



Impact of sudden stratospheric warmings on United Kingdom mortality

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RESEARCH ARTICLE

Impact of sudden stratospheric warmings on United Kingdom mortality

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Abstract

Sudden stratospheric warmings (SSWs) during boreal winter are one of the main drivers of sub-seasonal climate variability in the Northern Hemisphere. Although the impact of SSW events on surface climate and climate extremes has been clearly demonstrated, the impact of the resulting climate anomalies on society has not been so widely considered. In the United Kingdom (UK), SSWs are associated with cold weather, which is linked to significant increases in mortality. This study demonstrates, for the first time, that SSWs are linked to increases in mortality in the UK. A distributed lag nonlinear model and standard parameter settings from the literature is used to construct a daily time series of UK deaths attributable to cold weather between 1991 and 2018. Weekly mortality associated with SSWs is diagnosed using a superposed epoch analysis of attributed mortality for the 15 SSW events in this period. SSW associated mortality peaks between 3 and 5 weeks after SSW central date and leads to, on average, 620 additional deaths in the same period. Given that the impacts of SSWs can be skilfully predicted on sub-seasonal timescales, this suggests that health and social care systems could derive substantial benefit from sub-seasonal forecasts during SSWs.

KEYWORDS

mortality, public health, sub-seasonal prediction, sudden stratospheric warmings

1 | INTRODUCTION

Major, sudden stratospheric warming (SSW) events are one of the most dramatic and long-lived events in the wintertime extra-tropical atmosphere (O'Neill *et al.*, 2015). Around six times per decade (Charlton and Polvani, 2007; Butler *et al.*, 2017), the usually westerly polar vortex breaks down and is replaced, temporarily by easterly winds throughout the depth of the stratosphere. Recent interest in SSW events has centred on their long-lived influence on the tropospheric state (Baldwin and

Dunkerton, 2001; Baldwin *et al.*, 2003) and their potential value for sub-seasonal and seasonal predictions (Scaife *et al.*, 2015; Butler *et al.*, 2016; Karpechko *et al.*, 2017; Butler *et al.*, 2019). While there remains work to do to improve the ability of sub-seasonal prediction models to fully capture the predictability associated with SSW events (Domeisen *et al.*, 2020b), many recent studies have shown what might be gained from doing so (Karpechko *et al.*, 2018; Kautz *et al.*, 2019; Lee *et al.*, 2019).

SSW events are associated with an enhanced likelihood of negative Northern Annular Mode and/or North

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Atlantic Oscillation conditions (Hitchcock and Simpson, 2014). At a local-scale, this results cold surface temperature anomalies in Northern Europe and an enhanced likelihood of cold-air outbreaks (Kolstad *et al.*, 2010) and cold temperature extremes (Tomassini *et al.*, 2012; Kretschmer *et al.*, 2018; King *et al.*, 2019).

In the United Kingdom (UK), as in many European countries, cold temperatures lead to 30–40,000 (Hajat *et al.*, 2014) deaths every year (Hajat *et al.*, 2013) associated with a wide-range of health conditions including stroke, heart-attack, influenza, trips and falls and respiratory diseases (Arbuthnott *et al.*, 2018). Most projections of 21st century UK temperature indicate a reduction in the number of cold days. However, as the number of elderly, more vulnerable people increases, the number of cold weather deaths is likely to remain significant. Over the past 20 years, the UK has implemented a number of different government policies to reduce harm from cold weather (Staddon *et al.*, 2014). Since 2011, cold weather planning in the UK has been collected into the annual, Cold Weather Plan (CWP) produced by Public Health England, which includes the Cold Weather Alert (CWA) forecasting service provided by the Met Office (Chalabi *et al.*, 2016). Currently this forecasting service is focussed on short-range forecasts, where direct action to prepare for cold weather is advised.

Given the potential window-of-opportunity for sub-seasonal predictability of temperature in the UK following SSW events, there is clearly the possibility that there could be great benefit in making use of this information to inform cold weather planning for the health and social care sector. Similar arguments have been made when considering weather patterns that vary on sub-seasonal timescales (Charlton-Perez *et al.*, 2019). A key pre-requisite for exploring this idea in more detail is to establish if there is a measurable signal of enhanced cold weather mortality following SSW events. In this letter, we use a superposed epoch analysis of mortality following SSW events to demonstrate that this is the case and quantify the size and spatial variation of this signal.

