Exploring Winter Mortality Variability in Five Regions of England Using Back Trajectory Analysis

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ABSTRACT: This paper aims to define atmospheric pathways related with the occurrence of daily winter low temperature episodes (LTE) in England, for the 26-yr period 1974–99, and to reveal possible associations with increased mortality rates. For this purpose, backward airmass trajectories, corresponding to LTE in five regions of England, were deployed. A statistically significant increase in mortality levels, at the 0.05 level, was found for LTE, compared to non-LTE days across all five regions. Seven categories of atmospheric trajectory patterns associated with LTE were identified: east, local, west, North Atlantic, Arctic, southwest, and Scandinavian. Consideration of the link between airmass trajectory patterns and mortality levels by region revealed a possible west-to-east split in the nature of air masses connected with elevated mortality. Specifically, for the West Midlands and northwest regions, relatively warm winter weather conditions from the west, most likely associated with the eastward progression of low pressure systems, are allied with the highest daily average mortality counts, whereas, for the northeast, Humberside/York, and southeast regions, cold continental air advection from northern or eastern Europe, which lasts for several days and is linked with either a blocking pattern over the western margins of Europe or an intense high pressure anomaly over eastern or northern Europe, appears important in mortality terms. This finding confirms that winter weather health associations are complex, such that climate setting and airmass climatology need to be taken into account when considering climate and health relationships.

KEYWORDS: Winter weather and health; Air masses; Back trajectory analysis; Mortality; Low temperature episodes

1. Introduction

There is a burgeoning international literature on the association between episodes of extreme low or high ambient temperatures and adverse health effects (Hajat et al. 2007; Ferreira Braga et al. 2001; Wang et al. 2014), with strong links of temperature and increased mortality reported for a variety of countries (Eurowinter Group 1997; Donaldson et al. 2003; Guo et al. 2013, 2014; Urban et al. 2014). However, the nature of the climate and health association has been found to vary, depending on the location, the lifestyle and habits of the population, and quality of the housing, among a range of confounding factors (Eurowinter Group 1997; Donaldson and Keatinge 2003; Kovats and Kosatsky 2009). Added to this is the observation that for a number of regions, such as northern Europe, there has been a progressive reduction in temperature-related deaths from the beginning of the twentieth century until the present (Carson et al. 2006; Astrom et al. 2013). Nevertheless, although the relative risk of mortality during extreme temperature events appears to have fallen in northern Europe, such events still pose a threat to public health (Morabito et al. 2012; Scarborough et al. 2012; Astrom et al. 2013), primarily for the most sensitive groups of people like the elderly (Hajat et al. 2007; Xu et al. 2013).

Associations between cold weather and elevated mortality are widely recognized in the international literature (Keatinge 2002). For example, for China, 148 279 excess deaths were attributed to an unusual cold spell in 2008, resulting in an increased mortality of 44%, with the highest effects in southern and central China (Ma et al. 2013; Xie et al. 2013; Zhou et al. 2014). Similarly, for Italy in February 2012, an anomalous period of low temperatures resulted in a 25% increase in mortality among the 75+ age group across 14 cities (de'Donato et al. 2013). For

the United States, Curriero et al. (2002) have demonstrated the population sensitivity to cold weather for 11 cities, while, for 15 cities across Europe, Analitis et al. (2008) have revealed the considerable impact on public health arising from increases in cardiovascular, respiratory, and cerebrovascular disease–related deaths during cold spells. Cold-related causes of death have been uncovered for different areas of the Iberian Peninsula (Gomez-Acebo et al. 2010; Montero et al. 2010; Vasconcelos et al. 2013), while an unexpected correlation between the extreme cold temperatures and mortality from cancer, not previously reported, was observed, primarily among the elderly in the community of Cantabria in northern Spain (Gomez-Acebo et al. 2013). Across England, lower ambient winter temperatures associated with a strong negative phase of the North Atlantic Oscillation (NAO), as well as winter temperature seasonality, have been found to be associated with increased risk of ischemic heart disease and myocardial infarction (McGregor et al. 2004; McGregor 2005; Bhaskaran et al. 2010). As noted by Analitis et al. (2008) and Christidis et al. (2010), because of their significance, cold weather– or winter-related health effects should not be underestimated by public health authorities (Ghosh et al. 2014), despite the recent focus on heat waves as an emerging public health issue.

While the literature indicates gains in the epidemiological understanding of cold weather–related health outcomes, largely informed by time series–based Poisson regression and generalized additive models (GAMs) analyses and/or case-only or case-crossover studies, an appreciation of the climatology and meteorological origins of cold weather–related mortality is less well developed. This is undoubtedly because of the complexity of winter weather health associations, due to their moderation by nonweather, social, economic, and physiological factors (Díaz et al. 2005; Anderson and Bell 2009; Allen and Lee 2014). This is highlighted by McGregor (2001) who notes, in a study of the meteorological sensitivity of winter ischemic heart disease (IHD) mortality, that only 55% of 44 IHD mortality peaks over the period 1989–93 possessed any evidence of a weather signal. Further, unlike the acute response associated with heat-related mortality (Gosling et al. 2009), cold-related mortality may manifest itself in a time distributed way; this is often referred to as the lag effect (Ballester et al. 1997; Gasparrini et al. 2010; Zeka et al. 2014).

Given the need to bring different perspectives and apply a range of methodologies to comprehending cold-related mortality (Allen and Lee 2014), the purpose of this paper is to explore the use of back trajectory analysis for shedding light on the climatological associations between winter mortality and cold weather. The study focuses on the United Kingdom, which has one of the highest levels of excess winter mortality across Europe (Healy 2003) and where cold weather is often acknowledged as a contributor to the interannual variability of excess winter mortality (Donaldson 2010; McGregor 2005; Public Health England 2013; Hajat and Kovats 2014). To the authors' knowledge, this is the first time that back trajectory analysis has been applied to the examination of winter mortality in the United Kingdom and perhaps elsewhere.

Back trajectory analysis is one of a number of techniques applied in fathoming airmass history (Fleming et al. 2012). The development of the technique can be traced back to Petterssen (1940), with one of the first applications to the understanding of airmass origins and associated implications for identifying pollution

Figure 1. Office of National Statistics study regions. Study regions are those where a representative meteorological stations is indicated. Place names are for major regional cities.

sources attributable to Fox and Ludwick (1976). Although not without its problems and caveats (Draxler and Taylor 1982; Kahl 1993; Seibert 1993; Stohl 1998; Polissar et al. 1999; Hondula et al. 2010; Fleming et al. 2012), back trajectory analysis has been frequently applied in both meteorological and climatological analyses of environmental variables relevant to human health, such as air pollution (Riccio et al. 2007; Suthawaree et al. 2008; Karaca et al. 2009; Makra et al. 2011; He et al. 2013), precipitation and temperature (Theoharatos et al. 2010; Bednorz 2013; Hernandez-Ceballos et al. 2013; Katarzyna 2013; Tosic and Unkasevic 2013), pollen (Stach et al. 2007; Zemmer et al. 2012), and dust (Engelstaedter et al. 2009; Sunnu et al. 2013).

2. Data and methodology

2.1. Temperature and mortality data

For the purposes of this paper, we used November to February daily temperature and mortality data for the 26-yr period 1974–99, from five official Office of National Statistics (ONS) regions of England, namely, Yorkshire and the Humber, the West Midlands, northeast, northwest, and southeast regions (Figure 1). Daily all-cause mortality data were obtained from the ONS (deaths per day), as opposed to

Table 1. Average values of DMT (°C), DMINT (°C), and DTMORT (deaths per day) of the November–February period, during the time interval 1974–99, in the Yorkshire and the Humber, West Midlands, northeast, northwest, and southeast regions of England. Temperature data and coordinates are from the counties of West Yorkshire (Yorkshire and the Humber), West Midlands (West Midlands), Tyne and Wear (northeast), Great Manchester (northwest), and Hampshire (southeast).

