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Weather regimes and patterns associated with temperature-related excess mortality in the UK: a pathway to sub-seasonal risk forecasting

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Abstract

Non-optimal temperatures, both warm and cold, are associated with enhanced mortality in the United Kingdom (UK). In this study we demonstrate a pathway to sub-seasonal and medium range forecasting of temperature-related mortality risk by quantifying the impact of large-scale weather regimes and synoptic scale weather patterns on temperature-associated excess deaths in 12 regions across the UK. We find a clear dominance of the NAO− regime in leading to high wintertime excess mortality across all regions. In summer, we note that cold spells lead to comparable cumulative excess mortality as moderate hot days, with cold days accounting for 11 (London) to 100% (Northern Ireland) of the summer days with the highest 5% cumulative excess mortality. However, exposure to high temperatures is typically associated with an immediate but short lived spike in mortality, while the impact of cold weather tends to be more delayed and spread out over a longer period. Weather patterns with a Scandinavian high component are most likely to be associated with summer hot extremes, while a strong zonal jet stream weather pattern which rarely occurs in summer is most likely to be associated with summer cold spells.

1. Introduction

Excess mortality associated with extreme hot and cold temperatures represents a significant public health risk and consequently is a topic well studied in the public health literature (e.g. Analitis *et al* 2008, Basu 2009, Gasparrini *et al* 2015, Hajat *et al* 2016, Ryti *et al* 2016). Non-optimal temperatures have been found to be associated with 8.78% of the total mortality in the United Kingdom (UK; Gasparrini *et al* 2015). By the 2050s, Hajat *et al* (2014) estimate around 7000 heat-related mortality and 40 000 cold-related mortality annually in the UK. While the physiological effects differ, the main causes of mortality associated with both temperature extremes are related to increased occurrence of deadly heart attacks, strokes, and respiratory diseases (Keating 2002, Analitis *et al* 2008, Arbuthnott and Hajat 2017, Song *et al* 2017). The elderly are particularly vulnerable (Hajat *et al* 2007, Hajat *et al* 2016, Arbuthnott and Hajat 2017, Song *et al* 2017), highlighting the importance of forward planning for developed countries with an aging population such as the UK.

With the increased prevalence of climate change adaptation strategies, there is growing interest for early warning systems addressing various risks associated with weather and climate impacts that extend to health impacts of temperature extremes. On the epidemiology front, previous studies have mainly focused on the direct relationship between mortality and temperature (e.g. Hajat *et al* 2014, Gasparrini *et al* 2015), while fewer have noted synoptic weather patterns associated with enhanced excess mortality in different parts of the world (e.g. Kassomenos *et al* 2007, Pena *et al* 2015). An advantage of linking mortality to large scale weather patterns is the increased persistence, predictability, and forecast skill horizon with increasing spatial scales in the atmosphere (Boer

2003, Jung and Leutbecher 2008, Buizza and Leutbecher 2015).

In the case of the UK, a recent study by Psistaki *et al* (2020) investigated the relationship for regions in England using the Lamb Weather Type classification and a simple measure of all-cause mortality during each weather type and found the Easterly weather type to be particularly hazardous throughout the year. A previous study by Charlton-Perez *et al* (2019) employed the weather regimes perspective and found that the Greenland Blocking regime (also known as the NAO− regime) placed the most pressure on the UK health system. While both of these studies show that there can be significant sensitivity of mortality to different weather regimes, the necessary simplifications used in both studies make it difficult to fully quantify this link. In the case of Charlton-Perez *et al* (2019), a simple model of the mortality-temperature link is used, with uniform parameters across the UK. Charlton-Perez *et al* (2019) were also unable to quantify absolute death rates in any particular weather regime. In the case of the Psistaki *et al* (2020) study, since the total mortality during each weather type is used to measure the impact of weather regime variability, delayed impacts are not considered and it is possible that several confounding effects unrelated to true weather-related mortality are included.

In this study, we set out to more clearly quantify the impact of both large-scale and persistent weather regimes and smaller-scale daily weather patterns on ambient temperature-related mortality. We focus on the most extreme events with the potential for causing the greatest single-event mortality risks, which are the focus of heat and cold early warning systems. By making use of state-of-the-art, regionally derived estimates of the mortality–temperature relationship we are able to more accurately and more robustly quantify which weather regimes and synoptic patterns lead to the most significant temperature-related health risk for the UK population and the UK health and social care system. By adopting this broader perspective we aim to, in future, provide a pathway to longer range forecasting of temperature-associated excess mortality risk.

2. Data

Daily mortality and temperature data are obtained and analysed by UK regions defined according to the Nomenclature of Territorial Units for Statistics level 1 (NUTS 1), which include Wales, Northern Ireland, Scotland, and nine statistical regions in England. Daily mean temperatures are calculated as averages of the maximum and minimum daily temperatures from the HadUK-Grid dataset, available from 1960 to 2018 (Hollis *et al* 2019). Daily mortality data is obtained from the Office for National Statistics for regions of England and for Wales, from the Northern Ireland Statistics and Research Agency for Northern Ireland and from the National Records of Scotland for Scotland. Mortality data for Scotland is grouped by Scottish Health Boards. For consistency of geographic divisions across datasets, this is further consolidated to provide a daily cumulative mortality for the whole of Scotland. The maximum time period for which mortality data is available from all regions, 1991 to 2018, is used in subsequent analyses.

Daily 12 UTC ERA5 500 hPa geopotential height data with 0.25° resolution from 1979 to 2019 (Hersbach *et al* 2020) is used for weather regimes classification. Additionally, mean sea level pressure (MSLP) data from the daily European-North Atlantic mean sea level pressure dataset from 1850 to 2003 at 5° resolution (Ansell *et al* 2006) is used in combination with 12 UTC MSLP data from ERA5 up to 2019 for defining weather patterns.

3. Methodology

A two-stage approach is applied, wherein we first utilise statistical modelling to estimate the excess mortality associated with each daily mean temperature for each region. In the second stage, the time series of temperature-related excess mortality is matched with the time series of weather regimes/patterns to determine the range of excess mortality associated with each circulation pattern.

