Small-area assessment of temperature-related mortality risks in England and Wales: a case time series analysis

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Summary

Background Epidemiological literature on the health risks associated with non-optimal temperature has mostly reported average estimates across large areas or specific population groups. However, the heterogeneous distribution of drivers of vulnerability can result in local differences in health risks associated with heat and cold. We aimed to analyse the association between ambient air temperature and all-cause mortality across England and Wales and characterise small scale patterns in temperature-related mortality risks and impacts.

Methods We performed a country-wide small-area analysis using data on all-cause mortality and air temperature for 34 753 lower super output areas (LSOAs) within 348 local authority districts (LADs) across England and Wales between Jan 1, 2000, and Dec 31, 2019. We first performed a case time series analysis of LSOA-specific and age-specific mortality series matched with 1×1 km gridded temperature data using distributed lag non-linear models, and then a repeated-measure multivariate meta-regression to pool LAD-specific estimates using area-level climatological, socioeconomic, and topographical predictors.

Findings The final analysis included 10 716 879 deaths from all causes. The small-area assessment estimated that each year in England and Wales, there was on average 791 excess deaths (empirical 95% CI 611–957) attributable to heat and 60 573 (55 796–65 145) attributable to cold, corresponding to standardised excess mortality rates of 1·57 deaths (empirical 95% CI 1·21–1·90) per 100 000 person-years for heat and 122·34 deaths (112·90–131·52) per 100 000 person-years for cold. The risks increased with age and were highly heterogeneous geographically, with the minimum mortality temperature ranging from 14·9°C to 22·6°C. Heat-related mortality was higher in urban areas, whereas cold-related mortality showed a more nuanced geographical pattern and increased risk in areas with greater socioeconomic deprivation.

Interpretation This study provides a comprehensive assessment of excess mortality related to non-optimal outdoor temperature, with several risk indicators reported by age and multiple geographical levels. The analysis provides detailed risk maps that are useful for designing effective public health and climate policies at both local and national levels.

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Introduction

Several epidemiological studies have analysed the association between air temperature and mortality.[1–3] These studies have reported that the relationship in temperate climates is usually inverse J-shaped, with a higher risk of mortality from all causes in the presence of high or low temperatures, and the minimum risk observed at mild hot ranges.[4] Exposure to non-optimal outdoor temperatures affects the whole population and has been associated with substantial excess mortality, which, in the absence of adaptation, is expected to increase under the projected climate-change trends.[5]

Although these findings are consistent across the literature, the estimated excess mortality risks show substantial geographical heterogeneity.[6] This variability is likely to be dependent on the distribution of drivers of risk linked to individual and contextual characteristics, such as socioeconomic and demographic factors, housing conditions, and urban features.[7,8] The characterisation of such geographical patterns is a crucial step to map differences in health impacts and identify hotspot areas, as well as to design local and national interventions to attenuate present and future risks.[9]

Known barriers in this area of research include limitations in the availability of the relevant data and in their spatial and temporal resolution, as well as in study designs and statistical and computational methods. Previous studies have mainly relied on data aggregated at a broad spatial level, and were thus not able to show small-scale spatial contrasts to identify area-level risks.[10–12] Conversely, small-area analyses have mostly focused on selected urban areas, and often have low statistical power and representativeness.[13–17] Only a few studies have performed large-scale analyses using high-resolution data; however, they have relied on effect summaries that provide limited information on the complex risk

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Research in context

Evidence before this study

We searched PubMed in July, 2021, restricting the search to articles published in English from Jan 1, 2000, to July, 2021, using the terms ("temperature*" OR "heat" OR "cold") AND ("mortality" AND "risk"). Several epidemiological studies have assessed the association between non-optimal ambient temperature and mortality, and have consistently reported increased all-cause mortality risks with both heat and cold. However, most of these studies relied on analyses using largely aggregated data or limited effect summaries, which has so far prevented a thorough characterisation of temperature-related mortality risks and related impacts, and the identification of small-scale differences in vulnerability.