Region	Lat (°N)	Lon (°W)	Mean Temp (°C)	Min Temp (°C)	Total mortality (deaths per day)
Yorkshire and the Humber	53.81	1.76	4.23	1.64	187.0
West Midlands	52.47	1.83	4.70	1.91	182.0
Northeast	54.99	1.57	5.30	2.84	192.8
Northwest	53.48	2.25	4.98	2.42	194.6
Southeast	51.09	1.22	5.58	2.71	176.5

cause-specific mortality, as all-cause mortality has been shown to be widely related to periods of low temperature. The five regions, on which this study is based, were chosen because they were the only regions for which mortality data could be obtained. Fortunately, the regions do capture the range of winter temperature conditions across England and thus should offer insights into any geographical variations of winter climate and health associations. Because of the length of the period considered in this study, mortality data were detrended prior to analysis. Although more recent mortality data were not available, the 26-yr record of daily mortality, covering the period 1974–99, constitutes a substantive dataset for assessing the association between air masses and mortality, using back trajectory analysis. Daily mean temperature (DMT) and daily minimum temperature (DMINT) values in degrees Celsius (°C) were also provided to us by the ONS for each of the five regions. As winter mortality is focused on here, only temperature data for November to February were used. Temperature data are from one county level representative meteorological station in each of the regions (Figure 1), namely, west Yorkshire (Yorkshire and the Humber), West Midlands (West Midlands), Tyne and Wear (northeast), Greater Manchester (northwest), and Hampshire (southeast). Average values of DMT (°C) and DMINT (°C) for the November–February period are presented in Table 1.

2.2. Methodology

Following the synoptic climatological terminology of Yarnal (1994), environment-to-circulation and circulation-to-environment approaches are applied in this study. First, low temperature episodes (LTE) are identified in order to create a subset of all winter days (environment to circulation), which become the focus of further analysis, such that the origins of the air masses on those days are explored using back trajectory analysis. Subsequently, the association of airmass trajectory patterns with mortality levels is analyzed (circulation to environment). In this two-stage approach, it is important to remember that deaths are not attributed to any particular LTE. Rather what is of interest is, first, the identification of the range of airmass trajectory patterns associated with LTE for each study region and, subsequently, whether any of the LTE airmass trajectory patterns have high mortality associated with them. To determine the latter, for each region, one-way analysis of

variance (ANOVA) with unequal sample sizes (trajectory clusters are treated here as samples) and a post hoc Tukey honestly significant difference (HSD) test were applied (McGregor and Bamzelis 1995; Petrou et al. 2015). ANOVA indicates whether there is an overall statistically significant difference in mortality level between the airmass back trajectory categories, while the HSD test reveals which of the individual trajectories contribute to the overall difference in mortality level.

LTE days are defined as all days falling within the 5th percentile of minimum temperature for each of the study areas. These days formed the temporal starting points for ensuing 96-h back trajectory runs. Acknowledging that mortality may not be concurrent with the timing of a particular LTE but a period of low temperatures either side of a single day LTE (Ferreira Braga et al. 2001; Hajat et al. 2007), the 3 days prior to each LTE and the 3 days after each LTE were also considered as temporal starting points for the backward trajectories. When the consecutive days were identified as LTE, the aforementioned approach implemented for the selection of the trajectory temporal starting points was applied.

Airmass back trajectories (BT) were calculated using the Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model of the NOAA Air Resources Laboratory (Draxler and Rolph 2003), which has been applied widely to the analysis of airmass histories, related mainly to the analysis of air pollution episodes (Fleming et al. 2012). The starting point for the BT in each of the study regions was the latitude and longitude associated with the respective county-level meteorological station (Table 1). The 500 m above ground level (AGL) was set as the height for the origin of the BT in order to reveal the direct influence of advancing air masses on temperature (Hernandez-Ceballos et al. 2013). The time of every air parcel's arrival in all counties was set at 1200 UTC (Dimitriou and Kassomenos 2013). Once all trajectories had been calculated, the BT were grouped, according to their origin and path, in a similar fashion to that of Dorling et al. (1992) and Dorling and Davies (1995) by using *K*-means cluster analysis based on the Euclidean distance (Borge et al. 2007; Markou and Kassomenos 2010). The longitude and latitude of the trajectories over consecutive 1-h intervals were used as the clustering variables (Dimitriou and Kassomenos 2014a). Clusters that contained less than 3% of the total trajectories were not considered further because they composed too few cases to make meaningful conclusions about BT mortality associations. The airmass residence time of each trajectory cluster was analyzed on a $0.5° \times 0.5°$ resolution grid as the sum of the number of hourly trajectory points within each cell (Kavouras et al. 2013). The coordinates of the center of each $0.5° \times 0.5°$ grid cell were used as mapping points in order to define more efficiently the area covered from the trajectories of each set (Dimitriou and Kassomenos 2014b).

The number of BT clusters per region was established by analyzing a scree plot of a cumulative agglomeration coefficient. Qualitatively determined break points in the scree plot were taken as points in the clustering process, where several small clusters amalgamated into larger clusters. Such break points were used to establish the number of BT clusters. Each BT cluster was characterized using a number of variables, including mean and minimum temperature, mean daily mortality, trajectory path, and trajectory length and duration.

For each cluster of trajectories, a centroid trajectory was determined based on the median position of all latitude and longitude values at each point along the

Table 2. Percentage difference in mortality between LTEs (as well as 3 days before and after LTEs) and non-LTE days and associated 95% confidence intervals.

Region	DTMORT difference (%)	95% lower (l) and upper (u) confidence intervals (%)
Yorkshire and the Humber	10.7	9.2 (l); 12.1 (u)
West Midlands	10.9	9.5 (l); 12.4 (u)
Northeast	10.2	8.7 (l); 11.6 (u)
Northwest	9.0	7.6 (l); 10.4 (u)
Southeast	10.7	9.3 (l); 12.1 (u)

trajectory. Once defined, the centroid trajectory's length was determined using the Haversine formula, which calculates the distance of the curvature D between two adjacent points [Equation (1)]. Total trajectory length was, therefore, calculated as the sum of the distances D_i of each pair of hourly neighboring points, along the 96-h centroid trajectory, as expressed in Equation (2) (Markou and Kassomenos 2010; Dimitriou and Kassomenos 2014a). The application of this technique yields a better estimate of trajectory length, in comparison with the calculation of D as the distance between the first and last point of the entire centroid trajectory:

$$D_i = 2R \sin^{-1}\left\{ \left[\sin^2\left(\frac{\varphi_1 - \varphi_2}{2}\right) + \cos\varphi_1 \cos\varphi_2 \, \sin^2\left(\frac{\lambda_1 - \lambda_2}{2}\right) \right]^{0.5} \right\} \quad \text{and} \quad (1)$$

$$D = \sum_{i=1}^{96} D_i, \tag{2}$$

where D_i is the distance between two points of the Earth (km), φ is the latitude (rad), λ is the longitude (rad), and R is the radius of the Earth: "6367.45" (km).

Centroid trajectory length was, subsequently, classified into one of a number of length classes, in accordance with the ranges proposed by Markou and Kassomenos (2010) and Dimitriou and Kassomenos (2014a). These are as follows: short-range cluster: $0 < D < 1000$ (km), medium-range cluster: $1000.1 < D < 1800$ (km), long-range cluster: $1800.1 < D < 3000$ (km), and very long-range cluster: $3000.1 < D$ (km).