Two complimentary systems of weather circulation classifications are used. The first (in this study, weather regimes; Michelangeli *et al* 1995, Cassou 2008, Lee *et al* 2019) considers four categories per season. It captures distinct characteristics of the large-scale atmospheric flow which can persist for several days and can be forecast two or more weeks in advance (Ferranti *et al* 2018). In contrast, a 30-categories system (in this study, weather patterns; Neal *et al* 2016) captures regional details and day-to-day variability. This latter system is in use operationally by the UK Met Office for weather forecasting and has been related to variations in magnitude of a range of events or impacts (Richardson *et al* 2020, Neal *et al* 2018, Brown *et al* 2019). By examining both systems, we illustrate the applicability of both approaches and propose a tiered warning system whereby weather regimes, weather patterns, and temperature forecasts can be used, in that order, as one moves from long- to short-range forecasting.

3.1. Temperature-lag-mortality model

To derive the temperature–mortality relationship including lagged responses in time, we follow the modelling approach summarized in Vicedo-Cabrera *et al* (2019) with model setup choices following Gasparrini *et al* (2015). Time-series regression is performed on the daily mean temperature and the daily number of deaths for each of the NUTS 1 regions, considering lagged responses and assuming a quasi-poisson distribution.

The temperature-mortality relationship is represented by a distributed lag non-linear model (Gasparrini *et al* 2010), where both the exposure-response and the lag-response relationships are modelled using natural cubic spline functions, with three log-spaced spline knots in the lag dimension and knots at the region-specific 10th, 75th, and 90th percentiles in the temperature dimension. A maximum of 21 days of lag is considered. The baseline time-varying factors influencing the daily mortality, including seasonality and long-term trends, are quantified using natural cubic splines with 8 degrees of freedom per year, and the day-of-week is additionally considered as a confounding factor.

This analysis provides a measure of the relative risk (RR) of mortality as a function of the temperature and lag, where the RR is measured relative to the risk at the optimal temperature (around 15 to 19 °C, computed separately for each region), which is defined as the temperature associated with the minimum cumulative mortality (summed impact over the entire lag period). For each day in a time series, the model provides the fraction of temperature-associated deaths, and the number of associated deaths is subsequently determined by multiplying the fraction by the actual number of deaths observed on that day. For cumulative risk over a lagged period of time, the average deaths per day over the period is used for the conversion. In this study we focus on the forward cumulative perspective (hereafter simply referred to as 'cumulative'), where the excess deaths occurring over the next 21 days but associated with the initial day's temperature exposure are allocated to the exposure day.

3.2. Weather regimes

Weather regimes are identified by applying *k*-means clustering on the first 14 empirical orthogonal functions of the 12 UTC 500 hPa geopotential height anomaly for the 90°W–30°E/20°N–80°N North Atlantic-European domain. The dominant regime for each day is then identified as the closest matching (minimum Euclidean distance) weather regime, providing daily historical classifications from 1979 to 2019. The analysis is performed separately for the extended winter season (NDJFM, November to March) and the standard summer season (JJA, June to August) in agreement with typical occurrence of cold and hot temperatures during the year in the UK. Four clusters are identified for each season, following Cassou (2008) and Cassou *et al* (2005). The cluster centroid 500 hPa geopotential height anomaly patterns are shown in figure 1.

3.3. Weather patterns

Weather patterns are identified by *k*-means clustering of the MSLP anomaly to the closest matching weather pattern definition over a slightly smaller defined 30°W–20°E/35°N–70°N North Atlantic-European region. The assignment method is based on the MSLP field and weather pattern pairing with the smallest area weighted sum-of-squares differences at each grid-point. Using a larger number of clusters and a smaller domain allows for more local-scale synoptic variability to be captured. No separate patterns are defined for different seasons, though lower numbered patterns have weaker MSLP anomalies (atmospheric flow deviating less from the mean state and generally less pronounced pressure systems) and occur more frequently in summer, while higher numbered patterns have stronger MSLP anomalies and occur more frequently in winter (for a full description and MSLP maps, see Neal *et al* 2016). Overall, the patterns are ranked by their frequency of occurrence. To provide a link to the large-scale weather regimes, days within each season in the common period of 1979 to 2019 are analysed for the frequency that a weather regime overlaps with a weather pattern classification. The patterns are subsequently grouped by the regime with which the most overlap is found and ranked within each group by the frequency of concurrence.

4. Results

4.1. The temperature–mortality relationship

Accumulated over all 21 lag days considered, the RR-temperature relationship can generally be described as U-shaped: with a low RR for moderate temperatures and with elevated risks in both temperature extremes (figure 2(a)). For days above the optimal temperature, there is an immediate increase in associated mortality upon initial exposure, the effects of which taper off quickly over the subsequent days (figure 2(b)). To varying degrees, hot days are also commonly associated with a slight decrease in mortality after the initial peak as the heat exposure led to the death of people who would otherwise have died a few days later (mortality displacement; e.g. Ferreira Braga *et al* 2001, Hajat *et al* 2005). Significant mortality displacement within the 21 lag days could therefore lead to a lower cumulative impact. On the other hand, exposure to low temperatures leads to a decrease in mortality initially (figure 2(c)). The peak in RR associated with a single cold day occurs around 2 d after the initial exposure, which can be attributed to heart attacks resulting from increased blood viscosity (Keatinge 2002). Though the impact decreases in magnitude subsequently, it persists for a long lag period (figure 2(c)), resulting in the high cumulative excess mortality associated with cold temperatures.