2 | DATA AND METHODOLOGY

2.1 | Mortality data

Daily, all-cause, mortality data for regions of the UK is obtained from the Office for National Statistics for Nomenclature of Territorial Units for Statistics (NUTS) regions of England and for Wales (1970–2018), from National Records of Scotland for Scotland (1991–2018) and from the Northern Ireland

Department of Health for Northern Ireland (1974–2018). All analysis is conducted on the recent, common period (1991–2018).

2.2 | Temperature data

Daily temperature data, averaged over each of the same UK sub-regions as the mortality is obtained from the HadUK-Grid dataset (Hollis *et al.*, 2019). HadUK-Grid is an extensively quality-controlled and gridded estimate of UK temperatures derived from the Met Office station record. Daily maximum and minimum temperature data is available from 1960–2018. Mean temperature is estimated as the average of the maximum and minimum temperature.

2.3 | SSW central date

SSW central dates are taken from the JRA-55 version of the SSW compendium (Butler *et al.*, 2017), updated to include the February 2018 SSW event. SSW central dates differ little between different reanalyses. SSWs central dates, hereafter SSW events, were defined using the Charlton and Polvani (2007) criterion which focuses on the first date of easterly values for the zonal mean zonal winds at 10 hPa and 60 N. During the period 1991–2018, over which we have mortality data, there are 15 SSWs.

2.4 | Statistical model

We model the relationship between temperature and mortality for each sub-region of the UK and for the total mortality over the UK using a distributed lag non-linear model, following the tutorial in Vicedo-Cabrera *et al.* (2019). R code provided in the R-package, *dlnm* is used to construct the models. Mortality is modelled as a Poisson process with overdispersion. Following Vicedo-Cabrera *et al.* (2019), our model can be written as:

$$\log[E(Y_t)] = \alpha + f(x_t; \theta) + s(t; \beta)$$

where $E(Y_t)$ is the expected value of the daily mortality, $f(x_t; \theta)$ is the function representing the relationship with temperature (x_t), with parameters θ and $(s(t; \beta))$ is the function representing non-temperature related factors including the seasonal cycle of mortality and the slowly changing background mortality both as a function of time (t) with parameters β . We use standard assumptions about the functional form of f and

s (Gasparrini *et al.*, 2010; Gasparrini and Leone, 2014; Vicedo-Cabrera *et al.*, 2019). s is a natural cubic spline (Encyclopedia of Mathematics, 2020) in time with 8 knots (points at which the derivative of the spline are discontinuous) per year of analysis. f is also a natural cubic spline in both the time and temperature dimensions. In the time dimension, there are three knots, placed between 0 and 21 days from exposure at logarithmic intervals. In the temperature dimension, there are also three knots, placed at the 10th, 75th and 90th empirical percentiles of the temperature distribution. Indicator variables for day of the week are included. After the initial model fit with an assumed reference temperature of 19°C, model fits are rescaled to the minimum mortality temperature for that region. The model is fit to all days in the record, including summer days, but we focus on the relationship between temperature and mortality for cold temperatures.

2.5 | Mortality attribution

Attribution of daily mortality to cold temperatures follows the methods discussed by Gasparrini and Leone (2014). Both the fraction of deaths on a given day (AF_x) attributable to cold weather and the number of deaths on a given day (AD_x) are calculated for all days between 1991 and 2018. Since there are two dimensions in $f(x; \theta)$, temperature (exposure) and lag, attribution can be performed from both a “forward” and “backward” perspective. We use forward estimates (henceforth with a lower case “f” prepended) to determine the effect of a given temperature value on mortality for the following 21 days. Backward estimates (henceforth with a lower case “b” prepended) are used to determine the integrated effects of temperature on mortality on a given day.