3. Results

Based on the results from a series of independent variables t tests, overall, mortality on LTE days (as well as 3 days before and after LTEs) was found to be statistically significantly higher than all other winter non-LTE days across all five regions at the 0.05 level, suggesting a link between low temperature events and increased mortality. The percentage difference in mortality between LTE days (as well as 3 days before and after LTEs) and non-LTE days and associated 95% confident intervals are presented in Table 2. Interestingly, there appears to be little regional variation in the percentage increase of mortality for LTE, suggestive of a spatially consistent response of this health outcome to anomalous cold events.

For each region, K-means cluster analysis produced a small number of trajectory groups, which were divided into a number of categories reflecting trajectory

Table 3. Cluster classification at 500 m AGL. Blank cells correspond to clusters that included less than 3.0% of the total trajectories and were excluded from the procedure, while dashes stand for cases where the analysis resulted in fewer than 11 clusters.

Cluster	Yorkshire and the Humber	West Midlands	Northeast	Northwest	Southeast
1	W			W–SW	L
2	L–S	W	SW	W	NA
3	SW	AR			
4	SW	NA	S–AR		E
5		SW		AR	
6	E	E	E	E	SW
7	AR	W	W	L	AR
8	AR	L	L	NA	W
9	—	AR	AR	—	—
10	—	—	NA	—	—
11	—	—	NA	—	—

origins, namely, east (E), local (L), west (W), North Atlantic (NA), Arctic (AR), southwest (SW), and Scandinavian (S) (Table 3). For each trajectory group, trajectory centroid length, as well as DMT, DMINT, and daily total mortality (DTMORT), statistics are presented in Table 4. According to centroid trajectory lengths (Table 4), the medium-, long-, and very long-range trajectories possibly indicate rapidly moving weather systems, such as midlatitude cyclones and associated fronts and quickly changing atmospheric conditions or rapid advection of air over long distances. Such systems are typical of the type of weather that affects the study regions and the midlatitudes in general (Carlson 2012). The short-range trajectories (Table 3) represent slow-moving or stagnant air masses, possibly associated with blocking episodes. Graphical representation of all trajectories by group is presented in Figures 2–6. The average ambient and potential temperature values along the seven trajectory centroids for each region are presented in Figures 7–11. What follows is a region-by-region description of the association between air mass trajectories and mortality levels.

3.1. Yorkshire and the Humber

In the Yorkshire and Humber region (Figure 1), eight trajectory clusters were found to influence the region during LTE days (Table 3; Figure 2). Cluster 5 was excluded from the analysis because it summarized less than 3% of the total cases (Table 4). The largest fractions of trajectories were captured in cluster 2 (35.6%) and cluster 6 (18.0%). Cluster 2 included short–medium-range trajectories that arrived in England from northern neighboring areas and from over the Scandinavian Peninsula (Figure 2b), whereas cluster 6 describes long-range easterly air flows off the European continent, with origins over eastern Europe (Figure 2e). Cluster 2 (L–S) and cluster 6 (E) also account for the highest percentage of LTE, 52.5% and 24.1%, respectively (Table 4), as well as the lowest average levels of DMT and DMINT (Table 4). However, the highest average DTMORT rates occurred for clusters 3 and 4 (Figures 2c,d), which also possessed the highest average DMT (Table 4). The relative and consistent warmth of these SW trajectory groups, compared to their much cooler L–S and E counterparts, is confirmed by

Table 4. Trajectories (%); LTE (%); and statistics of DMINT, DMT, and DTMORT, corresponding to backward trajectory clusters at 500 m AGL (blank cells correspond to clusters that included less than 3.0% of the total trajectories and were excluded from the procedure, while dashes stand for cases where the analysis resulted in fewer than 11 clusters). Averages are weighted averages that account for differences in size of trajectory cluster membership.

Region	Clusters	1	2	3	4	5	6	7	8	9	10	11
Yorkshire and the Humber	Centroid length (km)	3431	1093	1693	4200		2195	3739	2314	—	—	—
	Average DMINT (°C)	−0.5	−3.7	−0.6	0.5		−4.0	−2.4	−2.7	—	—	—
	Std dev DMINT (°C)	2.5	2.8	2.8	3.7		2.6	2.6	2.9	—	—	—
	Average DMT (°C)	2.3	−0.9	2.0	3.3		−1.8	0.3	0.2	—	—	—
	Std dev DMT (°C)	2.3	2.1	2.6	3.3		2.1	2.4	2.3	—	—	—
	Average DTMORT	203.5	202.9	209.2	214.3		206.3	203.5	191.4	—	—	—
	Std dev DTMORT	26.4	25.1	25.0	28.3		21.9	23.5	23.7	—	—	—
	Trajectories (%)	7.7	35.6	12.3	7.7	0.2	18.0	4.7	13.8	—	—	—
	LTE (%)	1.2	52.5	4.3	1.2	0.6	24.1	3.1	13.0	—	—	—
West Midlands	Centroid length (km)	2355	2060	3152	2380		1969	4332	775	3487	—	—
	Average DMINT (°C)	0.9	−3.4	−2.6	0.3		−4.2	0.7	−3.2	−1.6	—	—
	Std dev DMINT (°C)	2.9	2.7	3.5	3.5		2.9	2.8	3.6	2.8	—	—
	Average DMT (°C)	3.8	−0.1	0.7	3.1		−1.7	3.7	−0.2	1.5	—	—
	Std dev DMT (°C)	2.4	2.1	2.8	3.4		2.4	2.7	2.8	2.5	—	—
	Average DTMORT	190.6	191.8	186.8	197.3		205.0	204.0	202.4	180.6	—	—
	Std dev DTMORT	26.4	25.5	25.6	32.8		25.6	24.2	30.2	25.6	—	—
	Trajectories (%)	5.4	16.6	6.9	8.4	0.2	23.4	9.0	25.6	4.1	—	—
	LTE (%)	0	20.4	7.6	1.9	0.6	35.0	0.6	30.0	3.2	—	—
Northeast	Centroid length (km)		2652	1561	1902	4371		829		3382	2259	2976
	Average DMINT (°C)		1.9	−1.9	−1.7	1.3		−1.0		−1.7	−0.9	0.2
	Std dev DMINT (°C)		3.0	2.9	2.5	2.5		3.3		2.7	2.8	2.0
	Average DMT (°C)		4.5	0.6	0.5	4.0		1.7		0.6	1.6	2.5
	Std dev DMT (°C)		2.7	2.3	1.8	2.6		2.7		2.8	2.3	1.9
	Average DTMORT		208.9	210.7	215.4	212.8		209.3		207.8	198.2	201.2
	Std dev DTMORT		28.5	30.1	31.9	24.1		29.4		29.3	26.6	26.9
	Trajectories (%)	0.2	13.3								12.8	7.6
	LTE (%)	0.6	2.5								15.1	4.4

Table 4. (Continued)