While all regions exhibit a similar qualitative temperature–lag–mortality relationship, the quantitative sensitivity to hot and cold extremes varies. Possible factors contributing to the differences include the climatology, demographics, and infrastructure, etc (e.g. Keatinge *et al* 2000, Lawlor *et al* 2000, Kovats

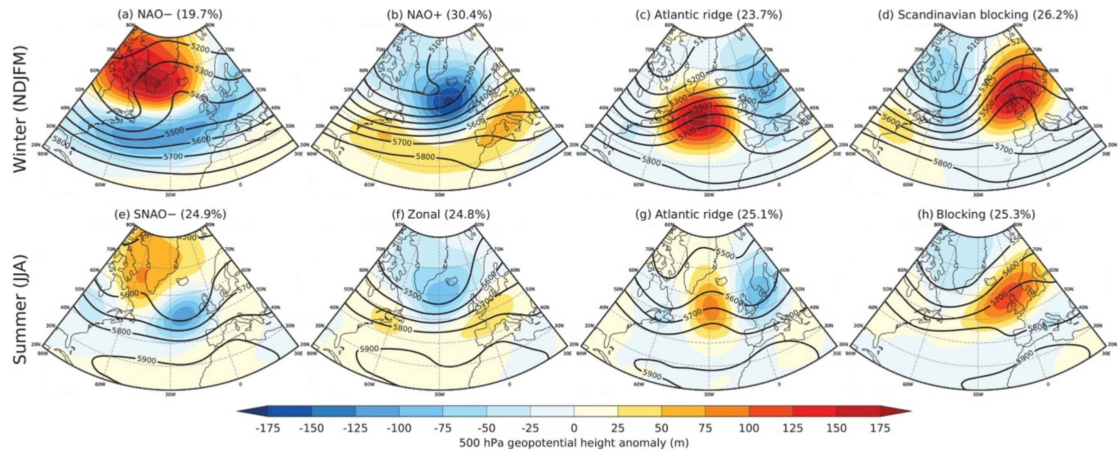

Figure 1. Regime centroid 500 hPa geopotential height (contours; m) and anomalies (colour shading; m), composited for the extended winter (November–March (NDJFM); top; (a–d)) and core summer (June–August (JJA); bottom; (e–h)) seasons. Each percentage represents the proportion of days in that regime for that season computed over 1979–2019.

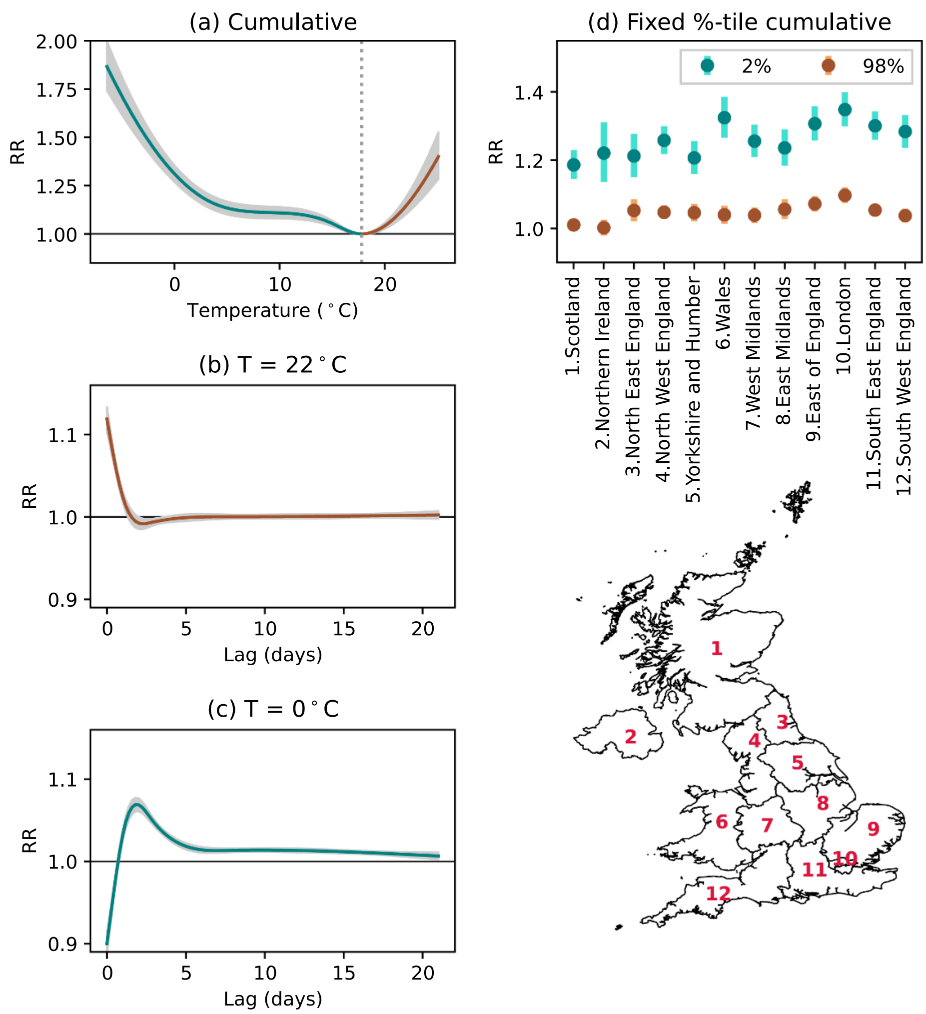

Figure 2. An example of (a) cumulative associated risk and predictor-specific associations of RR at (b) 22 °C and (c) 0 °C for South East England. The 95% empirical confidence interval is shaded in grey, and the optimal temperature is indicated by the dotted vertical line in panel (a). Panel (d) shows the cumulative RR and 95% confidence intervals at regional 2nd and 98th percentile temperatures. Corresponding locations of the UK NUTS 1 regions are labelled on the map in the lower right.

and Hajat 2008, McMichael *et al* 2008, Anderson and Bell 2009, Hajat and Kosatky 2010, Zanobetti *et al* 2013, Ng *et al* 2014, Son *et al* 2019). For the range of temperatures observed in each region, greater risks are associated with cold throughout the UK, and populations in southern regions tend to be more susceptible, particularly to the regional cold extreme (figure 2(d)).

