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Vulnerability to the mortality effects of warm temperature in the districts of England and Wales

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Supplementary Methods

Bayesian spatial case-crossover method

We estimated the association of temperature on/preceding the day of death with increased odds of dying from cardio-respiratory diseases. To assess vulnerability and resilience, we allowed the magnitude of the effects to vary across districts, while accounting for possible similarity in neighbouring districts.

We used a time-stratified case-crossover design, a method that is ideal for analysing time-varying exposures such as daily temperature. In a case-crossover analysis, each case acts as its own control,[1] a design that naturally controls for potentially confounding factors that are time-invariant or vary slowly over time, for example age, ethnicity, SES, smoking, and healthcare – although these factors may still be *modifiers* of the effect. Temperature on the day of death (case day), and as relevant preceding days, is compared with the temperature on control days on which the death did not occur. We used control days on the same day of the week as the case day, to automatically adjust for day of the week, and in the same calendar month to avoid the so-called overlap bias.[2] In addition, we adjusted for potential bias by variables that change in the same time scale as temperature, namely air pollution and whether a case/control day was a national holiday.

In both warm and cold weather, there may be little or no effect of temperature below/above some threshold, and a dose-response at higher/lower temperatures[3-9]. To reflect this possibility, we used a piecewise linear specification for the temperature-outcome association.

The model for death record i, case/control j, with $Y_{ij} = 1$ for cases ($j = 1$) and 0 for controls (j=2, 3, 4, 5), can be summarised as follows:

$$\mathrm{Y}_{ij} \sim Poisson(\lambda_{ij})$$

$$\log(\lambda_{ij}) = f(\beta_{0i}, \beta_{1i}, \mathrm{Temp}_{ij}) + \delta_i + C_{ij}$$

Where λ is the odds of death; δ_i is a parameter common to cases and controls from the same record i used to analyse a conditional logistic regression as a Poisson likelihood for computational efficiency[10]; Temp_{ij} is the temperature on/preceding the day of exposure of case/control j in the grid that contains the postcode of record i; β_{0i} is the threshold parameter for temperature response; β_{1i} is the slope parameter of the dose-response relationship above the threshold for warm weather and below the threshold for cold weather; and f is the linear threshold model. Confounders (C_{ij}) were air pollution and national holidays and are given by

$$C_{ij} = \beta_{PM10}.\mathrm{PM10}_{ij} + \beta_{holiday}.\mathrm{holiday}_{ij}$$

where $\mathrm{PM10}_{ij}$ is the PM_{10} (particulate matter below 10 μm in aerodynamic diameter) concentration on/preceding the day of exposure of case/control j in the grid that contains the postcode of record i and $\mathrm{holiday}_{ij}$ indicates whether the ij^{th} day was a national holiday.

As described in the main paper, we set the threshold (β_0) for each district in two alternative approaches: district-specific thresholds and a common threshold for all districts. We estimated the slope (β_1) parameters of the relationship at the district level, e.g. the slope parameter is given by $\beta_{1i} = \beta_1^{national} + \beta_{1d}^{district}$, where $\beta_{1d}^{district}$ measures deviation from the national average ($\beta_1^{national}$) in district d in which record i resides. The health effects of temperature may be more similar in neighbouring districts than those farther away. To allow for this, we used a Bayesian spatial structure, in which the estimated parameters for each district are influenced by its own data as well as by those of its neighbours. The extent to which neighbours influence one another depends on how uncertain the estimated effects in each district are, and on the empirical similarity among neighbouring districts. We used the Besag, York, and Mollie (BYM) model in which cross-district variance is partitioned into a spatial component, specified using a conditional autoregressive prior, and a district-specific random effect, specified using a Normal distribution[11].

We examined the role of community-level vulnerability/resilience factors (rural vs. urban status, deprivation, and green space) by introducing them into the above model as modifiers of the parameters that measure the effect of temperature as below:

$$\beta_{1i} = \beta_1^{national} + \beta_1^{district} + \gamma.\mathrm{Modifier}_i$$

where γ is a regression term that allows vulnerability/resilience factors ($\mathrm{Modifier}_i$) to influence the effects. $\beta_1^{district}$ continues to capture spatial variations in effects that are unexplained by these characteristics.

Additional cold-weather analysis methods

The statistical methods for analysis of winter mortality were identical to those of summer with effects quantified below thresholds, vs. above for analysis in summer months. Details are provided above. District-specific winter thresholds, given by the 90th percentile of each district's winter temperatures, ranged between 6.9°C in northeast England and 11.0°C in southwest England.

In the cold season, we used the average of temperature on day of death and the preceding twenty one days because the effects of cold temperature seem to be related to temperature over a longer duration than that of warm temperature[12-14], and because this duration of averaging provides results that are similar to a more flexible model of lagged temperatures[15].

Table S1. Sensitivity of the findings to methodological choices. All comparisons are made with a base case in which the average of daily-mean-temperatures over day of death from cardio-respiratory causes and the preceding three days were used (lag 0-3), and estimates were adjusted for national holidays and average of PM_{10} over the day of death and the preceding two days (lag 0-2).