Region	Clusters	1	2	3	4	5	6	7	8	9	10	11
Northwest	Centroid length (km)	2924	3974			2797	2204	870	2165	—	—	—
	Average DMINT (°C)	1.9	0.9			−2.4	−3.0	−2.1	−1.9	—	—	—
	Std dev DMINT (°C)	2.5	2.4			3.1	2.3	3.0	3.1	—	—	—
	Average DMT (°C)	4.3	3.7			0.6	−0.6	0.6	1.2	—	—	—
	Std dev DMT (°C)	2.1	2.3			2.5	2.0	2.3	2.4	—	—	—
	Average DTMORT	212.3	209.5			202.4	209.1	212.9	202.1	—	—	—
	Std dev DTMORT	23.6	28.5			23.9	24.5	32.0	26.7	—	—	—
	Trajectories (%)	12.9	9.8	0.2	1.2	8.8	17.3	30.8	19.0	—	—	—
	LTE (%)	1.3	1.9	0.6	1.9	10.8	23.4	35.4	24.7	—	—	—
Southeast	Centroid length (km)	997	2293		2268		1141	2351	3895	—	—	—
	Average DMINT (°C)	−2.6	−1.4		−4.2		0.3	−2.2	1.6	—	—	—
	Std dev DMINT (°C)	3.0	2.9		2.8		3.1	2.7	3.5	—	—	—
	Average DMT (°C)	0.5	2.0		−1.3		3.1	1.2	4.5	—	—	—
	Std dev DMT (°C)	2.7	2.4		2.7		2.5	2.5	2.8	—	—	—
	Average DTMORT	195.2	182.8		201.4		190.1	186.9	191.4	—	—	—
	Std dev DTMORT	27.4	19.2		28.8		25.7	20.4	19.5	—	—	—
	Trajectories (%)	27.0	15.6	0.2	18.4	0.2	11.2	13.8	13.6	—	—	—
	LTE (%)	32.5	14.0	0.6	31.2	0	5.1	15.3	1.3	—	—	—
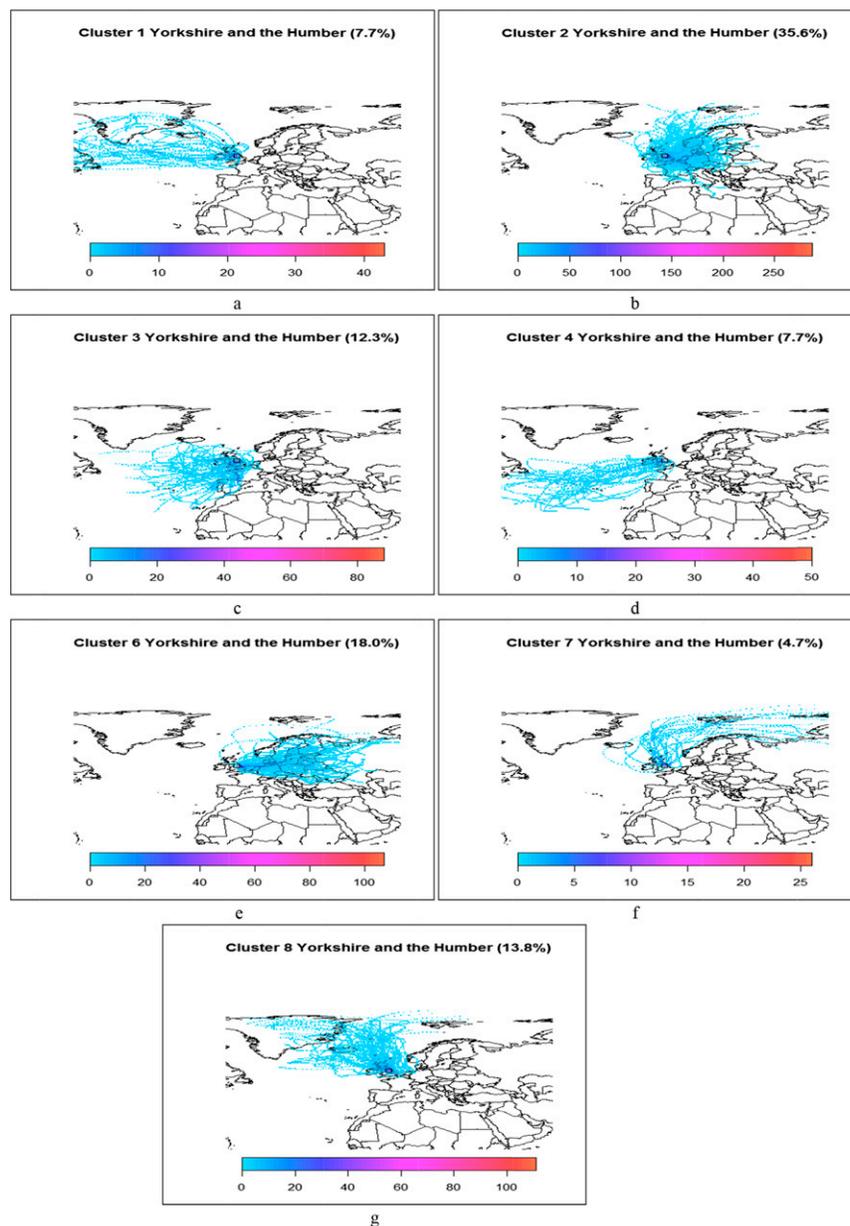
Figure 2. Airmass residence time surface maps of trajectory clusters arriving at 500 m AGL over Yorkshire and the Humber for the LTEs ±3 days. The arrival point is marked with a black square.

consideration of along-trajectory profiles of ambient and potential temperature of the composite trajectories (Figure 7), in accordance with their origins over ocean surfaces to the southwest. Tukey post hoc tests revealed that DTMORT was significantly increased in cluster 2 {6.0% [95% confidence intervals (CI): 0.6%, 11.5%]}, cluster 3 [9.3% (95% CI: 2.6%, 16.0%)], cluster 4 [12.0% (95% CI: 4.2%, 19.7%)], and cluster 6 [7.8% (95% CI: 1.7%, 13.9%)], in comparison with cluster 8.
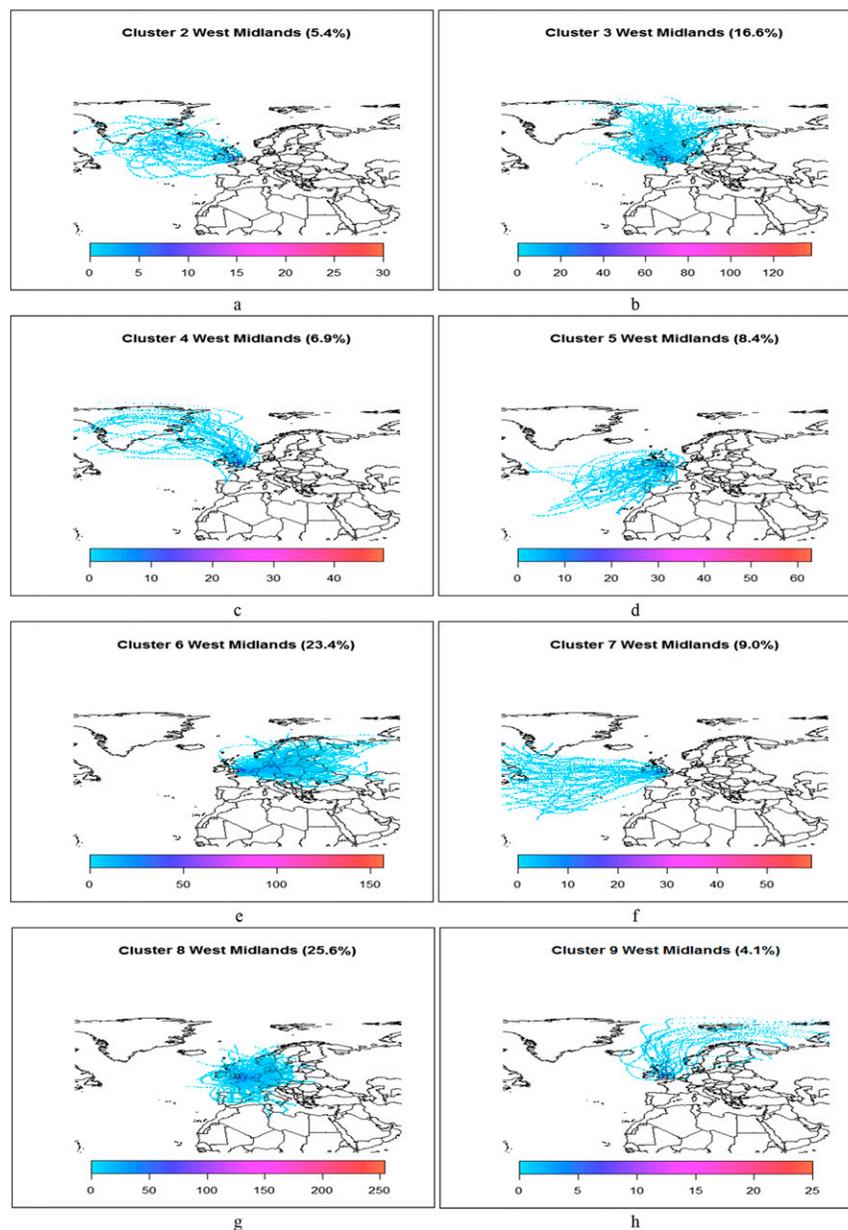
Figure 3. Airmass residence time surface maps of trajectory clusters arriving at 500 m AGL over the West Midlands for the LTEs ±3 days. The arrival point is marked with a black square.