Added value of this study

This study applied innovative design and statistical techniques to perform a small-area assessment of temperature-related mortality risks in England and Wales using high-resolution exposure and health data. This analysis offers a full characterisation of the association between temperature and all-cause mortality, with estimates of heat and cold-related risks, excess mortality and standardised rates, and optimal temperatures corresponding to minimum mortality risk, by age and geographical areas. The output of the analysis includes detailed maps of mortality risk defined by multiple effect summaries for each of the 34 753 small areas and higher geographical levels of aggregation.

Implications of all the available evidence

This analysis offers a comprehensive picture of the all-cause mortality risks associated with non-optimal temperature across the whole geographical domain of England and Wales. The provision of high-resolution risk estimates including age-specific and age-standardised excess mortality rates for both heat and cold allows a fine geographical comparison and the identification of high-risk areas. This evidence is crucial for designing national and local public health and climate policies.

associations with non-optimal temperature.[18–20] More importantly, these studies have not considered that variations in mortality risk are likely to be related to contributions of strongly correlated area-level factors that can lead to distinct geographical differences in risk.

We aimed to analyse the association between ambient air temperature and all-cause mortality across England and Wales, using novel methodologies that allow the linkage and analysis of high-resolution data and the identification of small-scale risks patterns across the whole geographical domain.

Methods

Study design

We conducted a case time series analysis using an extended version of the two-stage design previously proposed for multilocation time series studies,[6] adapted here to model country-wide small-area data. Additional algebraic and technical details of the study design are provided in the appendix (pp 1, 2–4). Informed consent was not required as the data were collected administratively by the Office of National Statistics (ONS) and provided to the research team following a specific application and agreement. The project obtained favourable ethical opinion by the Microdata Release Panel of ONS (data access agreement MRP 2291/2013) and the Research Ethics Committee of the London School of Hygiene & Tropical Medicine (reference 28043).

See **Online** for appendix

Procedures

We collected time series daily data on all-cause mortality and air temperature for 34753 lower super output areas (LSOAs) within 348 local authority districts (LADs) across England and Wales between Jan 1, 2000, and Dec 31, 2019. LSOAs are census-based aggregation units that included, on average, 1600 residents, nested within the LADs. Individual mortality data with LSOA identifiers were provided by ONS, and aggregated as LSOA-specific daily series of all-cause mortality counts. Daily mean values of air temperatures on a 1×1 km grid across the UK were extracted from the HadUK-Grid database, developed by the UK Meteorological Office.[21] We derived the corresponding LSOA-specific daily temperature series by computing the area-weighted average of the values of all the grid cells intersecting the LSOA boundaries, with weights proportional to the intersection areas.

We then built an integrated dataset with measures on several characteristics that are potentially linked with differential vulnerability to heat or cold. The dataset included 15 variables on demographic (proportion of population aged older than 65 years and population density), socioeconomic (measures of income, employment, and education), health and disability (score), housing and neighbourhood (access to housing or services, proportion of home central heating, average age of buildings, living environment score), landscape (albedo, surface imperviousness degree, enhanced vegetation index), and climatological (average annual range of temperature) characteristics. Additionally, we gathered the index of multiple deprivation (IMD) and urban or rural classification for each area. These small-area variables were derived for each LSOA and then aggregated at LAD level using population-weighted averages. Details on data sources and definitions are provided in the appendix (pp 1–2).

Geographical patterns of vulnerability to non-optimal temperature can depend on some of the variables included in this dataset. To maximise the prediction power and to analyse the joint effects of potentially correlated characteristics, we combined the 15 small-area variables in a principal component analysis (PCA).[22] This methodology is commonly used to reduce the dimensionality of a dataset by computing a new set of uncorrelated variables, the principal components, ordered so that the first few retain most of the information present in the original variables. These components were used as composite indicators of vulnerability to determine geographical differences in risks.

Statistical analysis

We estimated the association between temperature and all-cause mortality across small areas using a two-stage analysis followed by a downscaling procedure. In the first stage, we applied the novel case time series design, modelling multiple LSOA-specific series within each LAD through a conditional Poisson regression.[23,24] The model was fitted separately for the four age groups of 0–64 years, 65–74 years, 75–84 years, and 85 years or older. The LAD-specific and age-specific first-stage model included terms to flexibly control for long-term and seasonal trends at both LSOA and LAD levels, and indicators of days of the week. Temperature–mortality associations were modelled through distributed lag non-linear models (DLNMs), a flexible technique to estimate complex non-linear and lagged dependencies.[25] The lag window was defined as 0–21 days, to capture both the long delay of cold effects and the potential mortality displacement during hot periods.