4.2. High mortality regimes

As weather regimes are large scale patterns that impact the UK similarly across regions, the excess mortality is summed across regions to provide a measure of the UK-wide associated excess deaths in relation to the weather regimes. Note that by first calculating the regional mortality and then summing this mortality we are able to produce a more accurate picture of overall mortality risk than by considering UK-wide metrics only.

4.2.1. Winter

On average in winter, ambient temperature is associated with around 12% of the daily deaths in the UK. Amongst NAO− regime days, the average is slightly higher, at 15%, followed by Atlantic ridge and Scandinavian blocking days, 12%, and lastly for NAO+ days, 10% (supplemental table 1, which is available online at https://stacks.iop.org/ERL/15/124052/mmedia).

To investigate the regimes associated with the most extreme mortality days, winter days between 1991 and 2018 are ranked according to their cumulative associated excess mortality (figure 3(a)). In agreement with the difference in the average, we find the NAO− regime (negative phase of the North Atlantic Oscillation, characterized by a weakened jet stream and more frequent winds from the east and northeast bringing often dry and cold continental air during winter; figure 1(a)) to be the most prevalent during the most extreme mortality days, followed by Scandinavian blocking (figure 1(d)) and Atlantic ridge (figure 1(c)). Days under the influence of the NAO+ regime (mild and moist maritime air from the Atlantic) are rarely extremely cold, accounting for only 4% of the deadliest 5% days November to March, while 53% of these days occur during the NAO− regime.

Analysis is also performed by grouping days into weather regime events, defined as regimes persisting for at least 5 d, and considering the highest daily associated excess mortality within each persistent period. We find that there is a 31% chance that any one persistent NAO− event will lead to excess mortality above the 95th percentile of the 1991 to 2018 record (417 excess deaths). The likelihood is much lower for the Atlantic ridge and Scandinavian blocking regimes, at 16% and 11%, respectively, while for NAO+, it is extremely unlikely but not unprecedented (1%).

4.2.2. Summer

During summer, ambient temperature is associated with around 3% of the UK daily mortality on average. Across all regions except London (where the average is just slightly higher amongst Blocking days), the seasonal average cumulative associated mortality fraction related to Atlantic ridge days is slightly higher than the average amongst other regime days (supplemental table 1).

However, when focusing on the highest ranked mortality days, the Blocking regime is most frequently associated with high excess mortality (figure 3(b)), accounting for 36% of the deadliest 5% summer days. These are typically hot days associated with solar heating during clear, sunny days as a high pressure anomaly sits over the UK (figure 1(h)).

Interestingly, a significant number of summer days with associated excess deaths above the 95th percentile (113 excess deaths) occur during days with mean temperatures below the average optimal (16 °C). These are most often associated with the Atlantic ridge regime (figure 3(c)), which accounts for 21% of the deadliest 5% summer days. However, for the UK as a whole, excess mortality associated with the hottest days in the years 1991 to 2018 remain greater than that associated with the coldest days in summer. The 50 deadliest temperature-related mortality days are all associated with hot temperatures.

The likelihood of any persistent (≥5 d) regime event to contain at least 1 d exceeding the summer 95th percentile does not differ greatly. It is 17%, 20%, 20%, and 25% for SNAO−, Zonal, Atlantic ridge, and Blocking, respectively. Of these, 71%, 30%, 0%, and 80%, respectively, are heat events. However, if it is known in advance that the average temperature is above optimal, the likelihood of a persistent SNAO−/Blocking regime event to contain at least one day above the 95th percentile increases to 58/55%.

4.3. High mortality weather patterns

As weather patterns capture more synoptic variability compared to large-scale weather regimes, analyses are performed both at the regional scale and for the UK as a whole. As a metric more relevant for medium-range and sub-seasonal forecasting, we focus on examining the likelihood of extreme temperature-related excess mortality (above the seasonal 95th percentile) for any given day identified as matching a particular numbered weather pattern.

4.3.1. Winter

During winter, a consistent response is found across all regions, with weather patterns 27 (anticyclonic easterly) and 28 (cyclonic south-easterly) identified as most often being associated with high excess mortality (not shown) as well as having the highest likelihood of leading to extreme mortality events (figure 4(a)). These are weather patterns which most frequently coincide with the NAO− regime. Despite slight differences in the location and magnitude of geopotential height anomalies, both patterns 27 (figures 5(a), (b)) and 28 (figures 5(c), (d)) are associated with higher likelihoods of extreme excess