3.2. West Midlands

For the West Midlands, nine trajectory groups were identified (Table 3; Figure 3). Trajectory cluster 1 was not included in the analysis, as it accounted for less than 3% of the total trajectories (Table 4). The largest proportions of trajectories were associated with clusters 8 (25.6%), 6 (23.4%), and 3 (16.6%). Cluster 3 consists of long-range trajectories originating from the North Atlantic and Arctic
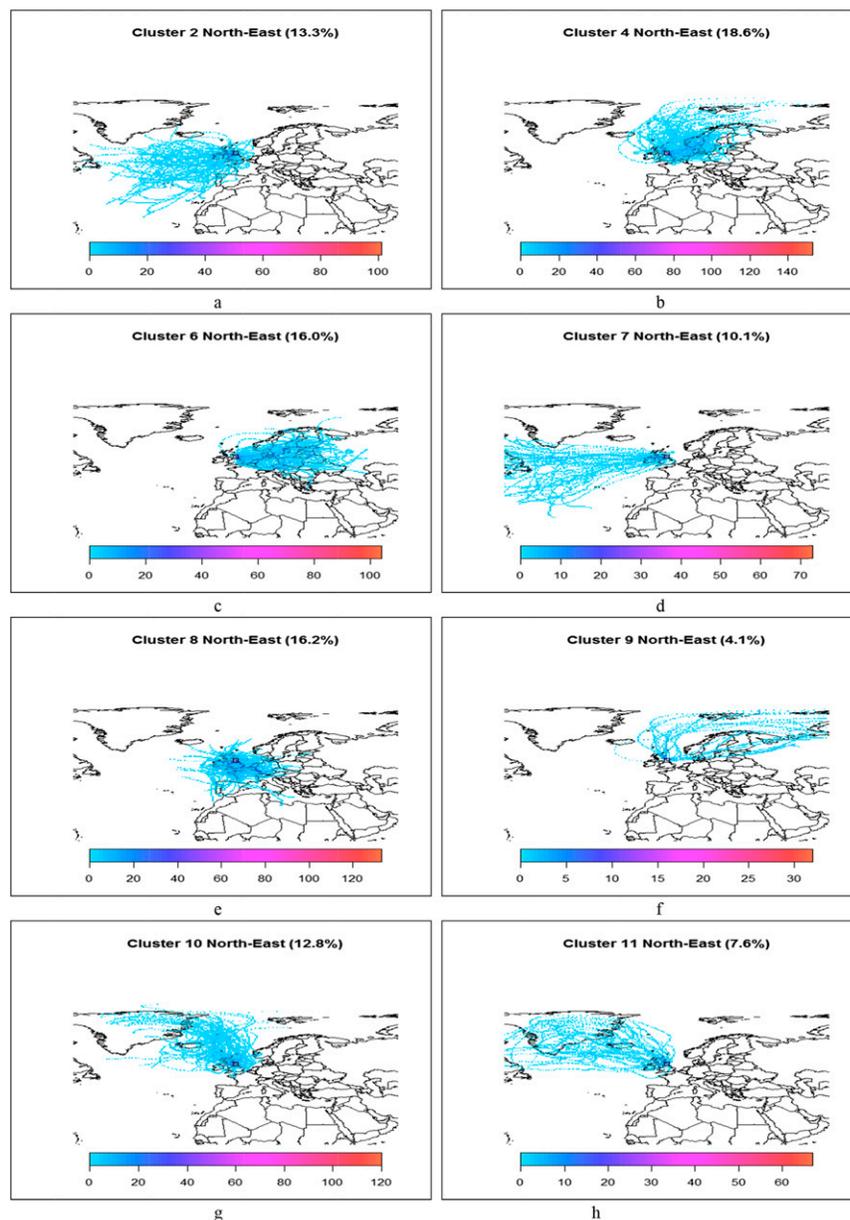
Figure 4. Airmass residence time surface maps of trajectory clusters arriving at 500 m AGL over the northeast for the LTEs ±3 days. The arrival point is marked with a black square.

regions (Figure 3b), whereas clusters 6 and 8 include long- and short-range trajectories respectively, with a continental European origin (Figures 3e,g). Clusters 8 (L), 6 (E), and 3 (AR) have the highest levels of LTE, with 30.0%, 35.5%, and 20.4% respectively, the lowest values of DMT and DMINT, and the highest levels of daily mortality (Table 4). Consideration of the along-trajectory profiles of potential and ambient temperature associated with clusters 3, 6, and 8 (Figure 8)
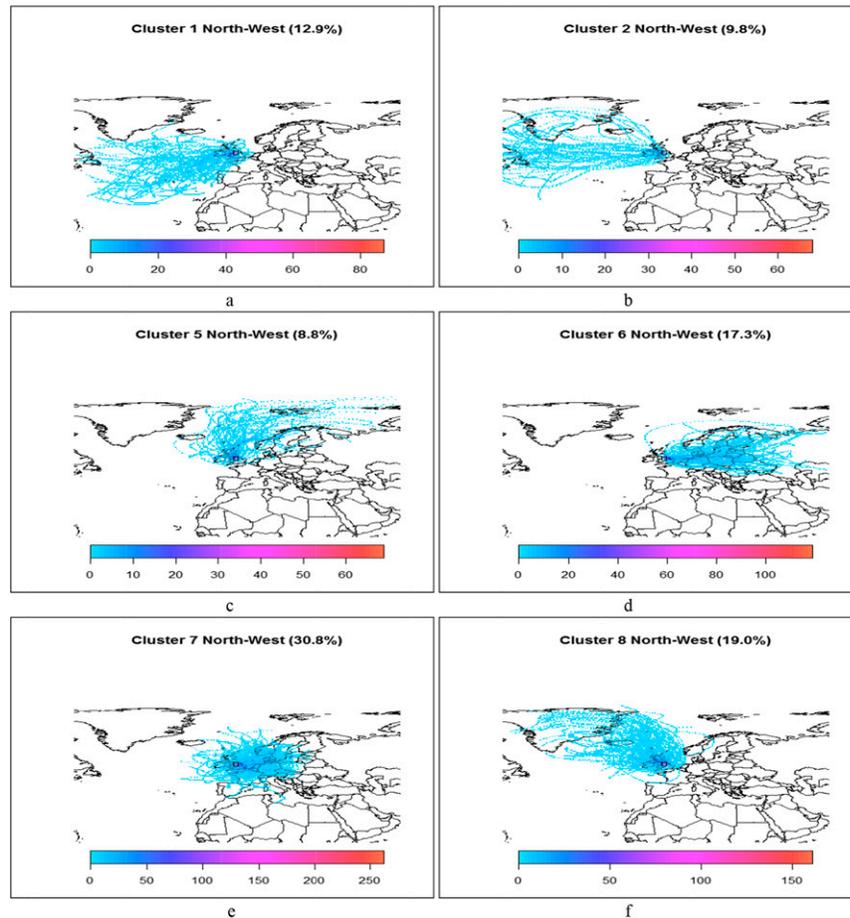
Figure 5. Airmass residence time surface maps of trajectory clusters arriving at 500 m AGL over the northwest for the LTEs ±3 days. The arrival point is marked with a black square.