In the second stage, we reduced the association to the overall temperature–mortality association, cumulating the risk over the lag dimension. Then, we pooled the estimated coefficients for the four age groups and the 348 LADs using a multivariate repeated-measure meta-regression.[26] The second-stage model included age and PCA indicators as meta-predictors to explain variations across LADs, with their contribution evaluated by likelihood ratio tests. The residual heterogeneity was assessed by the multivariate extension of Cochran's Q test and I^2 statistic.[26] Technical and methodological details are provided in the appendix (pp 2–4).

As a final step, we used the meta-analytical model from the second stage to downscale the risks at the LSOA level, given the combination of PCA vulnerability indicators defined by values of small-area variables at the corresponding spatial scale. We first derived LSOA-specific temperature–mortality curves, from which we identified the minimum mortality temperature (MMT) and MMT-related percentile (MMP) as the lowest point in the range from 1st to 99th percentile. The MMT and MMP were assumed to be the optimal reference temperature. We then summarised the risk for heat and cold by computing the relative risk (RR) and related 95% CI at the 99th temperature percentile versus the MMT and the 1st temperature percentile versus the MMT. We finally derived a measure of the effect of heat and cold by estimating the age-specific excess mortality (total number and fraction of deaths) attributable to temperatures higher than the MMT and lower than the MMT, respectively, following a previously described method.[27] These quantities were used to compute the standardised rate of excess all-cause mortality, using the 2013 European Standard Population as the reference. The related uncertainty was quantified as empirical CI using Monte Carlo simulations, adapting the computation to account for correlations due to dependencies in the downscaled risks (appendix p 3).

The rationale for developing such a complex study design, with two levels of analysis (LAD first and downscaling at LSOA) and the use of composite vulnerability indicators from PCA, was two-fold. First, this framework allows the use of data and the estimation of risk associations at the highest possible resolution without requiring the fit of LSOA-specific models, which would be unfeasible given the low number of deaths in each unit. Second, the definition of a few selected indicators through PCA reduction allows for the identification of vulnerability patterns related to the combination of multiple small-area characteristics, avoiding arbitrary selections or computational problems that can arise in the presence of a long list of factors.

All statistical analyses were performed with R (version 4.1.2), using the *dlnm* and *mixmeta* packages.

Role of the funding source

The funders of the study had no role in study design, data collection, data analysis, data interpretation, or writing of the report.

Results

The final analysis included 10 716 879 deaths from all causes that occurred in 2000–19; approximately 535 844 deaths per year. Table 1 shows descriptive

	LADs	LSOAs	Mean deaths per year	Population-weighted daily mean temperature, °C*
North East	12	1657	28 519	9·7 (–8·0 to 24·7)
North West	39	4497	73 829	10·3 (–9·7 to 27·1)
Yorkshire and The Humber	21	3317	52 968	10·1 (–10·4 to 26·5)
East Midlands	40	2774	44 508	10·3 (–9·1 to 27·3)
West Midlands	30	3487	55 162	10·3 (–11·0 to 26·0)
East of England	47	3614	55 952	10·8 (–8·4 to 27·8)
London	33	4835	53 333	11·6 (–6·5 to 29·5)
South East	67	5382	81 317	11·0 (–8·9 to 28·6)
South West	37	3281	56 507	11·0 (–10·7 to 26·8)
Wales	22	1909	33 747	10·4 (–9·0 to 27·0)
England and Wales	348	34 753	535 844	10·7 (–11·0 to 29·5)

Data are n or mean (range). LAD=local authority district. LSOA=lower super output area. *Computed as the weighted average of annual mean temperature across the LSOAs in the region, with weights proportional to the resident population.