Sensitivity analysis	Age group (years)	Mean difference [a]		Correlation	
		F	M	F	M
Additional adjustment for ozone on the day of death and the preceding two days (lag 0-2) [b]	<75	0.65	0.33	0.99	0.99
	75-84	0.31	0.16	0.99	0.99
	85+	-0.09	0.07	1.00	0.98
	All	0.29	0.19	0.99	0.98
Temperature one the day of death and the preceding three days (lag 0-3) and PM_{10} on the day of death only (lag 0)	<75	-0.13	-0.38	0.97	0.99
	75-84	-0.30	0.16	0.99	0.99
	85+	-0.23	-0.07	1.00	0.98
	All	-0.22	-0.1	0.99	0.98
Temperature on the day of death and preceding day (lag 0-1) and PM_{10} on the day of death (lag 0)	<75	0.32	0.12	0.72	0.70
	75-84	-0.44	-0.35	0.81	0.74
	85+	-0.84	-1.62	0.92	0.78
	All	-0.32	-0.62	0.81	0.57
Temperature and PM_{10} on the day of death (lag 0)	<75	0.32	0.09	0.75	0.71
	75-84	-0.45	-0.36	0.80	0.74
	85+	-0.85	-1.64	0.92	0.75
	All	-0.32	-0.64	0.80	0.55
All non-injury deaths	<75	1.74	0.91	0.74	0.69
	75-84	1.06	0.62	0.80	0.68
	85+	1.09	0.75	0.88	0.78
	All	1.30	0.76	0.83	0.71
Restrict to deaths in June-August	<75	0.11	0.39	0.96	0.98
	75-84	0.65	0.17	0.99	0.98
	85+	0.67	1.35	0.99	0.98
	All	0.48	0.64	0.98	0.91
Daily maximum temperature instead of daily mean	<75	-0.02	0.65	0.91	0.91
	75-84	0.25	0.20	0.94	0.91
	85+	0.39	-0.1	0.98	0.94
	All	0.21	0.25	0.96	0.88
Common threshold of 18°C	<75	-0.09	-0.04	0.84	0.90
	75-84	0.23	0.17	0.85	0.90
	85+	0.37	-0.06	0.98	0.83
	All	0.17	0.02	0.90	0.88

[a] The differences are reported in percentage points. A positive number indicates that the estimates in the base scenarios were on average larger than those in the sensitivity analysis, and vice versa.
[b] Gridded daily ozone was obtained using the same approach as PM_{10}. Average daily mean ozone in 100m×100m grids were from a land-use regression analysis[16].

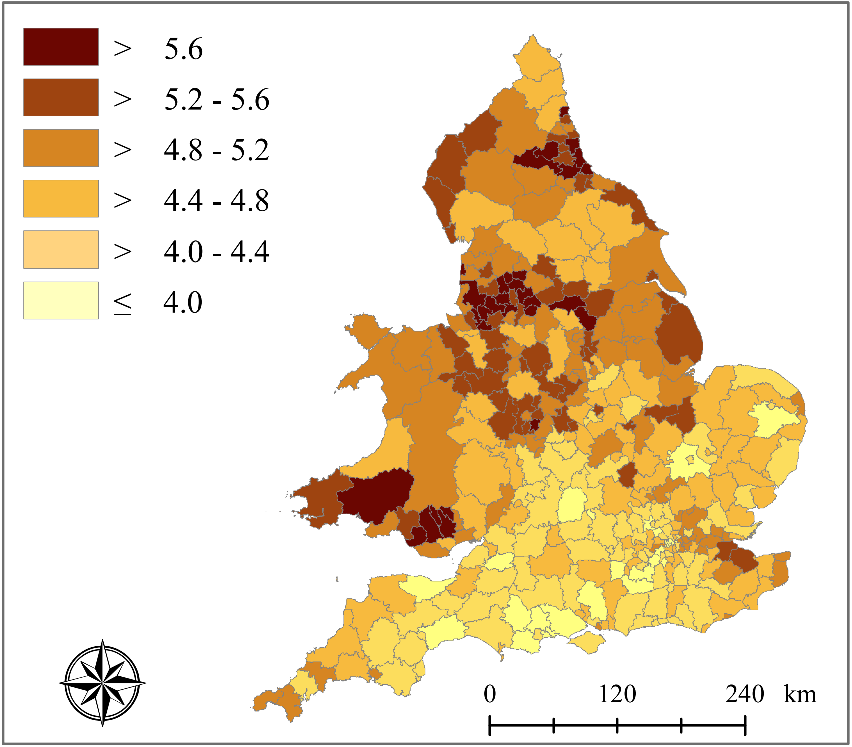
Table S2. National-level percentage increase in the odds of cardio-respiratory death for 1°C decrease in mean daily winter (November-March) temperature below district-specific thresholds. Numbers in brackets show 95% credible intervals, which are the 2.5th and 97.5th percentiles of the posterior distributions of effect size parameters from the Bayesian model. See Table 1 in the main paper for summer results.

