Developing H++ climate change scenarios for heat waves, droughts, floods, windstorms and cold snaps. London: Committee on Climate Change. Available online: <http://nora.nerc.ac.uk/id/eprint/512103>.
- Wilkinson, P., Pattenden, S., Armstrong, B., Fletcher, A., Kovats, R.S., Mangtani, P. & McMichael, A.J. (2004). Vulnerability to winter mortality in elderly people in Britain: population based study. *BMJ*, 329(7467), 647.
- Wilmoth, J.R. & Shkolnikov, V. (2008). Human Mortality Database. University of California, Berkeley (US), and Max Planck Institute for Demographic Research (Germany).
- Wood, S.N. (2006). *Generalized Additive Models: An Introduction with R*. Boca Raton: FL: CRC Press.
- Zanobetti, A., Wand, M.P., Schwartz, J. & Ryan, L.M. (2000). Generalized additive distributed lag models: quantifying mortality displacement. *Biostatistics*, 1(3), 279–292.

## Appendix 1 Poisson GAM Model Results

### Males

**Table A1.** England & Wales GAM Male Model Results, by Decadal Period

	1995–2004	2005–2014
(Intercept)	– 4.697*** (0.002)	– 4.972*** (0.002)
EDF: s(Age2)	4.638*** (9.000)	5.552*** (9.000)
EDF: s(tmean)	4.637*** (5.000)	4.615*** (5.000)
EDF: s(Month_Num)	4.493*** (5.000)	3.874*** (5.000)
EDF: s(Year)	4.931*** (5.000)	4.786*** (5.000)
Deviance	11,056.670	6,758.746
Deviance explained	0.956	0.978
Dispersion	6.057	3.656
$R^2$	0.853	0.835
GCV score	5.879	3.594
Number of observations	1,920	1,920
Number of smooth terms	4	4

GCV, generalised cross-validation.

\*\*\* $p < 0.001$ , \*\* $p < 0.01$ , \* $p < 0.05$ .

**Table A2.** Scotland GAM Male Model Results, by Decadal Period

	1995–2004	2005–2014
(Intercept)	– 4.606*** (0.004)	– 4.839*** (0.003)
EDF: s(Age2)	2.610*** (9.000)	3.507*** (9.000)
EDF: s(tmean)	3.227*** (5.000)	1.334*** (5.000)
EDF: s(Month_Num)	3.728*** (5.000)	2.226*** (5.000)
EDF: s(Year)	4.846*** (5.000)	2.880*** (5.000)
Deviance	2,532.136	2,224.150
Deviance explained	0.882	0.916
Dispersion	1.340	1.171
$R^2$	0.783	0.661
GCV score	1.340	1.172
Number of observations	1,920	1,920
Number of smooth terms	4	4

GCV, generalised cross-validation.

\*\*\* $p < 0.001$ , \*\* $p < 0.01$ , \* $p < 0.05$ .

## Females

Table A3. England &amp; Wales GAM Female Model Results, by Decadal Period

	1995–2004	2005–2014
(Intercept)	– 5.105*** (0.002)	– 5.319*** (0.002)
EDF: s(Age2)	4.605*** (9.000)	3.525*** (9.000)
EDF: s(tmean)	4.761*** (5.000)	3.847*** (5.000)
EDF: s(Month_Num)	4.575*** (5.000)	4.014*** (5.000)
EDF: s(Year)	4.951*** (5.000)	4.906*** (5.000)
Deviance	13,327.797	9,762.213
Deviance explained	0.969	0.977
Dispersion	7.308	5.323
R <sup>2</sup>	0.816	0.893
GCV score	7.088	5.177
Number of observations	1,920	1,920
Number of smooth terms	4	4

GCV, generalised cross-validation.

 $p < 0.001$ , \*\* $p < 0.01$ , \* $p < 0.05$ .

Table A4. Scotland GAM Female Model Results, by Decadal Period

	1995–2004	2005–2014
(Intercept)	– 4.992*** (0.003)	– 5.151*** (0.003)
EDF: s(Age2)	3.279*** (9.000)	3.083*** (9.000)
EDF: s(tmean)	4.735*** (5.000)	0.860*** (5.000)
EDF: s(Month_Num)	4.136*** (5.000)	3.239*** (5.000)
EDF: s(Year)	4.862*** (5.000)	4.817*** (5.000)
Deviance	3,055.257	2,568.891
Deviance explained	0.921	0.937
Dispersion	1.620	1.348
R <sup>2</sup>	0.564	0.643
GCV score	1.622	1.356
Number of observations	1,920	1,920
Number of smooth terms	4	4

GCV, generalised cross-validation.

 $p < 0.001$ , \*\* $p < 0.01$ , \* $p < 0.05$ .