***Table 1:* Descriptive statistics by regions of England and Wales for the period 2000–19**

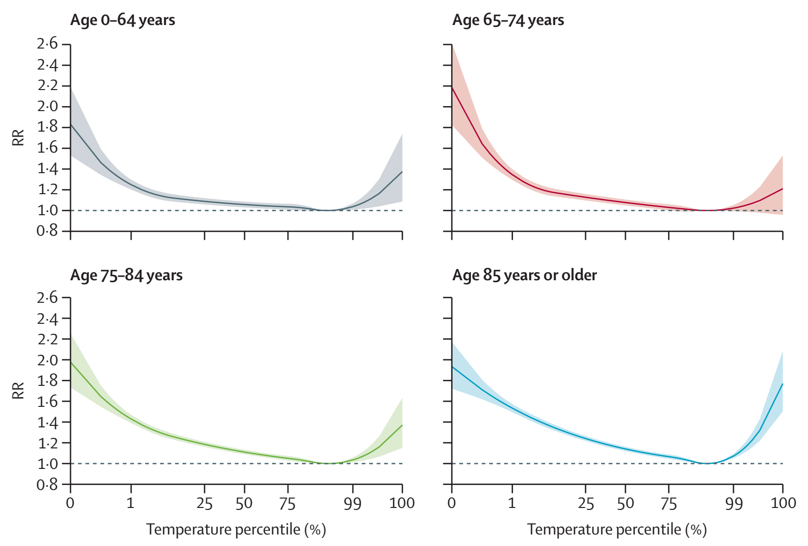

Figure 1: **Pooled estimates of the overall cumulative exposure–response relationships between temperature percentile and all-cause mortality by age group**

Temperature percentile used an average temperature distribution. Shaded areas on the curves are 95% CI. RR=relative risk.

	Annual excess deaths		Standardised excess mortality rate, deaths per 100 000 person-years	
	Cold	Heat	Cold	Heat
North East	3260 (2710–3749)	23 (2–42)	140·45 (117·01–161·01)	1·02 (0·11–1·80)
North West	7849 (6996–8611)	79 (43–109)	128·54 (114·98–140·60)	1·27 (0·70–1·76)
Yorkshire and The Humber	5857 (5321–6373)	56 (34–75)	126·88 (115·51–137·87)	1·20 (0·73–1·60)
East Midlands	4921 (4444–5406)	50 (33–66)	121·29 (109·72–133·13)	1·23 (0·80–1·62)
West Midlands	5913 (5411–6391)	101 (77–124)	119·11 (109·05–128·52)	2·02 (1·53–2·45)
East of England	6414 (5832–6984)	78 (55–98)	115·72 (105·20–126·05)	1·38 (0·97–1·76)
London	5768 (4926–6551)	170 (131–210)	113·97 (97·43–129·03)	3·21 (2·47–3·97)
South East	9620 (8797–10 431)	140 (103–174)	117·17 (107·14–127·22)	1·69 (1·23–2·10)
South West	6941 (6141–7713)	63 (29–87)	122·04 (107·72–135·85)	1·09 (0·49–1·52)
Wales	4030 (3622–4427)	31 (15–43)	136·95 (123·26–150·58)	1·04 (0·51–1·47)
England and Wales	60 573 (55 796–65 145)	791 (611–957)	122·34 (112·90–131·52)	1·57 (1·21–1·90)

Data are point estimate (empirical 95% CI).

Table 2: **Annual excess deaths and standardised excess mortality rates attributable to cold and heat by regions of England and Wales in the period 2000–19**

statistics for temperature and mortality data in the ten regions of England and Wales (appendix p 9 shows the geographical subdivisions for the regions). As expected, temperature was characterised by a geographical gradient, with mean daily values across LSOAs increasing from 9·7°C (range –8·0 to 24·7) in the North East region to 11·0°C (–8·9 to 28·6) in the South East region and 11·0°C (–10·7 to 26·8) in the South West region, and reaching a peak of 11·6°C (–6·5 to 29·5) in the London region.

Figure 1 shows the pooled estimates of the overall cumulative exposure–response relationship by age group, predicted at the mean value of the other meta-regressors. The pooled curves show the usual inverse-J shape, with a relatively high average MMP, corresponding to the 95th temperature percentile, and increased risks at both cold and hot temperatures. There was a clear age gradient, showing increases in both cold-related and heat-related risks, with the RR rising from 1·249 (95% CI 1·202–1·298) at the 1st percentile and 1·038 (1·008–1·069) at the 99th percentile in people aged 0–64 years to 1·553 (95% CI: 1·495–1·573) at the 1st percentile and 1·072 (95% CI: 1·050–1·095) at the 99th percentile in people aged 85 years or older. The curves had slightly different shapes for each age group, with older people showing higher risks with moderately cold temperature and steeper heat-related risks. The age stratification, together with the inclusion of the PCA indicators, explains eventually all of the variation in risks across LADs, with little evidence of residual heterogeneity (Cochran's *Q* test p=0·45; I^2=0·2%).