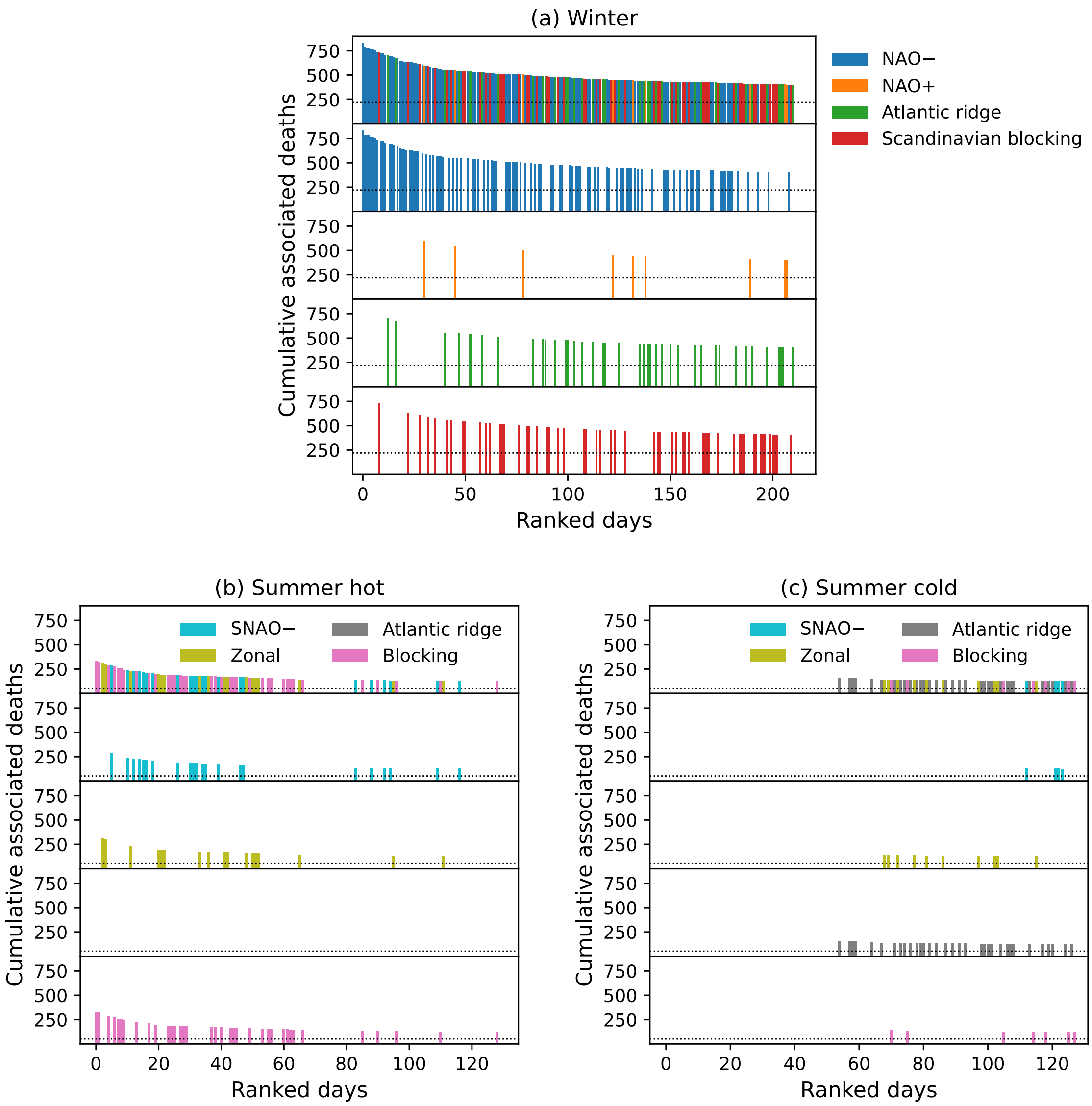

Figure 3. The top 5% of days in (a) November to March and (b), (c) June to August between 1991 and 2018 ranked by the UK-total daily cumulative temperature-associated excess mortality. Ranked summer days are separated by whether the UK-mean temperature is (b) above or (c) below the average optimal temperature of 16 °C. Colours indicate the dominant weather regime on the day. Horizontal dotted lines indicate the daily cumulative associated deaths averaged over the season.

mortality across all regions. Patterns 9 (anticyclonic north-easterly) and 29 (cyclonic southerly), which also coincide with the NAO− regime on more than 60% of the days, however, are rarely associated with high excess mortality. This points to the benefit of weather patterns, which capture more regional differences, in addition to weather regimes, which have a longer forecasting lead time.

4.3.2. Summer

Similar to the analysis for weather regimes, hot days with high excess mortality are associated with circulation patterns with a Scandinavian high component (figure 4(b), patterns 5, 16, 17, and 22; Neal *et al* 2016). This is especially pronounced for weather pattern 16, associated with heating of most of the European region during sunny days as a high pressure system sits over the southern Norwegian Sea and the North Sea (figures 6(a), (b)). Notably, not all of these Scandinavian high-type weather patterns predominantly coincide with the Blocking regime, as the concurrent presence of a low geopotential height anomaly west of the UK can lead to greater similarity of the weather pattern to the SNAO− regime over the North Atlantic-European domain.

On the other hand, weather pattern 30 (cyclonic westerly or south-westerly) has the greatest likelihood of being associated with cold summer days with highly elevated mortality related to temperature (figure 4(c)). As can be noted from its high pattern number, it rarely occurs in summer (four occurrences between 1979 and 2018; an additional occurrence in 2019). This pattern (coinciding with the SNAO− regime on 60% of days and the Zonal