indicate that air masses that follow these trajectories show little evidence of warming along their paths, such that associated, persistent cold conditions may assist with explaining elevated mortality for these trajectory groups. Interestingly, trajectory cluster 7 (Figure 3f), associated with high average DMT and DMINT, as well as a very small fraction (0.6%) of LTE (Table 4), also presented increased levels of mortality. Given the nature of cluster 7's trajectory (long distance and direct west to east), it is likely that elevated mortality associated with this trajectory group is more related to rapidly changing weather conditions as opposed to cold-related thermal stress. Tukey post hoc tests showed that a statistically significant DTMORT increment was evident for cluster 6, in comparison with cluster 3 [6.9% (95% CI: 0.9%, 12.9%)], cluster 4 [9.7% (95% CI: 1.3%, 18.1%)], and cluster 9 [13.5% (95% CI: 2.8%, 24.2%)]. In addition, DTMORT was significantly increased in cluster 7, in comparison with cluster 9 [12.9% (95% CI: 1.0%, 24.8%)], and also in cluster 8, in comparison with cluster 4 [8.3% (95% CI: 0.1%, 16.6%)] and cluster 9 [12.0% (95% CI: 1.4%, 22.7%)].
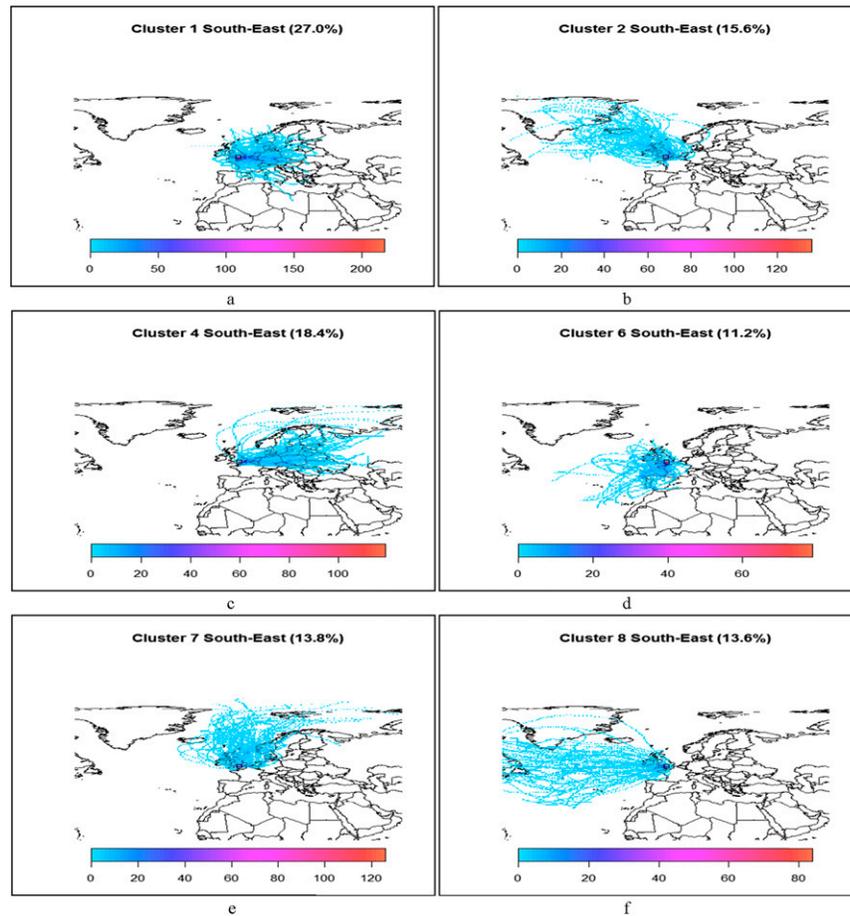
Figure 6. Airmass residence time surface maps of trajectory clusters arriving at 500 m AGL over the southeast for the LTEs ±3 days. The arrival point is marked with a black square.

3.3. Northeast

For the northeast region (Figure 1), 11 groups of airmass trajectories were identified (Table 3; Figure 4). Trajectory clusters 1, 3, and 5 were excluded from the analysis because of their small number of members (Table 4). The prevalence of severe cold episodes in the northeast region can be attributed, primarily, to the influence of cluster 4 (S–AR), which accounted for 30.8% of the LTE (Figure 4b), whereas cluster 6 (E) possessed 17.6% of the LTE (Figure 4c; Table 3). Cluster 4 consisted of medium-range trajectories that approached England from the northeast direction, crossing the Scandinavian Peninsula, whereas cluster 6 grouped continental trajectories originating from central Europe (Figure 4c). Associated with both of these trajectory groups were the lowest DMT and DMINT and highest average DTMORT values (Table 4). Interestingly, weighted average mortality levels for trajectory groups with a general westerly origin were relatively low, indicating, for the northeast region, that air masses with an Arctic/continental
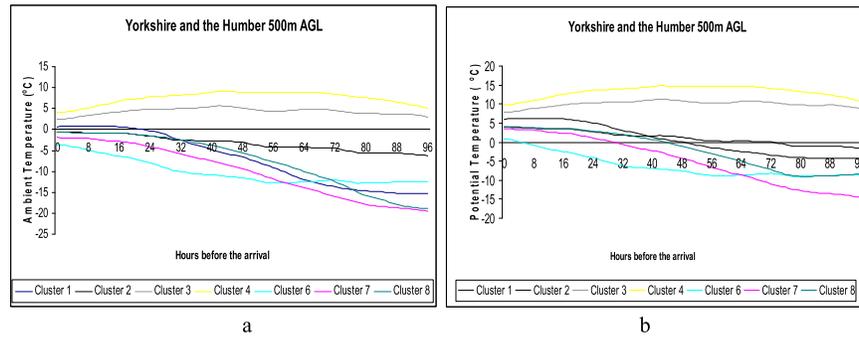
Figure 7. Variation of (a) ambient and (b) potential temperature along each cluster's airmass trajectories, arriving at 500 m AGL over Yorkshire and the Humber.

origin, characterized by low ambient and potential temperature trajectory profiles, are, in mortality terms, climatologically important. A statistically significant increase in DTMORT was found for cluster 6, in comparison with cluster 10 [8.7% (95% CI: 1.6%, 15.7%)].