The 15 small-area variables showed various degrees of correlation, with the Pearson *r* statistic ranging from –0·70 to 0·96, similarly at LAD and LSOA levels (appendix p 7). The optimal number of components from the PCA was identified by minimising the Akaike information criterion (AIC) in the meta-regression. The first three components, which accounted for 70·8% of the overall variation (appendix pp 7–8), were selected as vulnerability indicators and were included as meta-regressors in the second-stage model. A likelihood ratio test indicated that these three components were significantly associated with differential risks of non-optimal temperature (p=0·0019). The model was then used to predict risks and excess deaths downscaled at LSOA level.

Our analysis showed marked geographical differences in excess mortality associated with heat and cold, both at regional and small-area scales. Table 2 shows the estimates across the ten regions in England and Wales and overall. On average across the study period and in the whole of England and Wales, non-optimal temperature was associated with 791 excess deaths (empirical 95% CI 611–957) each year for heat and 60 573 excess deaths (55 796–65 145) each year for cold, corresponding to a standardised excess all-cause mortality rate of 1·57 deaths (empirical 95% CI 1·21–1·90) per 100 000 person-years for heat and 122·34 deaths (112·90–131·52) per 100 000 person-years for cold.

Figure 2 shows the standardised excess mortality rates across the ten regions, by IMD quintile, and by rural or urban classification. Heat-related excess mortality varied to some extent by region and reached a maximum of 3·21 deaths (empirical 95% CI 2·47–3·97) per 100 000 person-years in London, while standardised excess mortality rates associated with cold were lowest in the southern regions. The effect of non-optimal temperature was correlated with the deprivation score of the area, and the standardised excess mortality associated with cold (and, to a lesser extent, the excess mortality associated with heat) was higher in areas with greater socioeconomic deprivation. The heat-related standardised excess mortality rate varied substantially across rural and urban categories, with greater rates in conurbations, while cold-related mortality was slightly higher in rural areas than in urban areas. The same comparison in terms of (non-standardised) excess fraction of deaths is reported in the appendix (p 10).

Figure 3 shows the downscaled LSOA-specific heat-related and cold-related standardised mortality rates and the MMT across England and Wales, with a focus on Greater London and then on a single LAD corresponding to the Borough of Camden (central London). Corresponding maps of the 15 small-area characteristics, the three PCA indicators, and age-specific RRs are provided in the appendix (pp 5, 11–13), as well as the distribution of several effect summaries across LSOAs by age group (appendix p 5). Heat-related standardised excess mortality rates were highly heterogeneous across LSOAs, ranging from –0·74 deaths per 100 000 person-years to 13·16 deaths per 100 000 person-years, with a higher risk of mortality in inner regions and hotspots in urban areas (figure 3). Standardised excess mortality related to cold ranged from 1·34 deaths per 100 000 person-years to 242·03 deaths per 100 000 person-years (figure 3). The effects of cold were greater in the more remote areas, including in the Northern England, Wales, and South West regions, and cold generally had less effect in urban areas. The MMT varied from 14·9°C to 22·6°C, and showed a clear north-to-south and west-to-east increase pattern (figure 3; corresponding maps of MMP are shown in appendix p 14). The maps for London and the Borough of Camden showed high small-scale variation in mortality risks across LSOAs in the same areas, suggesting strong patterns of vulnerability dependent on small-area characteristics. The comparison with equivalent maps at the LAD level (appendix p 15) confirms the advantage of downscaling the risks at a higher geographical resolution.