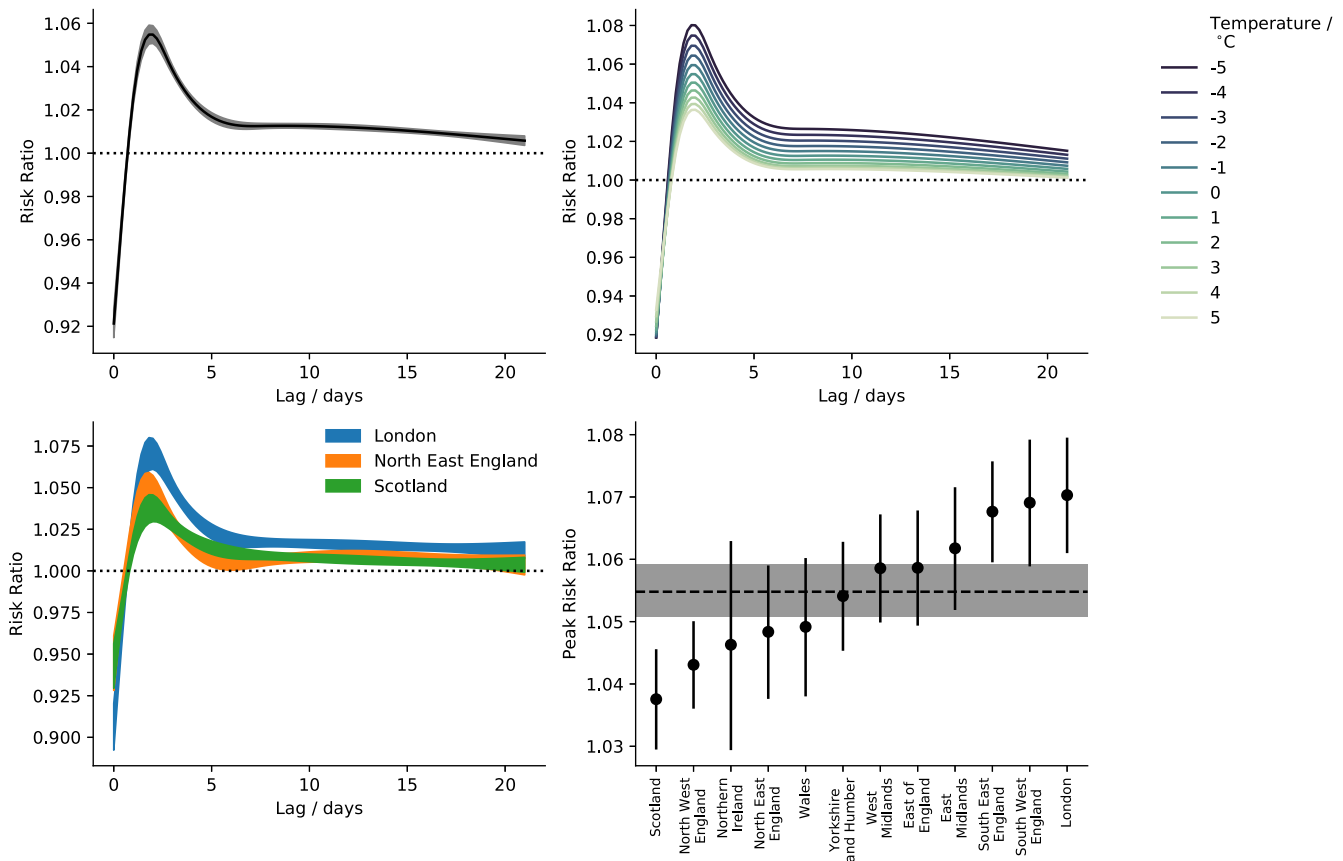


FIGURE 1 Sensitivity of risk ratio of mortality to lag and temperature based on statistical model fit. Top left panel shows risk ratio (RR) for UK mortality as a function of lag, following exposure to a temperature of 0°C. black line shows central estimate and grey shading shows 95% confidence interval. Top right panel shows the variation of the central estimate of RR as a function of lag for temperature exposure between -5 and 5 °C. Bottom left panel shows how the functional structure of the RR-lag relationship varies between three example regions of the UK (all for temperature exposure of 0°C). Bottom right shows the peak risk ratio for all regions (for a temperature exposure of 0°C), ordered by central estimate. The central estimate of the peak is shown with a dot, and the 95% confidence interval is shown with the vertical, black bar. The central estimate and 95% confidence interval (derived from the model fit) for the all-UK estimate of the same quantity is shown with a dashed line and grey shading

All attributions of mortality assume a counter-factual case of “optimal” minimum mortality temperature which varies between regions. Since SSWs can occur at different points during the winter, with different background temperature and cold attributable mortality, we also consider attributable mortality anomalies from the “climatological” attributable mortality (as for example shown in Figure 2). Climatological attributable mortality is calculated by taking multi-year daily averages excluding dates with 31 days of an SSW central date and then smoothing the resulting estimate using a B-spline with knots placed every 30 days and the series repeated three times to avoid edge effects.