3.4. Northwest

Eight trajectory clusters were identified for the northwest region (Table 3; Figure 5). Clusters 3 and 4 were not included in any further analysis because of their low overall percentage membership. Trajectory clusters 7 (L), 8 (E), and 6 (NA) possessed the highest proportion of LTE (Table 4). However, of the three low temperature trajectory groups, only group 7, consisting of short-range trajectories with origins immediately to the east (Figure 5e), possessed elevated mortality. DTMORT levels were significantly increased in cluster 7 [5.3% (95% CI: 0.5%, 10.2%)], in comparison with cluster 8. The other high mortality trajectory group, cluster 1, was relatively warm, as evidenced by the potential temperature trajectory profiles, with air masses originating from a west to southwest direction (Figures 5a, 10).
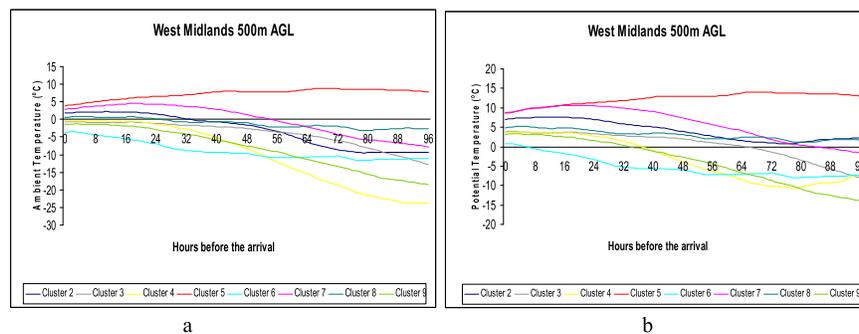
Figure 8. Variation of (a) ambient and (b) potential temperature along each cluster's airmass trajectories, arriving at 500 m AGL over the West Midlands.
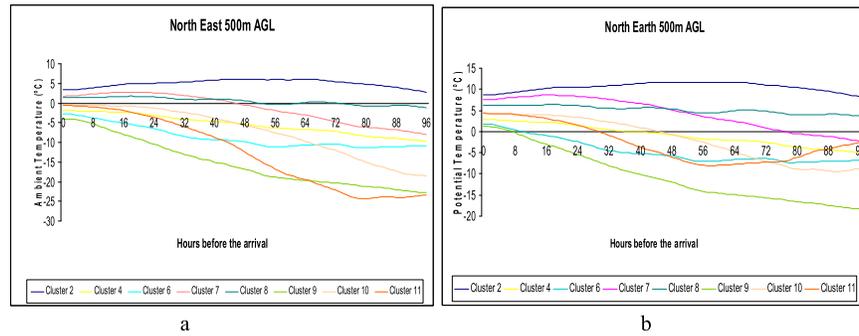
Figure 9. Variation of (a) ambient and (b) potential temperature along each cluster's airmass trajectories, arriving at 500 m AGL over the northeast.

The results for the northwest region suggest that winter cold weather–related mortality may be associated with two quite contrasting situations, namely, rapidly moving weather systems off the North Atlantic from the southwest and stable conditions associated with blocking to the east.

3.5. Southeast

Airmass trajectories reaching the southeast region were categorized into eight clusters (Table 3; Figure 6). Clusters 3 and 5 possessed less than 3% of the trajectories and were excluded from further analysis (Table 4). Cluster 1 (L) and cluster 4 (E) accounted for 27.0% and 18.4% of the total trajectories and 32.5% and 31.2% of LTE, respectively (Table 4). The high proportion of LTE for these two trajectory groups can be understood through the geographical origins of the air masses, as represented by the trajectory patterns. In both cases, trajectories indicate flows of continental air from nearby or distant continental Europe. In the case of cluster 1, airmass trajectories are short (Figure 6a) and, although hinting at origins over the western margins of continental Europe, are suggestive of stagnant or recirculating air associated with a blocking situation. In comparison, the distances
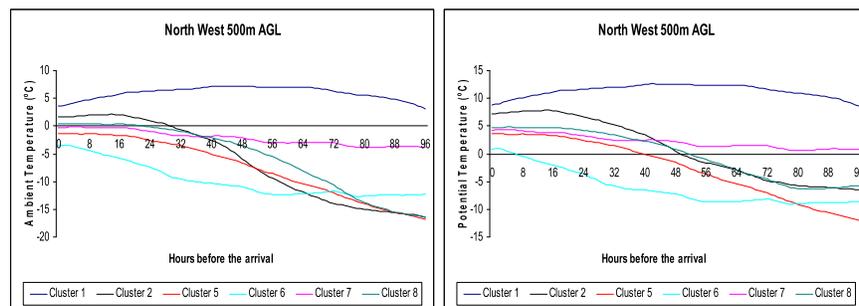
Figure 10. Variation of (a) ambient and (b) potential temperature along each cluster's airmass trajectories, arriving at 500 m AGL over the northwest.
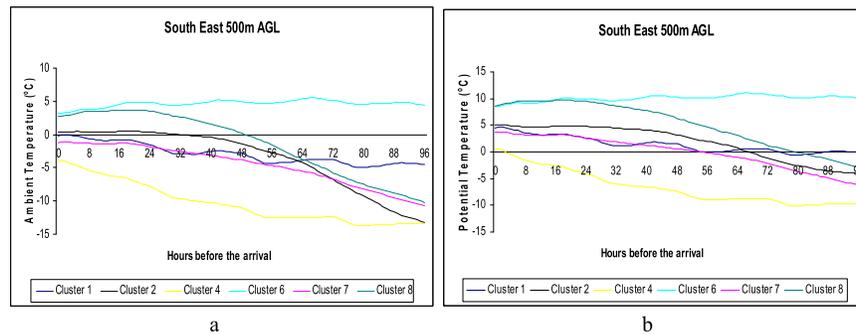
Figure 11. Variation of (a) ambient and (b) potential temperature along each cluster's airmass trajectories, arriving at 500 m AGL over the southeast.

traveled by air masses associated with trajectory pattern 4 are large, with origins over central/eastern Europe (Figure 6c). Trajectory pattern 4, therefore, describes conditions associated with rapid advection of cold continental air over the southeast, with substantially lower average values of DMT and DMINT, compared to the more "local" cluster 1 (Table 4), as manifested by contrasting airmass trajectory temperature profiles (Figure 11). The highest DTMORT values are also associated with trajectory patterns 4 and 1, suggesting that acute cold-related adverse health effects in the southeast are associated with cold stable air, coeval with blocking over the western margins of Europe or rapidly advected cold continental air from eastern Europe. A statistically significant increase in DTMORT was evident for cluster 4 [10.2% (95% CI: 4.3%, 16.0%)] and cluster 1 [6.8% (95% CI: 1.3%, 12.2%)], in comparison with cluster 2, whereas DTMORT was also significantly increased in cluster 4 [7.8% (95% CI: 1.9%, 13.7%)], compared with cluster 7.

4. Discussion

This paper has presented, for the first time, an analysis of the association between airmass history, as determined by back trajectory analysis, and winter mortality for a range of low temperature events across the United Kingdom. To achieve this, a two-stage analysis approach was adopted. Initially, a subset of low temperature episode days were identified for the winter period, with back trajectory analysis of the LTE conducted. Subsequently, cluster analysis of the resultant trajectory patterns was performed in order to identify the main trajectory patterns associated with LTE. The daily mortality levels for each LTE trajectory pattern by region was then established so as to allow conclusions to be drawn based on the outcome of ANOVA and HSD tests, regarding the association of airmass history with winter mortality levels.

On the whole, weighted average daily mortality on LTE days was found to be significantly higher than non-LTE. While this result corroborates previous findings related to the health impacts of cold weather in the United Kingdom and nearby European countries (Keatinge and Donaldson 2001; Wilkinson et al. 2004; Hajat et al. 2007; Ekamper et al. 2009; Brown et al. 2010), the chief interest of this paper

has been the definition of atmospheric pathways related with daily LTEs and their possible association with elevated mortality rates.

For the five regions considered in this study, *K*-means cluster analysis of back trajectories produced by the HYSPLIT model revealed a number of distinct trajectory patterns associated with LTE for the period November to February. These were grouped into seven categories in relation to their origin, namely, east, local, west, North Atlantic, Arctic, southwest, and Scandinavian. Across all five regions, high proportions of LTE were, primarily, associated with local and east (European) trajectories and, second, with North Atlantic (Greenland, Iceland, and North Atlantic) and Arctic–Scandinavian (Arctic Ocean and Scandinavian Peninsula) trajectory patterns. Allied with this finding, lower average values of DMT and DMINT were observed, particularly for local, east (European continental), North Atlantic, and Arctic–Scandinavian trajectory groupings, compared to the west and southwest trajectories.