Age Group	Men	Women
< 75 years	2.8 (2.3, 3.3)	3.5 (2.9, 4.3)
75-84 years	3.4 (2.9, 3.9)	4.0 (3.5, 4.5)
85+ years	3.9 (3.3, 4.4)	3.8 (3.3, 4.3)

Table S3. Number of fewer cardio-respiratory deaths that would be expected during 5 winter months if temperatures were warmer by 2°C by broad regions. See Table 2 in the main paper for summer results.

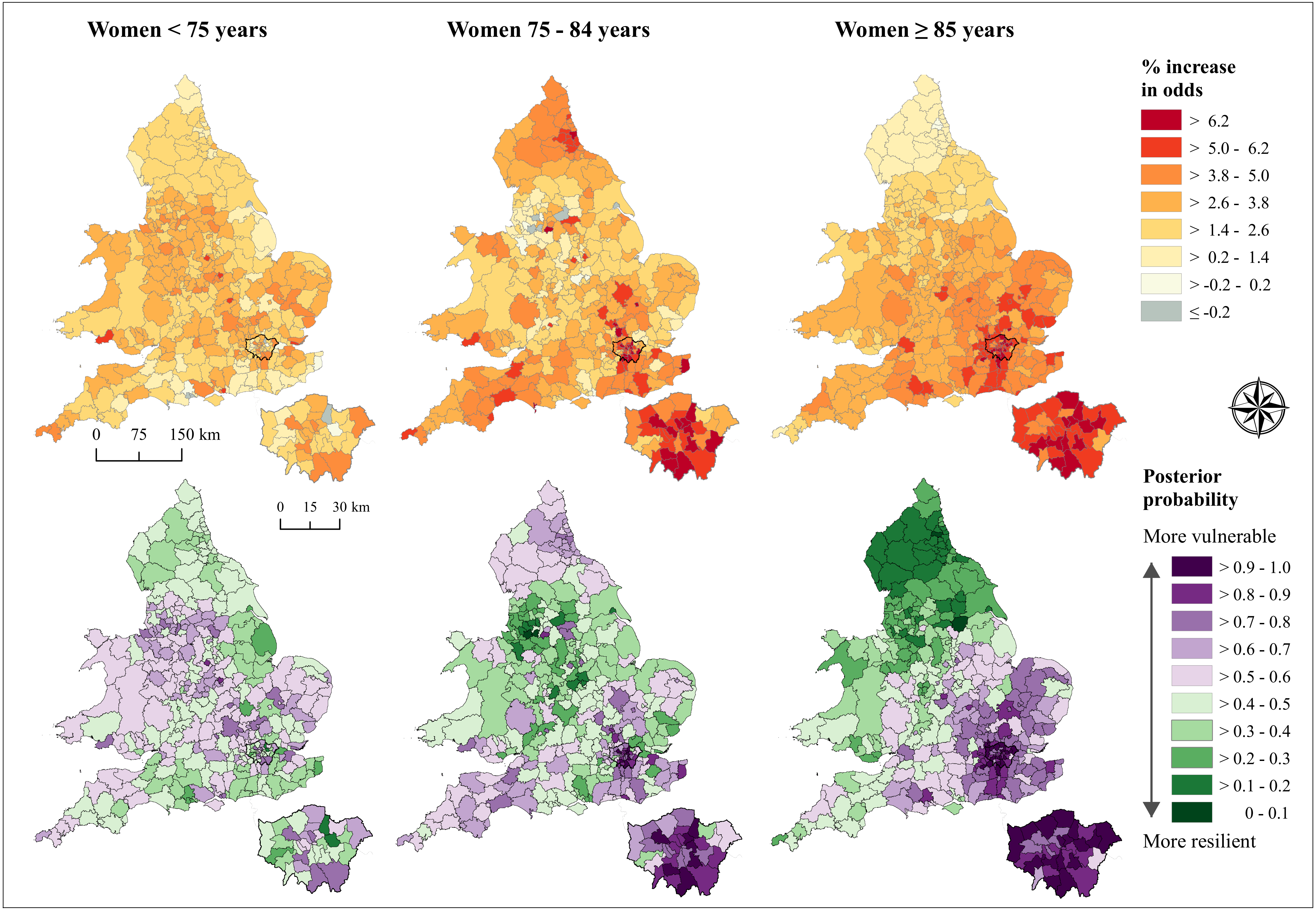
Region	Number of deaths (95% credible interval)
Southern England (South East, South West, London, and East of England)	2,997 (2,817, 3,163)
Midlands (East Midlands, West Midlands)	1,175 (1,087, 1,290)
Northern England (North East, North West, Yorkshire and the Humber)	1,683 (1,536, 1,818)
Wales	399 (347, 451)
Total	6,255 (5,963, 6,581)

Figure S1. Age- and sex-standardised cardio-respiratory death rates per 1000 per year for the 376 districts in England and Wales over the period 2001 to 2010.