3 | RESULTS

3.1 | Cold weather mortality in the UK

Examples of the relationship between lag, temperature and mortality diagnosed from the model fit are shown in Figure 1. Although making use of updated mortality and temperature datasets, these relationships replicate the impact of cold temperatures on mortality shown in a number of previous studies that use the same modelling framework (e.g., Vicedo-Cabrera *et al.*, 2019). On the day of exposure to cold temperatures, mortality is suppressed, likely due to widespread protective action taken on the day of exposure, but then quickly increases to a peak 2–3 days after exposure (Figure 1, top left). Following the initial peak, mortality is elevated for at least 3 weeks following exposure to cold temperatures. A similar lag-exposure relationship is found for all regions of the UK (Figure 1, bottom left) and at a range of different extreme to moderate cold temperatures (Figure 1, top right). At colder temperatures, mortality at all time lags at and after the mortality peak is enhanced. There is some variation in the sensitivity of mortality to extreme temperature across the UK, related to differences in socio-economic factors (e.g., age and health profile of the population, fuel poverty) and acclimatisation to more frequent cold temperatures. Peak sensitivity is qualitatively related to the latitude of each region (Figure 1, bottom right) with more southerly regions having the highest sensitivity.

There is significant variation in cold weather mortality over the winter season. Excluding days following SSW events, Figure 2 shows the mean evolution of various mortality metrics during the full period of the analysis (1991–2018). Mean all-cause mortality is strongly peaked in the weeks leading up to and following the first of January (Figure 2, purple line). This is also the period of coldest mean temperatures in the UK, although note that February and March are, on average colder than

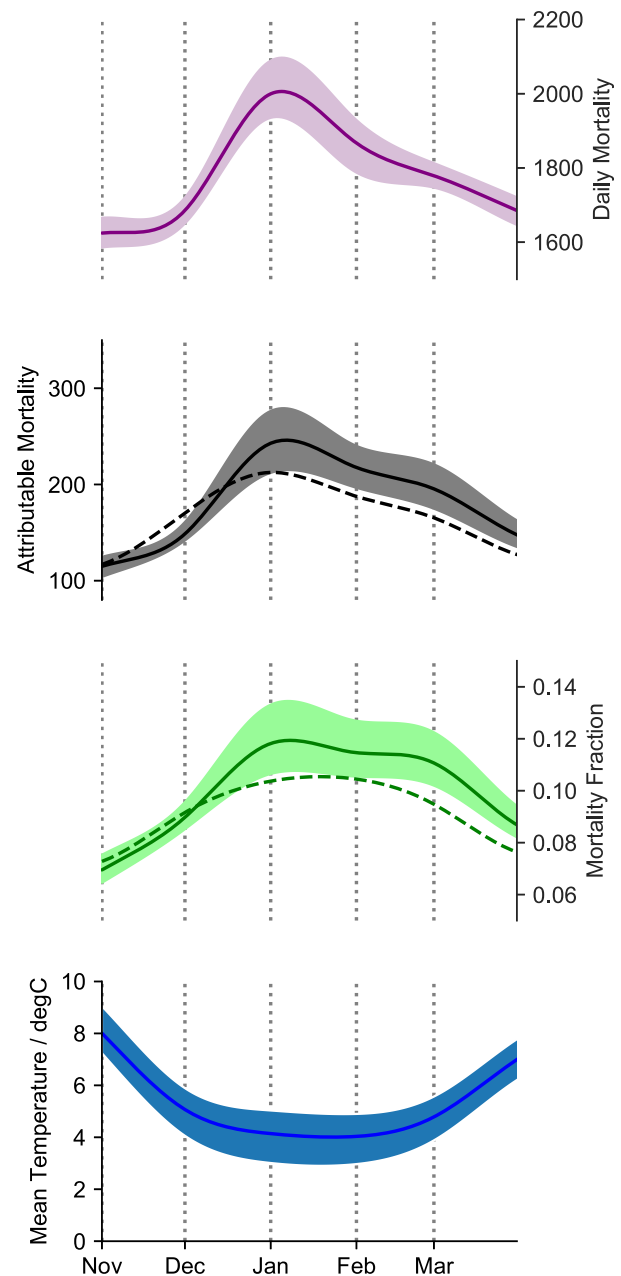


FIGURE 2 Estimates of the long-term average value (1991–2018) of different mortality and temperature parameters for the UK. Dotted lines indicate the first day of each month. The central estimate of the climatology (shown in the solid line) is estimated as the median of all days excluding those immediately (0–30 days) following observed SSW events. After averaging, B-spline smoothing is applied to the central estimates, with knots placed every 30 days. 95% confidence estimates, shown in the coloured shading, are estimated from 1,000 bootstrap samples (with replacement) of the days which make up the long-term average. The magenta line shows the daily, all-cause mortality. The black solid line shows the deaths attributable to cold weather using the backward attribution method, the black dotted line shows the same quantity estimated with the forward attribution method. The green solid and dashed lines show the fraction of mortality attributable to cold weather. The blue line shows the daily mean UK temperature