With specific regard to the aim of this study, for all regions elevated DTMORT rates were observed for days with airmass origins falling within the local, east, Arctic, and North Atlantic trajectory categories. Of these trajectory patterns, only the members composing the local pattern group possess short trajectories. This finding suggests, for the regions considered here, that advection of cold air masses over long distances plays an important role in elevating mortality and that the origins of cold air are geographically diverse. Further, as indicated by the along-trajectory temperature profiles, east, Arctic, and North Atlantic trajectories demonstrate little warming throughout their history, with minimal modification of air mass properties between the point of origin and their arrival points in the regions considered.

The trajectory patterns identified in this study with a high proportion of LTE match the generally known atmospheric circulation patterns associated with periods of anomalously low temperatures over the broader United Kingdom–European region. For example, Sillmann et al. (2011) and Pfahl (2014) note that the advection of cold air masses westward over Europe is associated with blocking anomalies over the North Atlantic and northern Europe and cyclonic anomalies to the southeast. This is in line with the observation of Walsh et al. (2001) and Cattiaux et al. (2013) that outbreaks of cold air over Europe are concomitant with a negative phase of the North Atlantic Oscillation and positive sea surface pressure anomalies over the Arctic. In terms of the physical evolution of cold events, Walsh et al. (2001) also point out that the trajectories of the coldest westward-moving air masses over Europe are typified by subsidence of several hundred hectapascals before they reach the surface. As well as tropospheric processes, Tomassini et al. (2012) have suggested that stratosphere–troposphere coupling may play a role in the generation of winter cold spells over Europe. This may occur via erosion of the stratospheric polar vortex that leads to a decrease in the height of the tropopause, with the resulting compression of the tropospheric column, favoring strong positive pressure anomalies and thus blocking over high northern latitudes. A consequence of this anomalous pressure pattern is the advection of cold air over northern Europe, with air masses following a trajectory resonant with the Arctic–Scandinavian pattern identified here as being important for LTE occurrence and elevated mortality levels.

The observation that high daily mortality is also associated with the local trajectory pattern is interesting. This may be indicative of an association between cold stagnant air and elevated mortality, perhaps via the synergistic effects of low

temperatures and poor air quality, although more research in the field is required, as noted by Scarborough et al. (2012) and Milojevic et al. (2014) in the case of England.

Despite their importance for accounting for a relatively high number of LTE and attendant elevated daily mortality, air masses originating from the north and east were not always linked with the highest mortality levels. This is especially clear for the northwest and West Midland regions, where highest mortality levels are allied with, in relative terms, warm air masses that have their origins to the west or southwest, over the Atlantic Ocean. Such a finding is perhaps not all that surprising, given that the number of cold-related deaths associated with moderate temperatures is not insignificant, as described by Hajat and Kovats (2014). In relation to this, Gasparrini and Leone (2014) note for London that 70% of all cold-related deaths occur on days warmer than 5°C. For such warm airmass situations, perhaps a physical change in atmospheric properties, in addition to those that drive straight cold exposure (Keatinge 2002), may elevate mortality. A possible candidate is rapid changes in atmospheric pressure and/or temperature. For example, Dawson et al. (2008) have noted, for Glasgow, that an increased risk of hemorrhagic stroke admissions is linked with rapid falls in atmospheric pressure over a preceding 2-day period. Danet et al. (1999) have also shown that myocardial infarction and coronary deaths increase with atmospheric pressure decreases, while Feigin et al. (2000) and Rusticucci et al. (2002) demonstrate associations between low pressure and a number of health outcomes for Argentina and Siberia, respectively. Similarly, McGregor (1999) found, for the United Kingdom, that warm maritime air masses, associated with rapid eastwardly moving low pressure systems and changes in atmospheric pressure, were important for precipitating short-term winter ischemic heart disease mortality peaks. More recently, for the Czech Republic, Plavcová and Kyselý (2014) have convincingly demonstrated the close associations between sudden air pressure changes and hospital admissions for cardiovascular diseases, noting that rapid changes in atmospheric conditions are associated with eastwardly moving mid-latitude cyclone systems, with concomitant changes in air masses. Given this, it seems plausible that the elevated mortality levels identified for the long distance trajectories, emanating from over the Atlantic Ocean, are a consequence of swiftly shifting atmospheric conditions, as manifest by the steep along-trajectory alterations of ambient and potential temperature observed for air masses approaching the West Midlands and northwest regions from the west to southwest (Figures 8, 10), Frustratingly, and as noted by Dawson et al. (2008), the identification of a physiological mechanism that accounts for a connection between health effects and fast-moving weather systems and attendant rapid changes in atmospheric pressure and temperature (Buxton et al. 2001) remains elusive, although increases or decreases in blood viscosity, pressure, and platelet count are likely candidates in the case of cardiovascular and cerebrovascular mortality (Keatinge et al. 1984).

5. Conclusions

The aim of this paper has not been to simply confirm that episodes of cold winter weather cause a rise in daily mortality but rather to understand the

meteorological origins of cold weather associated with elevated mortality at the daily time scale. In doing so, study results bear implications for the development of short- to medium-term weather forecast–based, winter weather–health warning systems. Further, the application of back trajectory analysis brings a new perspective to the exploration and understanding of the climatological associations between winter low temperature episodes and mortality. Results have revealed that, for the five regions considered, certain airmass trajectory patterns have the highest number of low temperature episodes and highest mortality levels, when compared with other low temperature winter days and related trajectory patterns, associated with them. Generally, air masses approaching the study regions from the east produce the greatest frequency of low temperature episodes but not necessarily the highest average daily mortality counts, especially in western regions of north and central England, where maritime air masses emanating from the Atlantic are more important, in mortality terms, compared to their continental European counterparts. This finding points to a possible geographic contrast in the population sensitivity to winter weather, such that regional aspect and associated direct exposure to the region from where weather systems originate plays a role in the type of weather that accounts for elevated mortality. It should be emphasized, however, that because of the exploratory nature of the research presented here, this conclusion is a tentative one, one that lays the basis for hypothesis formulation and further analysis related to the role of climate setting in determining weather sensitivity.

Analysis of back trajectory patterns has clearly shown that elevated winter mortality during low temperature episodes is associated with two broad types of weather conditions. These are rapidly changing relatively warm weather conditions from the west, most likely associated with the eastward progression of low pressure systems, and cold continental air advection over England, from northern or eastern Europe, that lasts for several days, related to either a blocking pattern over the western margins of Europe or an intense high pressure anomaly over eastern or northern Europe. This finding, along with those emerging from studies conducted elsewhere, points to the equifinality or possible multiplicity of winter weather health associations. This is undoubtedly a factor that adds to the complexity of deciphering the drivers of winter mortality on a range of space and time scales. Notwithstanding this, back trajectory analysis and the conclusions that can be drawn from its application to winter weather mortality associations appears to be a worthy addition to the suite of methodologies available for the biometeorological analysis of winter cold weather–related mortality. However, in the case of future analyses of winter mortality, using this technique with a dataset updated to as recently as possible, due consideration should be given to adopting an environment-to-circulation approach, in which winter mortality peaks are first identified with a subsequent examination of trajectory patterns and their evolution in terms of airmass physical properties undertaken. To elucidate the nature of possible lag effects, the duration and temporal starting points of back trajectories could also be extended beyond the time periods used in this study. Last, future interregional analyses of winter weather health associations may have to take into consideration how to control for regional differences in socioeconomic characteristics, given that regional variations in health status are likely to modify weather health associations.

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