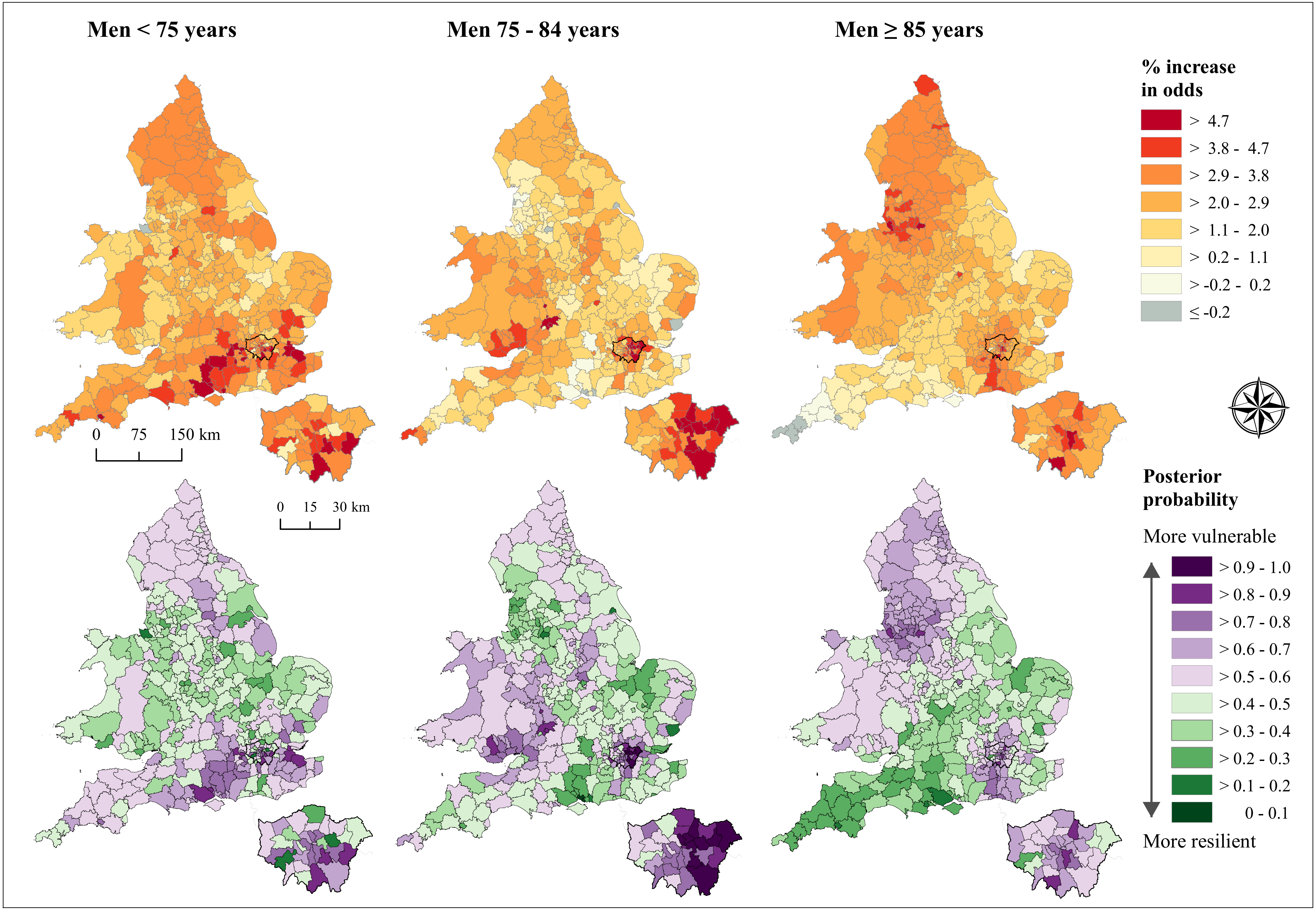
> 5.6
> 5.2 - 5.6
> 4.8 - 5.2
> 4.4 - 4.8
> 4.0 - 4.4
≤ 4.0
0
120
240
km

Figure S2. Percentage increase in the odds of cardio-respiratory death (women) for 1°C increase in mean daily summer temperature above a common temperature threshold of 18°C, and the posterior probabilities (PP) that the estimated effect size is different from the national average. See Figure 1 in the main paper for results with district-specific thresholds.