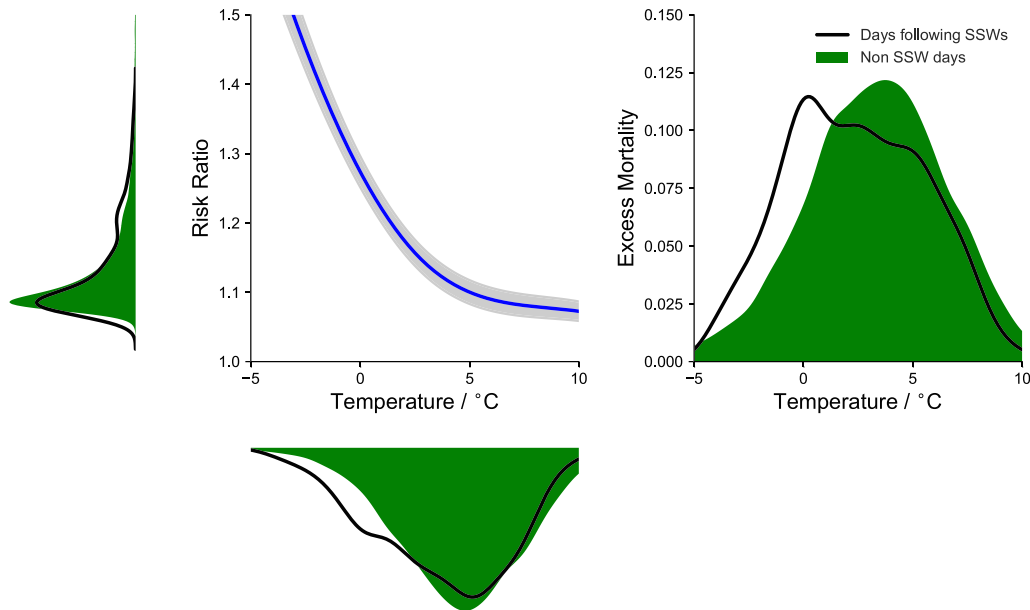


FIGURE 3 The blue line (central estimate) and grey shading (95% confidence interval) show the overall mortality risk ratio as a function of temperature for the UK. Marginal, kernel density estimates (KDE) for days which follow SSW events (black lines) and all other winter (NDJFM) days (green fill) are shown for temperature and mortality risk ratio. Right panel shows the combined distribution of excess mortality as a function of temperature for days following SSW events and non-SSW days