Discussion

This study provides a country-wide evaluation of the health impact of non-optimal temperature, with a comprehensive assessment of mortality risks across the 37 453 small census areas of England and Wales. Our findings indicate that, on average, an excess of 791 deaths associated with heat and 60 753 deaths associated with cold occur every year in England and Wales, corresponding to a standardised excess mortality rate of 1·57 deaths per 100 000 person-years with heat and 122·34 deaths per 100 000 person-years with cold. The population of England and Wales showed some degree of adaptation to the local climate, with the optimal temperature identified as the MMT ranging from 14·9°C to 22·6°C, and on average was close to the 95th percentile of the local temperature distribution. The analysis revealed strong differentials in temperature-related impacts, with greater mortality associated with cold in northern and western regions, and heat-related risks much greater in urban areas. Older people showed a higher susceptibility to non-optimal temperatures, with the 85 years or older age group having more than twice the mortality risk of people aged 0–64 years, for both heat and cold.

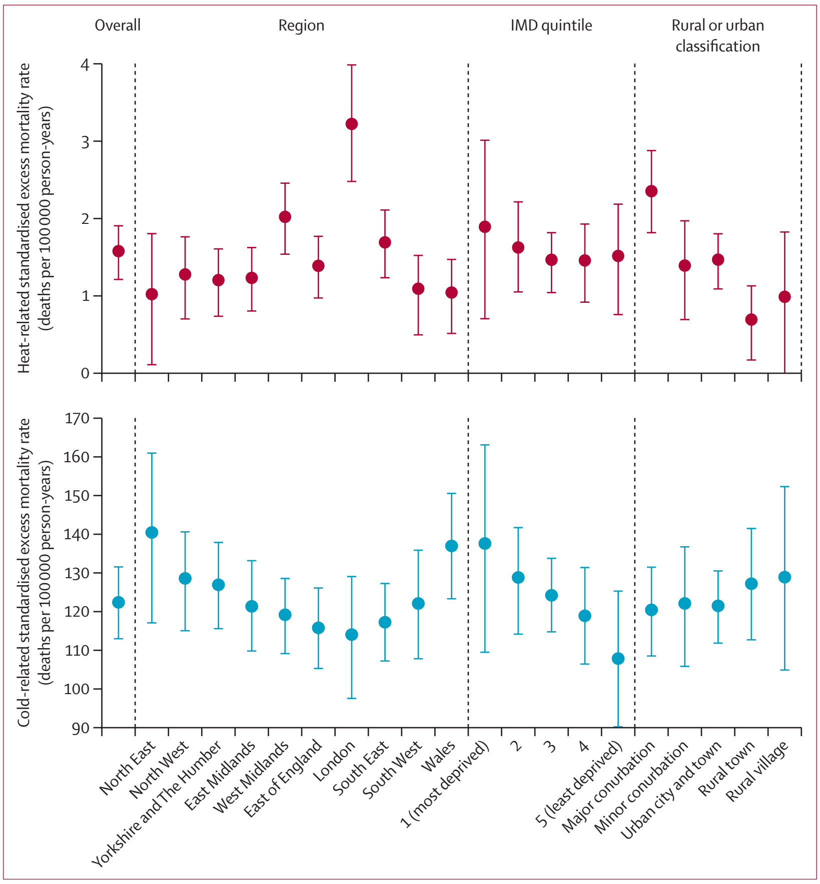

Figure 2: **Standardised excess mortality rates attributable to heat and cold in England and Wales, stratified by region, IMD quintile, and urban or rural classification**

Error bars are empirical 95% CI. IMD=index of multiple deprivation.

An original aspect of this study was the ability to identify differences in health impacts at a small geographical scale, revealing geographical patterns across census units within the same area. These findings support evidence from literature reviews that have reported a considerable heterogeneity in the mortality risks with heat and, to a lesser extent, with cold.[7,8] The results of this study indicate that, after demographic differences had been accounted for, the mortality impacts of both heat and cold were stronger in more deprived areas, consistent with the literature. The analysis by categories of urban or rural classification confirms that heat-related risks were substantially greater in urban areas,[28] while vulnerability to cold showed a more nuanced pattern. On this topic, conflicting evidence has been reported,[29,30] partly due to the use of different temperature indices and risk functions.