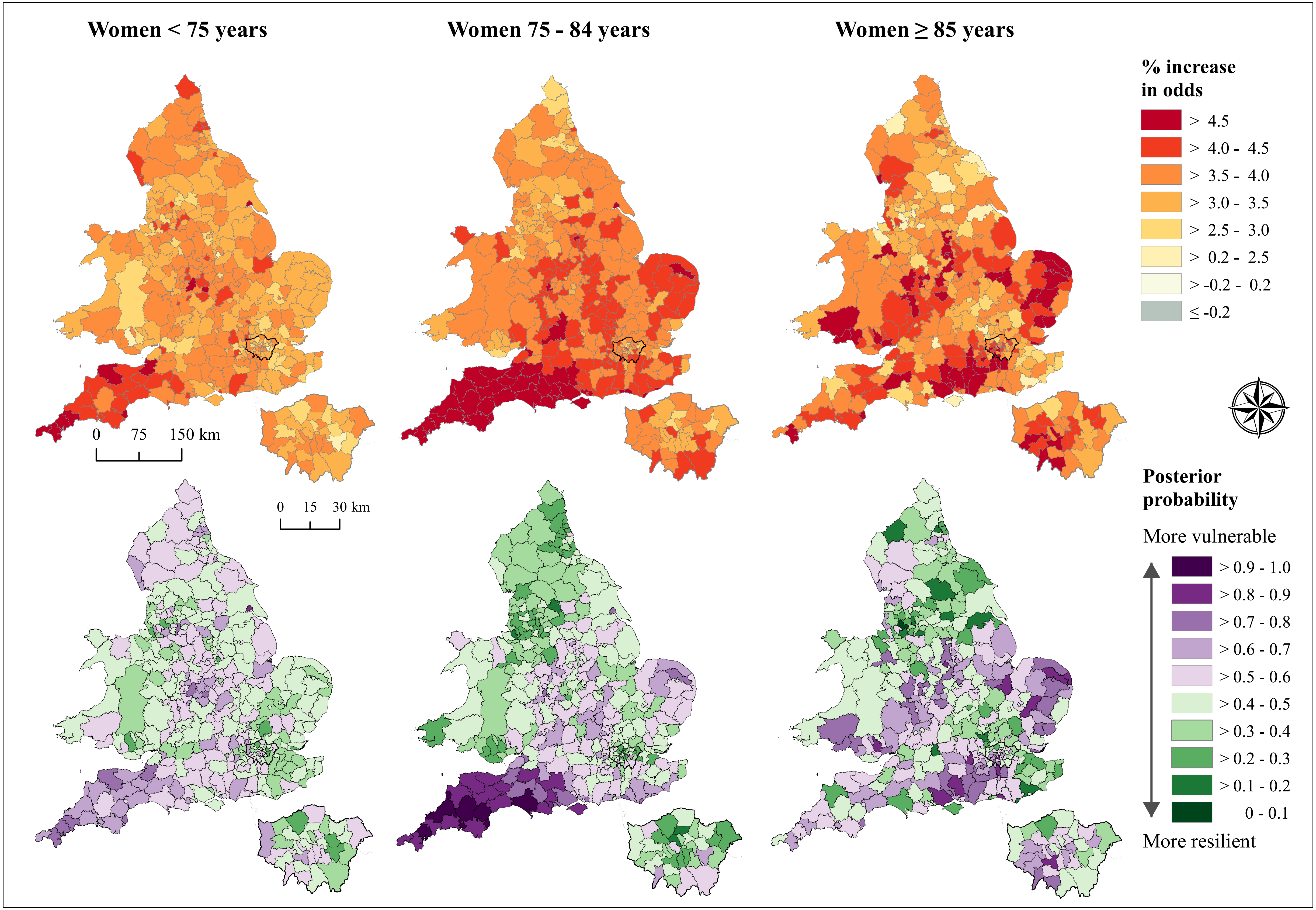
Women < 75 years
Women 75 - 84 years
Women ≥ 85 years
% increase in odds
> 6.2
> 5.0 - 6.2
> 3.8 - 5.0
> 2.6 - 3.8
> 1.4 - 2.6
> 0.2 - 1.4
> -0.2 - 0.2
≤ -0.2
0 75 150 km
0 15 30 km
Posterior probability
More vulnerable
> 0.9 - 1.0
> 0.8 - 0.9
> 0.7 - 0.8
> 0.6 - 0.7
> 0.5 - 0.6
> 0.4 - 0.5
> 0.3 - 0.4
> 0.2 - 0.3
> 0.1 - 0.2
0 - 0.1
More resilient

Figure S3. Percentage increase in the odds of cardio-respiratory death (men) for 1°C increase in mean daily summer temperature above a common temperature threshold of 18°C, and the posterior probabilities (PP) that the estimated effect size is different from the national average. See Figure 2 in the main paper for results with district-specific thresholds.