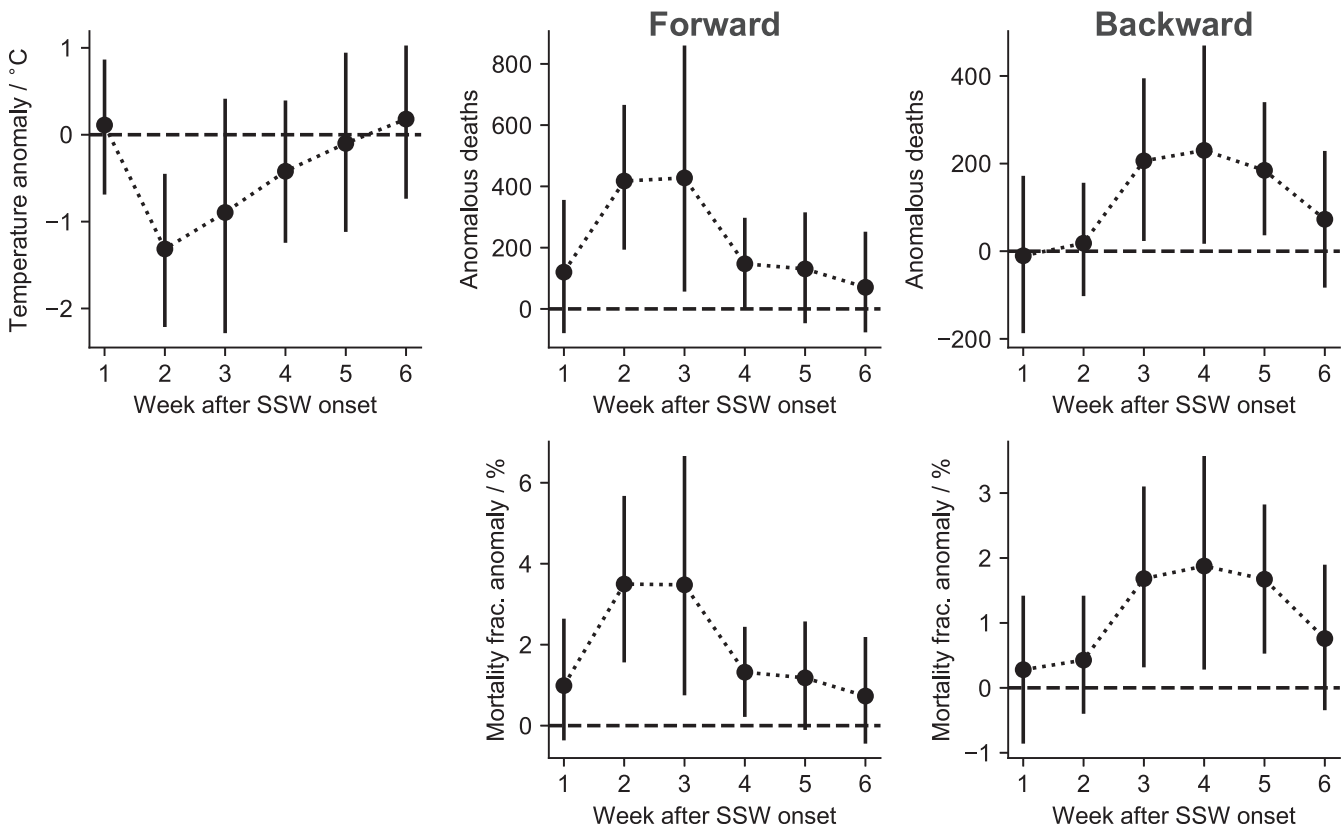


FIGURE 4 Superposed epoch analysis of weekly average temperature and mortality anomaly following SSW central date for the 15 SSWs in the period 1991–2018. In each plot, the central estimate is shown with a dot and the 95% confidence interval obtained from a 1,000 member bootstrap resampling (with replacement) of the 15 events. Left column shows UK mean temperature, middle column shows forward mortality attribution and right column shows backward mortality attribution. For mortality estimates, top row shows the anomaly of attributed deaths, bottom row shows anomalous mortality fraction