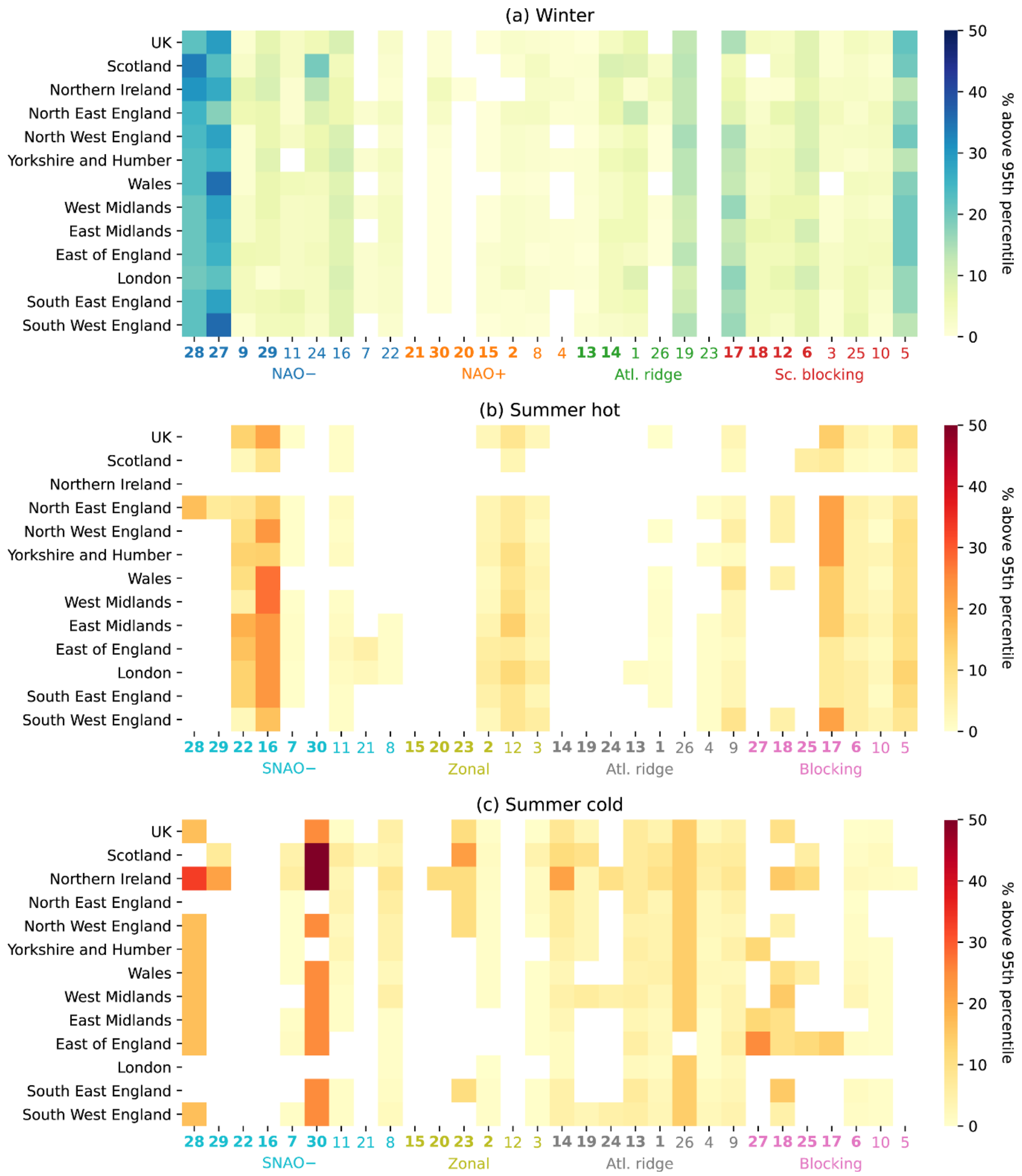

Figure 4. (a) The likelihood of the regional temperature-associated mortality for a weather pattern day in November to March to exceed the seasonal 95th percentile. Panel (b)/(c) shows the likelihood of a weather pattern day in June to August to both exceed the seasonal 95th percentile in excess mortality and be warmer/cooler than the regional optimal temperature. Weather pattern numbers are grouped and colour coded according to the weather regime with which the pattern most often coincides during the respective season. Within each group, weather patterns are ordered according to the frequently of co-occurrence with the regime, and pattern numbers are highlighted in bold when at least 60% of its days coincide with a regime.

regime on the remaining 40%) is characterized by a strong zonal jet stream over southern parts of the UK, bringing cool and wet maritime air during summer (figures 6(c), (d)). Historical daily weather records indicate showery weather, at times heavy, during all summer occurrences of pattern 30.

Given the predominance of lower numbered weather patterns in summer months, they are also more commonly observed even in the most extreme days. Consequently, the weak Atlantic ridge-type pattern 1 (cyclonic north-westerly, figures 6(e), (f)) is most often identified amongst the deadliest summer cold spell days, while the lowest numbered Scandinavian high weather pattern 5 is most frequently found during the deadliest hot summer days (not shown).

4.4. Hot and cold days in summer

As shown above, in contrast to winter, both significant hot- and cold-related mortality can occur in summer in the UK. While most of the summer excess deaths from temperature extremes are associated with hot days in most regions of the UK, a non-negligible 22%–43% of the deadliest 5% days are associated

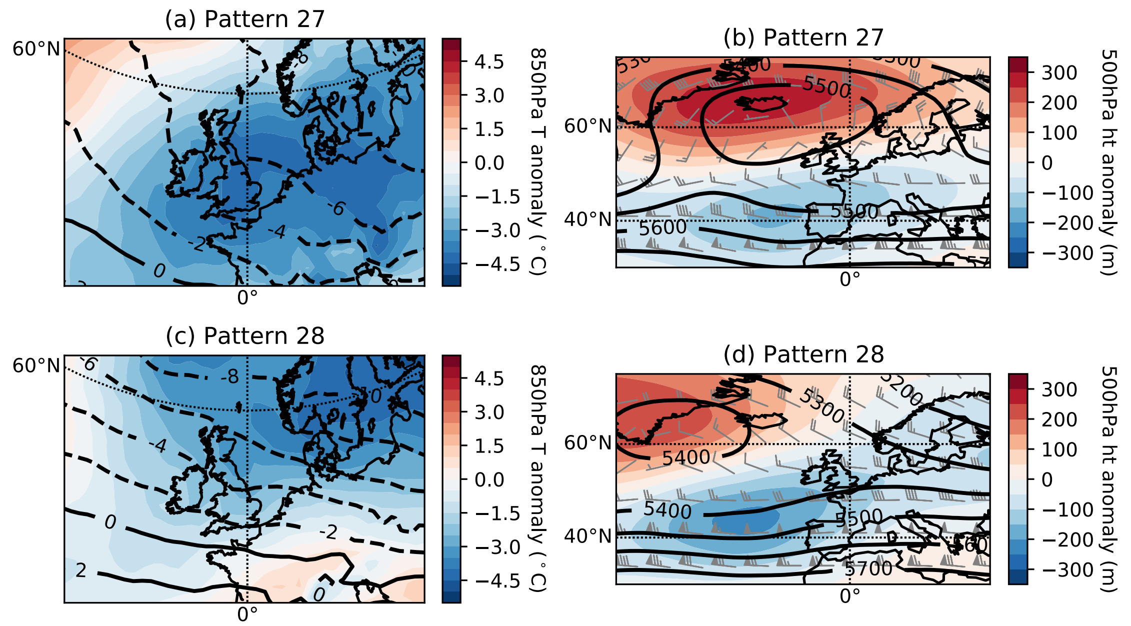

Figure 5. Mean (in contours/wind barbs) and anomaly relative to the ±5 days climatology (in colour): left column: 850 hPa temperature (°C), right column: 200 hPa wind (knots) and 500 hPa geopotential height (m) for all extended winter days with weather patterns (a), (b) 27 and (c), (d) 28.