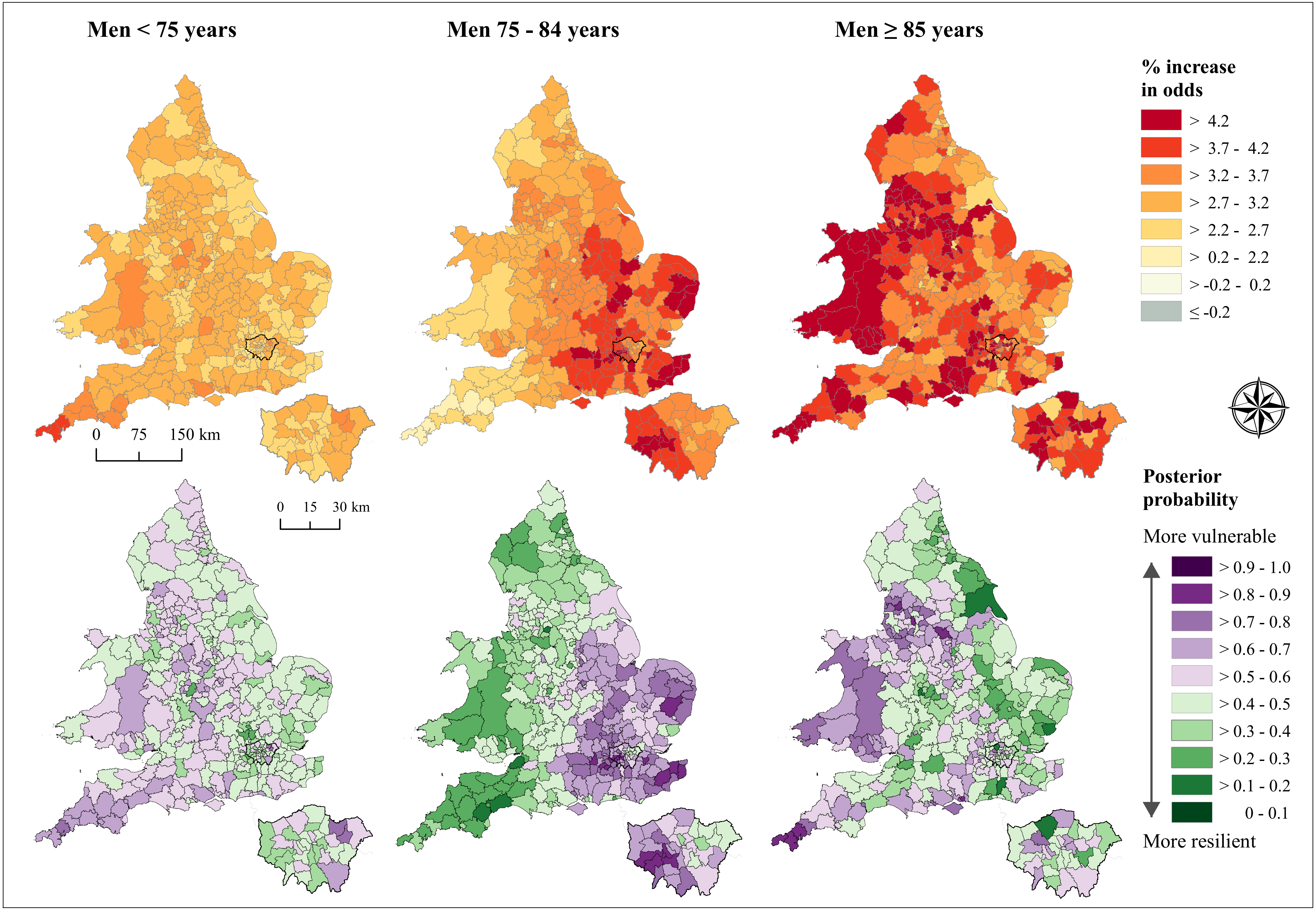
Men < 75 years
Men 75 - 84 years
Men ≥ 85 years
% increase in odds
> 4.7
> 3.8 - 4.7
> 2.9 - 3.8
> 2.0 - 2.9
> 1.1 - 2.0
> 0.2 - 1.1
> -0.2 - 0.2
≤ -0.2
0 75 150 km
0 15 30 km
Posterior probability
More vulnerable
> 0.9 - 1.0
> 0.8 - 0.9
> 0.7 - 0.8
> 0.6 - 0.7
> 0.5 - 0.6
> 0.4 - 0.5
> 0.3 - 0.4
> 0.2 - 0.3
> 0.1 - 0.2
0 - 0.1
More resilient

Figure S4. Percentage increase in the odds of cardio-respiratory death (women) for 1°C decrease in mean daily winter (November-March) temperature below district-specific thresholds, and the posterior probabilities (PP) that the estimated effect size is different from the national average. See Figure 1 in the main paper for summer results.