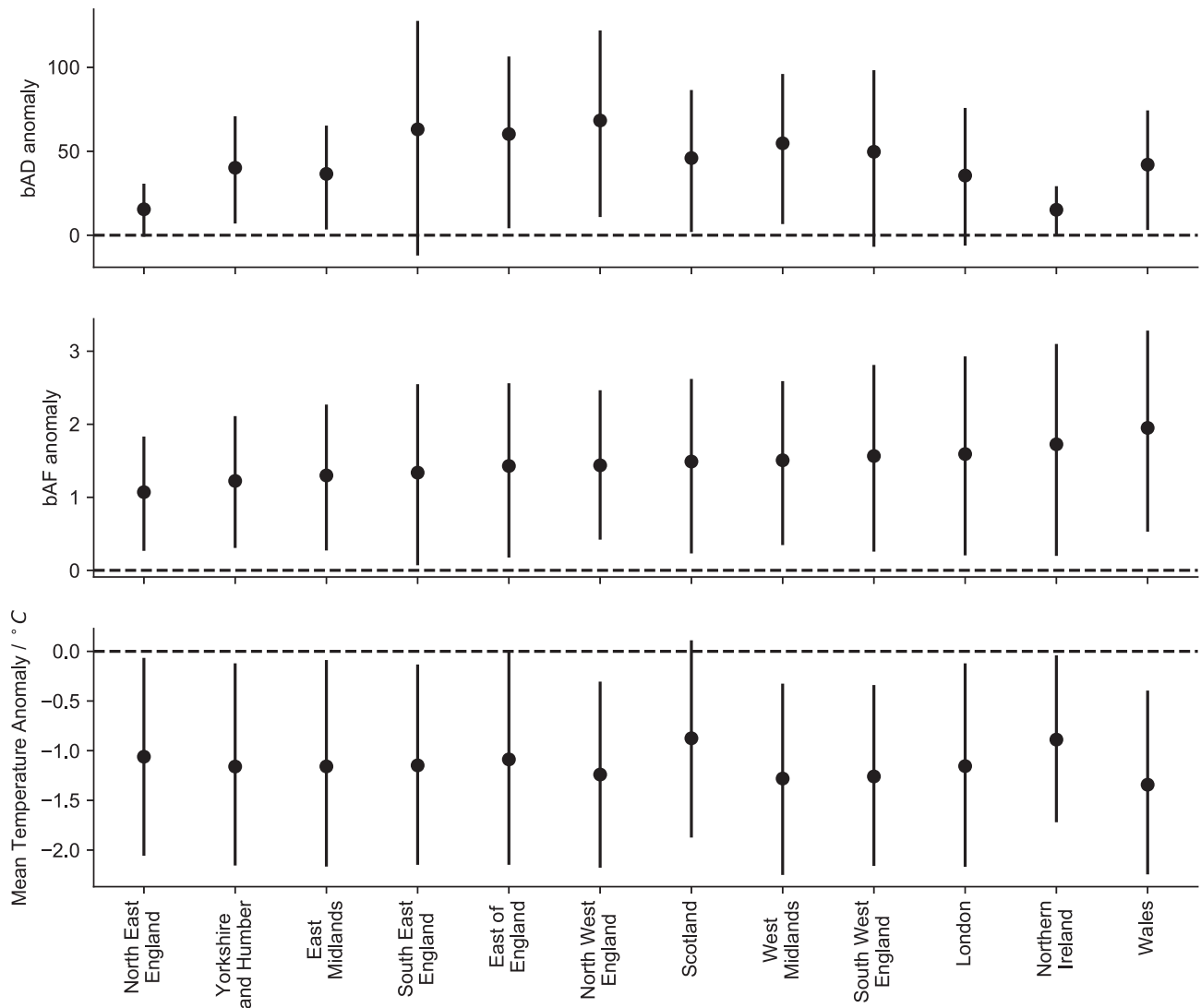


FIGURE 5 Regional variations in the impact of SSW events on mortality and temperature. Top panel shows mean total bAD anomaly during weeks 3, 4, and 5 following the SSW central date. Each point plots the mean estimate for the 15 SSW events during the period 1991–2018 and a 95% confidence interval based on a 1,000 member bootstrap resampling (with replacement) of those events. Middle panel shows mean bAF anomaly for the same 3 weeks. Bottom panel shows mean temperature anomaly during weeks 2 and 3 following the SSW central date. Regions are ordered left to right in order of increasing bAF anomaly

November and December respectively. The seasonal cycle of attributable mortality reflects both of these effects. bAF (Figure 2, green line) has largest values of 10–12% of total mortality during January and February with sharp increases during November and a sharp decline during March. bAF is generally greater than fAF throughout mid-winter, reflecting the increased likelihood of consecutive days of cold weather. bAD peaks around January first (Figure 2, black line) reflecting the higher all-cause mortality at this time. Integrated over the extended winter season, there are an average 28,403 bAD during non-SSW days, an average of 181 deaths per winter day.

3.2 | Cold weather mortality and SSW events

To estimate the impact of SSW events on cold weather mortality, we first examine the distribution of cold weather and mortality on winter (NDJFM) days following SSW events (Figure 3). The widespread impact of SSW events on temperature in the UK is shown in Figure S1. Compared to other winter days, there are more very cold days following SSW events which have a disproportionate impact on mortality. The exposure-response relationship has a large degree of nonlinearity for temperatures below the mean, winter temperature (Figure 3, blue line). This

means that the increase in the probability of cold temperatures following SSW events (compare black line and green fill in Figure 3, bottom panel) results in substantial increases in the proportion of days with high mortality risk (compare black line and green fill in Figure 3, leftmost panel). When translating this change in mortality into the excess mortality distribution (Figure 3, right panel) it is clear that a much greater fraction of the mortality following SSW events occurs at temperatures below the UK winter mean of 3.7°C (for this time period). More than 50% of the mortality following SSW events occurs for temperatures below 2.5°C , as opposed to around 40% for other winter days.