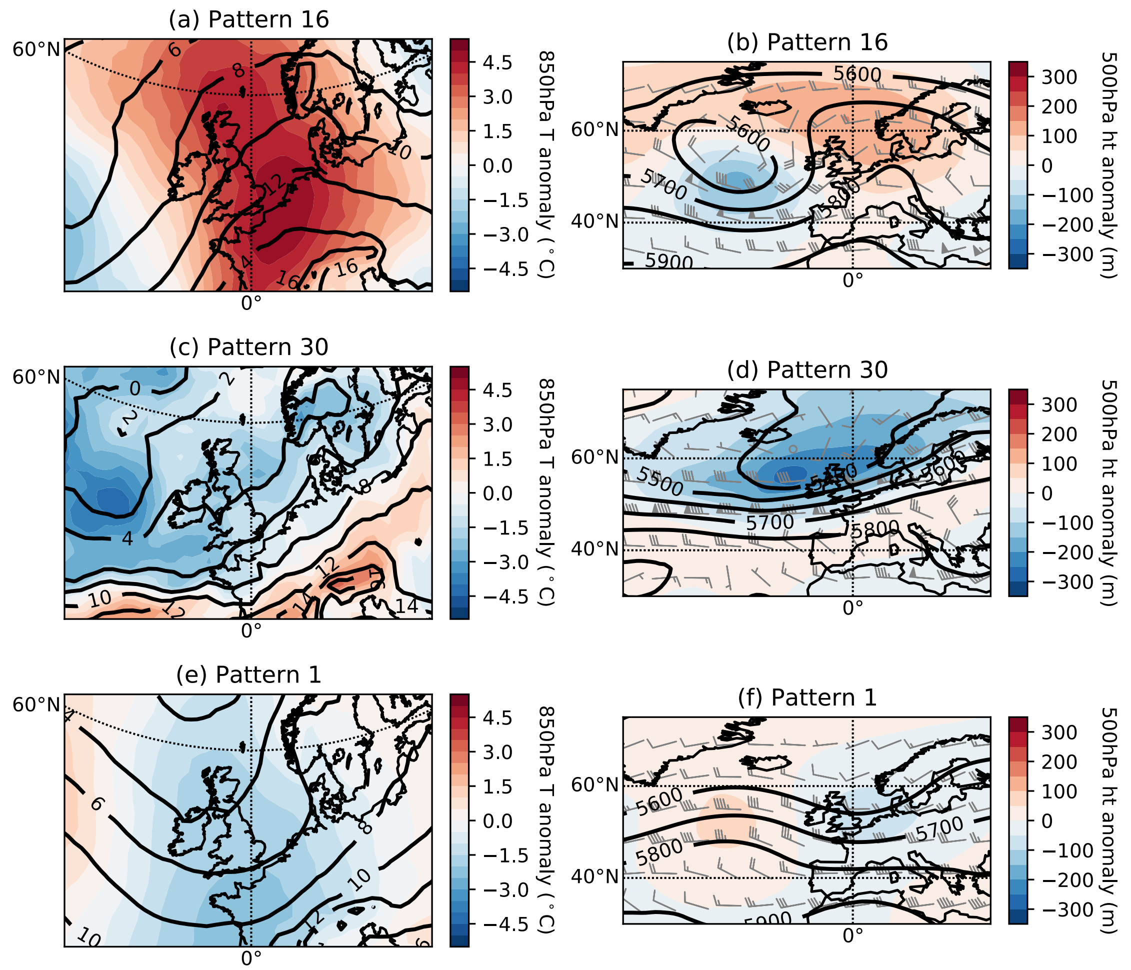

Figure 6. As figure 5 but for all summer days with weather patterns (a), (b) 16, (c), (d) 30, and (e), (f) 1.

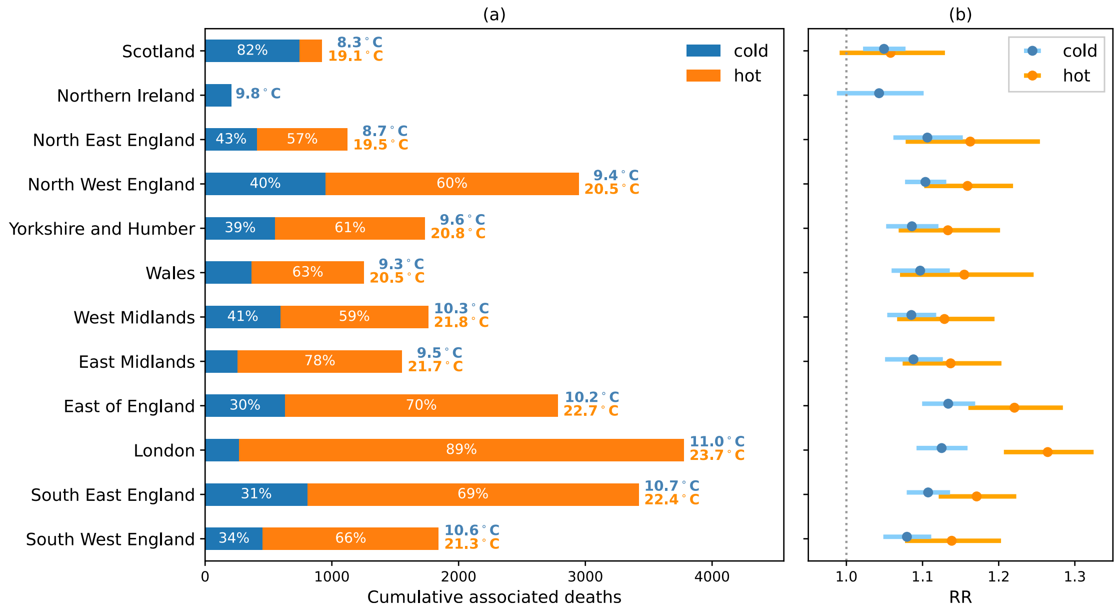

Figure 7. (a) The cumulative temperature-associated excess mortality from the deadliest 5% of the summer days in each region's available historical record, divided into contributions from days warmer than the regional optimal temperature (hot) and those from days cooler than the regional optimal (cold). Percentages indicate the proportion of days that are cold/hot within the sample of the deadliest 5%. Mean temperatures over the relevant cold and hot days are labelled for each region. (b) The cumulative RR associated with each region's mean low and high extreme temperatures as labelled in panel (a), along with their 95% confidence interval.