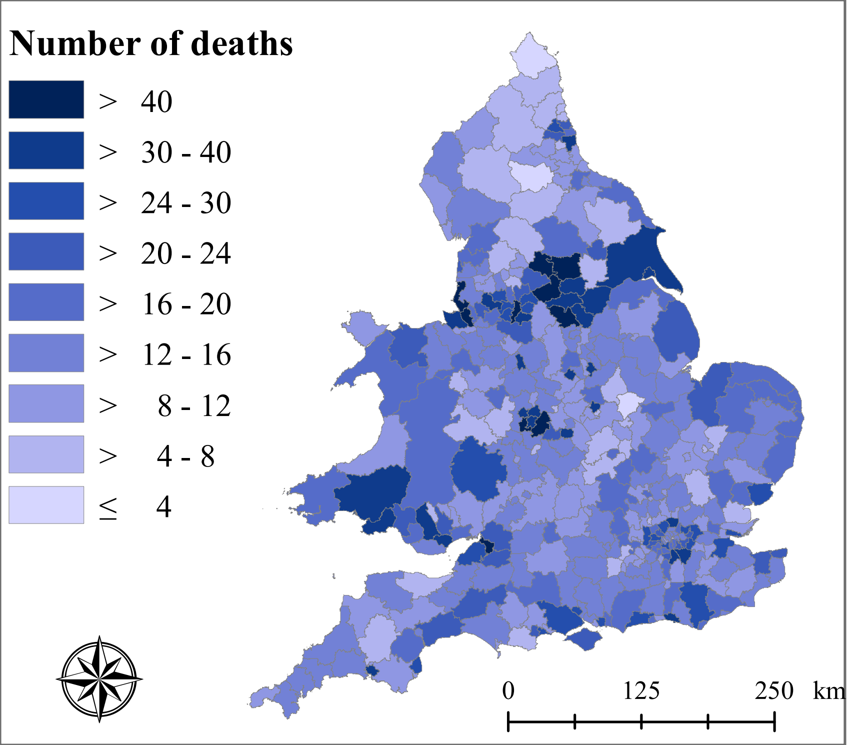
Women < 75 years
Women 75 - 84 years
Women ≥ 85 years
% increase in odds
> 4.5
> 4.0 - 4.5
> 3.5 - 4.0
> 3.0 - 3.5
> 2.5 - 3.0
> 0.2 - 2.5
> -0.2 - 0.2
≤ -0.2
0 75 150 km
0 15 30 km
Posterior probability
More vulnerable
> 0.9 - 1.0
> 0.8 - 0.9
> 0.7 - 0.8
> 0.6 - 0.7
> 0.5 - 0.6
> 0.4 - 0.5
> 0.3 - 0.4
> 0.2 - 0.3
> 0.1 - 0.2
0 - 0.1
More resilient

Figure S5. Percentage increase in the odds of cardio-respiratory death (men) for 1°C decrease in mean daily winter (November-March) temperature below district-specific thresholds, and the posterior probabilities (PP) that the estimated effect size is different from the national average. See Figure 2 in the main paper for summer results.



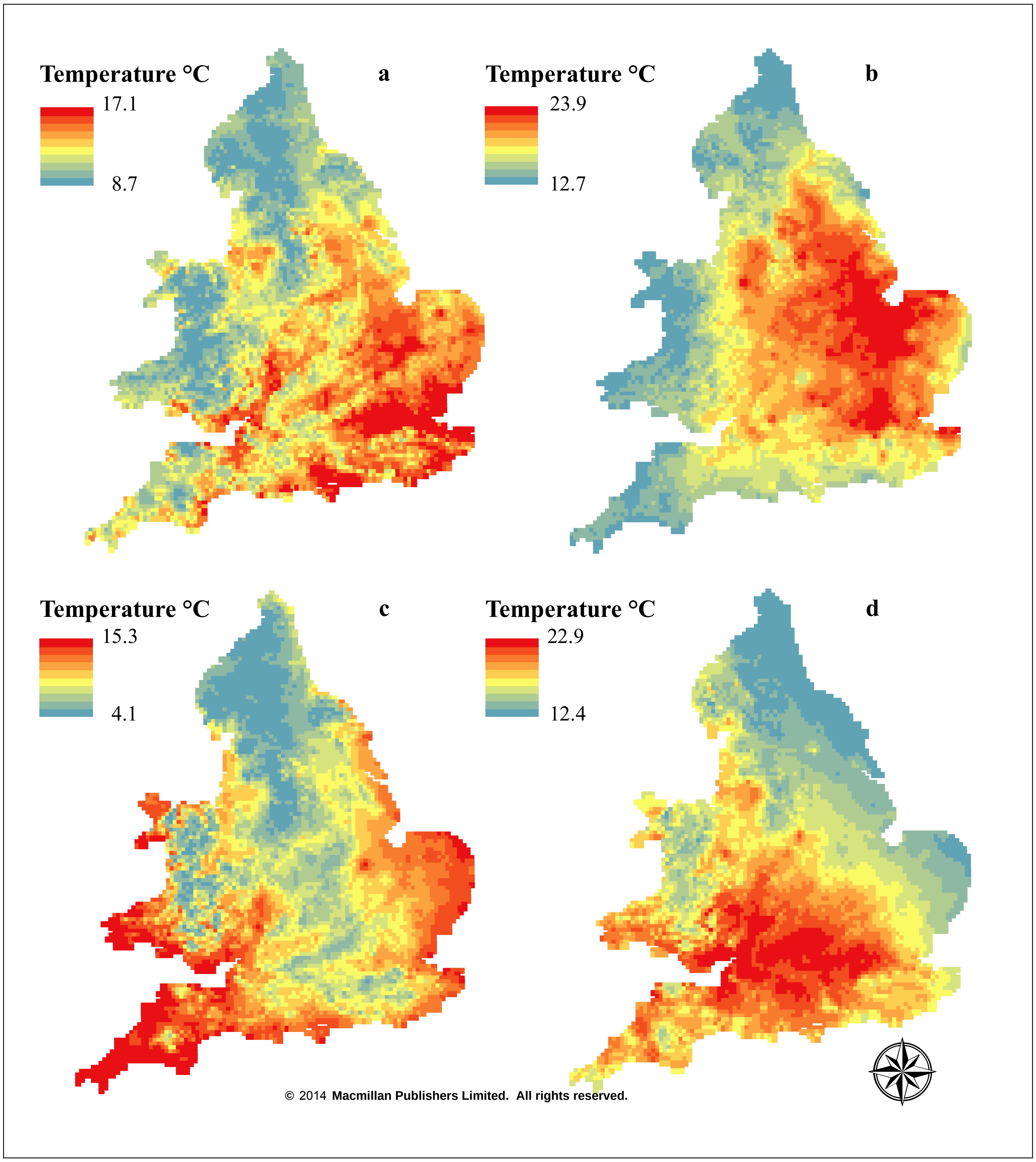
Men < 75 years
Men 75 - 84 years
Men ≥ 85 years
% increase in odds
> 4.2
> 3.7 - 4.2
> 3.2 - 3.7
> 2.7 - 3.2
> 2.2 - 2.7
> 0.2 - 2.2
> -0.2 - 0.2
≤ -0.2
0 75 150 km
0 15 30 km
Posterior probability
More vulnerable
> 0.9 - 1.0
> 0.8 - 0.9
> 0.7 - 0.8
> 0.6 - 0.7
> 0.5 - 0.6
> 0.4 - 0.5
> 0.3 - 0.4
> 0.2 - 0.3
> 0.1 - 0.2
0 - 0.1
More resilient