The impact of SSW events on cold weather mortality is further quantified through a composite or superposed epoch analysis of conditions in the weeks following the SSW central date (Figure 4). For the UK, SSWs lead to average cold conditions for the month following onset (Figure 4, left panel). Largest mean temperature anomalies of -1.3°C occur in week 2 and decline thereafter. These cold temperatures lead to significant anomalies in both attributable mortality fraction and attributable deaths in the weeks after the SSW. Using a forward attribution perspective (Figure 4, middle column), the cold conditions in weeks 2 and 3 after the SSW are responsible for 418 and 428 additional deaths, an increase of 3.5 percentage points above the non-SSW climatology in each week. Forward attribution for a given day is the number of additional deaths at any time in the following 21 days linked to exposure to cold temperatures on a specific day. The impact on daily mortality is anticipated by looking at the backward attribution (shown in Figure 4, right column). Backward attribution for a given day is the sum of mortality due to exposure to cold temperatures at any time in the previous 21 days. As SSWs are associated with an extended period of enhanced likelihood for cold weather in the UK, there is also a clear impact on mortality of 206, 230, and 185 additional attributed deaths in weeks 3, 4, and 5, an increase of 1.7, 1.9, and 1.7 percentage points of anomalous mortality. It is therefore clear that, on the national scale, SSW events pose a significant additional mortality risk.

3.3 | Regional variation of SSW effects

In order to best prepare for the impacts of SSW events on public health, it is also useful to consider if there are clear regional differences in SSW impact. Since regional estimates of temperature and daily mortality are available, the analysis shown in Figure 4 can be repeated at the regional scale. A summary of SSW impacts on mortality and temperature are shown in Figure 5. Given the small number

of SSW events present in the record over this time period ($n = 15$) these estimates have large uncertainty. Nonetheless, it is clear that there are similar increases in fractional mortality of 1.1–1.9 percentage points averaged over weeks 3, 4, and 5 after the central SSW date for all regions of the UK (Figure 5, middle panel). As might be expected for climate variability with large spatial scales, temperature anomalies associated with SSW events are broadly consistent across regions of the UK (Figure 5, bottom panel) and variation between SSW events is generally larger. Due to differences in population size and demographics and the exposure response relationship between regions (Figure 1, bottom right), the total number of anomalous deaths associated with SSW events (Figure 5, top panel) does vary significantly between regions. There is no obvious single physical or socio-economic predictor that would explain the variations in bAD in Figure 5 and it is likely that the variation is the result of a complex set of differences between the different regions.

4 | CONCLUSIONS

Using a standard statistical model to attribute population-level deaths in the UK to exposure to cold weather, this study shows that there is a significant increase in mortality following SSW events. This increase is largest between 3 and 5 weeks after the SSW central date and results in 621 (95% empirical confidence interval [eCI] = 84, 1,136) additional deaths or a 1.7 (eCI = 0.4, 3.1) percentage point increase above median mortality. This work adds to a growing literature assessing the influence of atmospheric flow types on mortality (Paschalidou *et al.*, 2017; Charlton-Perez *et al.*, 2019; Psistaki *et al.*, 2020).

Future work should explore the extent to which there is a discernible impact on public health in other countries with large climate variability associated with SSW events, particularly those in Northern Europe and Canada with different levels of acclimatisation to cold weather. To aid this analysis, different approaches to associating stratospheric variability, environmental stressors in the troposphere and public health datasets might be more widely employed (Runge *et al.*, 2019; Shepherd, 2019). The methodology used in the study allows us to isolate the impact of SSWs on public health through their impact on temperature alone, because we only compare mortality that can be attributed to adverse temperature through statistical model we develop. Since SSWs are associated with large-scale changes to the tropospheric flow regime, it is possible that other factors like changes in air quality following SSWs, might also lead to changes in mortality (e.g., Vanasse *et al.* (2017)).

The large increase in mortality means that winter pressures on the health and social care system are likely to be most acute in the weeks following SSW events, assuming that morbidity is similarly increased. It also means that health alert systems might benefit from sub-seasonal forecasts during SSW events, particularly since there is a three-week delay between the onset of SSW events and the largest adverse health effects. A number of studies have demonstrated that there is enhanced tropospheric forecast skill following SSW events (Sigmond *et al.*, 2013; Tripathi *et al.*, 2015; Domeisen *et al.*, 2020a, 2020b), although there is of course event to event variability between SSW events (Rao *et al.*, 2020).

There is little clear evidence that SSW events will become more or less frequent over the 21st century, or that the surface response to these events will become noticeably stronger or weaker (Ayarzagüena *et al.*, 2020). It would seem prudent, therefore, to consider how the impact of SSW events on public health might be mitigated. This paper adds to the small, but growing, literature on the societal impacts of SSW events (Beerli *et al.*, 2017). Given the broad impact of SSW events on many climate variables, there are many other sectors for which similar analysis might be beneficial.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.

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