with low ambient temperature (figure 7(a)). London, Northern Ireland, and Scotland are exceptions. Due to its higher mean temperature, only 11% of the deadliest summer days are cold-related in London, while in Northern Ireland and Scotland, all or nearly all of the deadliest 5% summer days are cold. Sensitivity analysis reveals a high uncertainty in the exact ratio of hot to cold days within the deadliest 5% (supplemental figure 1), however, the qualitative difference across regions is robust.

The significance of cold summer days results from the U-shaped nature of the cumulative temperature–mortality relationship (figure 2(a)), whereby the coldest summer days can be associated with comparable cumulative excess mortality as moderately warm days. Where high cumulative heat risks are observed, the average heat-related cumulative risk is still greater than the cold-related risk (figure 7(b)). However, the small difference in cumulative RR between summer cold spell temperatures of around 9 °C and heatwave temperatures of just over 20 °C is indicative of the importance of cold exposure during summer in the UK.

The low hot-to-cold ratio amongst the deadliest exposure days in Scotland and Northern Ireland does not equate to the complete lack of heat-related mortality in these regions. While milder temperatures increase the relative importance of summer cold spells, mortality displacement can also lead to minimal cumulative excess deaths. When only examining excess mortality on the day of exposure, we find evidence of heat-related deaths in both regions (supplemental figure 2). In Scotland, immediate temperature-associated deaths on the hottest 5% summer days are even greater than the 21-days cumulative deaths related to the same number of mostly cold summer days.

5. Conclusions

In this study, we apply the epidemiological modelling approach described by Vicedo-Cabrera *et al* (2019) to estimate the temperature–lag–mortality relationship in 12 regions across the UK. These relationships are then used to indirectly associate excess mortality due to non-optimal temperatures with two sets of four large-scale seasonal weather regimes and a set of 30 weather patterns. Analyses are performed separately for the extended winter season from November to March and for the summer season from June to August.

During winter, the NAO− regime and its related weather patterns 27 (anticyclonic easterly with high pressure centred over the Norwegian Sea) and 28 (cyclonic south-easterly with a southerly tracking low centred to the south-west of the UK) are found to be most highly associated with high excess mortality, as winds with an easterly component bring cold and often dry continental air over all regions in the UK. The NAO− regime is associated with 53% of the deadliest 5% extended winter days from 1991 to 2018. Any persistent NAO− event lasting at least 5 d has a 31% chance of including a day with UK-wide excess mortality above the seasonal 95th percentile.

The picture is less straight-forward for summer. In particular, we find that the cumulative associated excess mortality due to summer cold days can be comparable to moderate hot days in most regions. The Blocking regime and weather patterns with a Scandinavian high signature (particularly pattern 16, with a ridge over southern Norwegian Sea and the North Sea and a trough west of the UK) are most likely to be associated with days with high heat-related mortality. The Atlantic ridge regime is most likely to be associated with high summer cold-related mortality. This is reflected in the weather pattern analysis, as the weak Atlantic ridge-type pattern 1, is most frequently identified amongst the deadliest cold summer days. However, pattern 30 (cyclonic westerly with a strong zonal jet over southern England and associated with heavy showers), which rarely occur in summer, has the highest likelihood of leading to high summer cold-related mortality if observed.

On a regional basis, we find greater cold-sensitivity to the south and greater heat-sensitivity to the north. Due to warmer temperatures, however, excess mortality during summer are mostly heat-related in southern regions, though non-negligible contributions from cold days can still be noted. The proportion of warm days decreases to around 60% in northern England, though the ratio of associated deaths tend to be greater. In Northern Ireland and Scotland, exceptionally, minimal extreme heat events can be identified based on cumulative excess mortality. Hot days do occur in these regions, however, with peaks in associated excess mortality on the temperature exposure day.

Despite the comparable cumulative RR from summer low and high extreme temperatures in most regions in the UK, the evolution of their associated mortality over time varies greatly. For emergency and health services, the strong initial peak in excess mortality over a short period of time associated with heat events may be more challenging to manage than the accumulation of elevated excess mortality over a long period associated with cold days, as they have the potential to lead to rapid increases in healthcare demand.

The current study presents a first analysis relating weather regimes and patterns with excess mortality in the UK, results of which could be applied to existing probabilistic circulation type forecasting tools (e.g. Buizza *et al* 2007) allowing for estimates of excess mortality to be made potentially several weeks in advance. Mortality risk forecasting at these sub-seasonal time scales could provide more time for social care or other healthcare services to ensure that risk mitigation measures are in place. It may therefore be beneficial to combine it with current temperature threshold-based warning systems, which are forecast with greater certainty but shorter lead times, to address different needs. Additionally, identifying weather regimes and patterns associated with high excess mortality can be beneficial in understanding how mortality risks may change in the future.

There are various more complex and detailed aspects of the relationship which are not considered here, however. For instance, we do not account for changes in the healthcare system or demographics between 1991 and 2018 that may have had an impact on the population susceptibility to ambient temperature. For future studies, it may also be beneficial to additionally consider accumulation of mortality from persistent weather regimes and patterns, intra-seasonal acclimatisation (Lee *et al* 2014), and intra-regional differences in the mortality-temperature relationship (owing to urban/rural, socio-economic, and demographic differences, etc; e.g. Li and Bou-Zeid 2013, Li *et al* 2015, Heaviside *et al* 2016, Murage *et al* 2020). These will be particularly important in understanding how and why the health and social care system in the UK needs to adapt to the changing risk associated with the warming climate.

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