Figure S6. The expected reduction in the number cardio-respiratory deaths in England and Wales's districts that would be expected during 5 winter months (November-March) if temperatures were warmer by 2°C. See Figure 3 in the main paper for summer results.



Number of deaths
> 40
> 30 - 40
> 24 - 30
> 20 - 24
> 16 - 20
> 12 - 16
> 8 - 12
> 4 - 8
≤ 4
0
125
250
km

Figure S7. (a) Average temperature over May-September in 2001-2010 and (b), (c), and (d) temperature on individual example days. Comparison of panel (a) with panels (b), (c), and (d) shows that temperature on individual days can have spatial patterns that are substantially different from the seasonal average.


Temperature °C
17.1
8.7
a
Temperature °C
23.9
12.7
b
Temperature °C
15.3
4.1
c
Temperature °C
22.9
12.4
d

References

1 Maclure, M. The case-crossover design: a method for studying transient effects on the risk of acute events. *Am J Epidemiol* 133, 144-153 (1991).

2 Janes, H., Sheppard, L. & Lumley, T. Overlap bias in the case-crossover design, with application to air pollution exposures. *Stat Med* 24, 285-300 (2005).

3 Armstrong, B. G. *et al.* Association of mortality with high temperatures in a temperate climate: England and Wales. *J Epidemiol Community Health* 65, 340-345 (2011).

4 Basu, R. High ambient temperature and mortality: a review of epidemiologic studies from 2001 to 2008. *Environ Health* 8, 40 (2009).

5 Baccini, M. *et al.* Heat Effects on Mortality in 15 European Cities. *Epidemiology* 19, 711-719 (2008).

6 Hajat, S., Kovats, R. S. & Lachowycz, K. Heat-related and cold-related deaths in England and Wales: who is at risk? *Occup Environ Med* 64, 93-100 (2007).

7 Gasparrini, A., Armstrong, B., Kovats, S. & Wilkinson, P. The effect of high temperatures on cause-specific mortality in England and Wales. *Occup Environ Med* 69 (2012).

8 Yu, W. *et al.* Time course of temperature effects on cardiovascular mortality in Brisbane, Australia. *Heart* 97, 1089-1093 (2011).

9 Basu, R. & Samet, J. M. Relation between elevated ambient temperature and mortality: a review of the epidemiologic evidence. *Epidemiol Rev* 24, 190-202 (2002).

10 Agresti, A. *Categorical Data Analysis*. (John Wiley & Sons, 1990).

11 Besag, J., York, J. & Mollie, A. Bayesian Image-Restoration, with 2 Applications in Spatial Statistics. *Ann I Stat Math* 43, 1-20 (1991).

12 Anderson, B. G. & Bell, M. L. Weather-related mortality: how heat, cold, and heat waves affect mortality in the United States. *Epidemiology* 20, 205-213 (2009).

13 Armstrong, B. Models for the relationship between ambient temperature and daily mortality. *Epidemiology* 17, 624-631 (2006).

14 Analitis, A. *et al.* Effects of cold weather on mortality: results from 15 European cities within the PHEWE project. *Am J Epidemiol* 168, 1397-1408 (2008).

15 Gasparrini, A. & Armstrong, B. Reducing and meta-analysing estimates from distributed lag non-linear models. *BMC medical research methodology* 13, 1 (2013).

16 Al-Aidarous, F. *Space-time exposure modelling of troposheric O3 in Europe.* Doctor of Philosophy (PhD) thesis, Imperial College London, London, (2013).