Our analysis indicates that the excess in mortality attributable to cold was almost two orders of magnitude

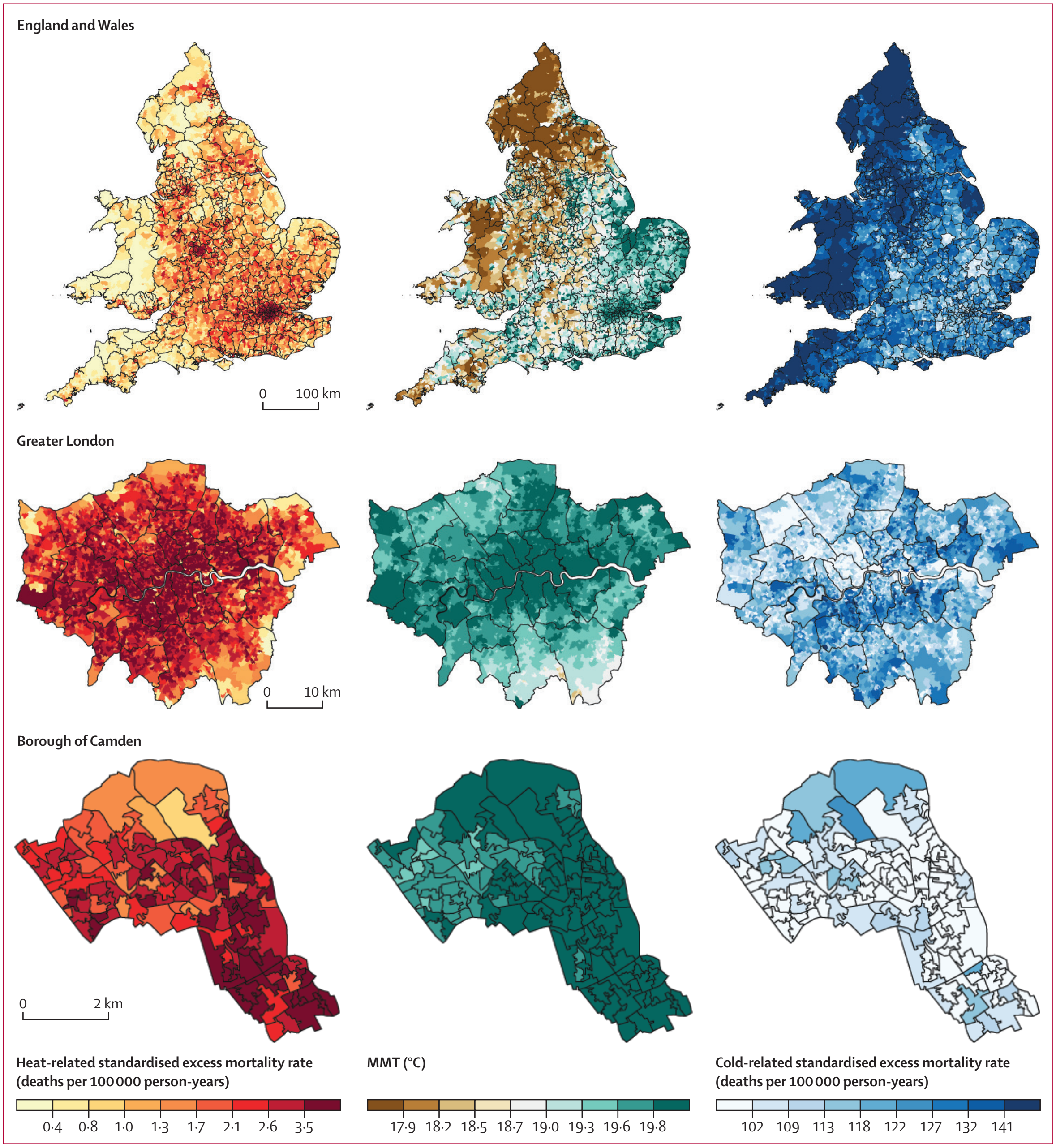

***Figure 3*: Geographical distribution of standardised excess mortality rates attributable to heat and cold and the MMT across LSOAs**

The maps show the distribution across the whole spatial domain of England and Wales, and then with a focus on Greater London and the local authority district corresponding to the Borough of Camden. LSOA=lower super output area. MMT=minimum mortality temperature.

higher than the excess in mortality attributable to heat. While these results are consistent with previous assessments in similar geographical and climatological areas,[6,12] they should be interpreted with caution. The quantification of the effect is dependent on the chosen effect summary, based on a reference corresponding to the MMT. In this analysis, the measured excess was computed versus a counterfactual climate with a constant exposure corresponding on average to the 95th percentile of the observed temperature. Therefore, the majority of days throughout the year were contributing to the cold-related mortality excess, whereas the effect of heat was limited to the few days when temperatures were higher than this relatively warm threshold. Nonetheless, our results suggest that current public health policies related to temperature should be complemented by actions focused on preventing the considerable health burden associated with non-optimal cold temperatures.

This study has several strengths. The innovative study design offered a flexible and computationally efficient analytical framework, making it feasible to perform country-wide analyses using high-resolution measurements assigned at small-area level. Most of the previous studies on temperature–mortality associations were based on time series analyses of largely aggregated data[10–12] or, alternatively, on small-area assessments that only included single cities.[13–17] Additionally, the use of advanced statistical models permitted the inspection of complex features of temperature–health dependencies and the definition of multiple effect summaries, avoiding the use of risk functions depicting approximate associations previously used in large-scale analyses.[18–20] Importantly, geographical differences were modelled through the definition of composite vulnerability indicators, computed as a combination of multiple contextual characteristics, overcoming limitations and potential biases resulting from separate analyses of individual factors.[11,17]

This study also has some limitations. First, the proposed two-stage design and downscaling procedure relied on the assumption that risk patterns identified at LAD level were representative of associations at the lower LSOA scale. However, the similar magnitude and structure of correlation at the two levels (appendix p 7) suggests that this assumption was reasonable. More importantly, while the use of composite PCA indicators offered an efficient method to characterise patterns of risk due to multiple correlated small-area factors, the process prevented the identification of the independent contributions of the actual drivers of risk. Further modelling developments are required to extend the methodology and address this question. Another limitation is that the effect estimates were computed at small-area level and over a relatively long study period, and individual-level factors and potential temporal variations in risks were not accounted for. The results should therefore be interpreted as average effects across the 20-year study period. Additionally, the flexible exposure-lag-response parametrisation ensured that lagged effects and mortality displacement within a period of 3 weeks were accounted for, but the analysis could not estimate by how long deaths were brought forward. Finally, although the analysis made use of high-resolution temperature data linked with small-area information, these are produced by an interpolation procedure of station-based observations, the uncertainty of which was neither quantified nor considered in the analysis.

In conclusion, this study provides a comprehensive assessment of temperature-related mortality risks across England and Wales in the period of 2000–19. The analysis evaluated several features of the associations, reporting multiple effect summaries that characterise the impact of cold and heat, together with optimal temperature. The results, shown at various levels of geographical aggregation and categories of socioeconomic deprivation and rural or urban settings, can be used for informing, targeting, and implementing area-level public health policies and in future epidemiological analyses, as well as for projecting risks and impacts at small-area level under climate-change scenarios.

Contributors

AG and AMV-C conceptualised the study. AG led the funding acquisition, study design, methodology and software development, writing of the manuscript, and general supervision of the study. PM and FS contributed to methodological developments, software implementation, and algebraic results. AG, PM, MS, and AMV-C performed the statistical analysis and summarised the output. AG, MS, AMV-C, and RS collected, cleaned, and prepared the data. AG and PM directly accessed and verified the underlying data. All authors contributed to the interpretation of the results, drafting and editing of the manuscript, and conclusions.
The corresponding author had full access to all the data in the study and had final responsibility for the decision to submit for publication after obtaining approval from all coauthors.

Declaration of interests

We declare no competing interests.

Data sharing

Individual mortality data used to create the LSOA-specific daily time series were provided by the ONS through a specific agreement (MRP 2291/2013). These data cannot be shared by the authors and must be requested directly from the ONS. Daily temperature data over the 1×1 km grid were gathered from the HadUK-Grid database, publicly available through the UK Meteorological Office's Integrated Data Archive System (MIDAS), stored at the Centre for Environmental Data Analysis archive (https://archive.ceda.ac.uk/). Information on the small-area characteristics was gathered from public sources, with links provided in the appendix (p 1). The documented R code for replicating the full analysis and outputs is available from the corresponding author.

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