Temperature Related Mortality in Germany and England and Wales in the 21st Century

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Research Question

Background: Extreme temperatures were accountable for the highest proportion of deaths from natural disasters in Europe in the period of 1970-2012 [1]. Various studies have discussed the effects of climate change and heat waves on mortality [2–8]. The research question we address is how temperature impacts mortality in Germany and England and Wales and if that impact has changed within the first two decades of the 21st century.

Data

The estimation of temperature effects on mortality demands regional daily mortality data. This paper uses German all-cause daily mortality counts for each of the 16 Federal States from the Federal Statistical Office of Germany. The data for England and Wales stem from the Office of National Statistics of the United Kingdom that issues the daily all-cause mortality counts for each of the nine regions of England and the region Wales.

Daily mean-temperatures originate from the German Weather Service and the MET Office Hadley Centre observation datasets. They each contained the means over all weather stations in a region for a day. Temperatures were measured two meters above the ground. The data were trimmed accordingly to cover the observation period from Jan 1st, 2000 to Dec 31st, 2019. For reproducibility of the results, all used data are publicly available.

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Statistical Analysis

The relationship between temperature and mortality was assessed by a two-stage analysis. In a first step, region-specific estimates were modeled. Secondly these were pooled through a meta-analysis framework , compiling an exposure-response relationship for each Germany and England and Wales separately.

The region-specific estimates were modeled by applying a distributed lag model (DLM). Amstrong (2006) and Gasparrini et al. (2010 and 2017) developed this method not only to account for non-linear relationships but also the lag effect of the exposure-response relationship of the temperature-mortality association [9–11]. This method offers built-in model selection procedures whilst flexibly smoothing the shape of the relationship through penalties. This eliminates the bias of a-priori model specifications. The underlying idea of these models is that the risk of mortality y at a specific time point t is defined by the weighted sum of effects of a series of past exposures x_{t-0}, . . . , x_{t-L} experienced over a defined lag period l=0,. . . ,L [12].

A cross-basis defines the two dimensions: the exposure-response relationship and the lag [9]. Our model captures the delay of mortality effect by 25 days after exposure, which caps the lag at L=25. The exposure-response dimension is modelled by the use of penalised splines with nine degrees of freedom (df), while the splines of the lag dimension are determined by 10 df. A natural cubic spline allows to account for seasonal and long-term trends with 10 df per year of observation [9]. In addition, the model controls for the day of the week. The model is doubly penalised which incorporates a ridge penalty. This enables the identification of the lag period even when the model is extended beyond the relevant lag [11].

In addition to the original model, we include the logarithmic size of the exposed population as an offset to account for changes in the mortality data due to changes in the population size.

From the first-stage cumulative exposure-response associations, the attributable risk to each heat and cold was computed. We applied the forward perspective, proposed by Gasparrini and Leone (2014). The attributable fraction interprets with regard to the counterfactual of exposure x=0 as the fraction or number of deaths that will occur after the exposure x in the period of t+L, in comparison to the deaths that would have occurred with exposure x=0 [12]. The fraction is naturally computed as the number of temperature-related deaths by the total number of all deaths in the specified period of time.

In a second step, we pooled the estimated region-specific overall cumulative temperature-mortality associations by using a meta-analytical model[13]. From the pooled region-specific coefficients, an overall exposure response per country was constructed. They are the mean curves of all regions per country, weighted by the precision of each region's estimate. This approach allows for to quantification and comparison of the heterogeneity between the two countries.

As a last step, we conducted our analysis for two periods separately. Each ten year time span had newly estimated exposure-response surfaces, attributable deaths and overall-cumulative pooled exposure response curves to allow a inter-country comparison of possible adaption effects between the periods 2000–2009 and 2010–2019.

Results

Model and Associations: Figure 1 illustrates the three-dimensional exposure-lag-response surface for London, capturing the joint effects of the temperature and the lag on the relative mortality risk. The second row presents two-dimensional slices of the surface, simplifying the interpretation across lag times. At high temperatures, the mortality risk increases immediately and sharply, with the strongest effects observed within the first 0–3 days following exposure to heat. Thereafter, the risk declines and returns to the baseline level within two weeks. In contrast, low temperatures show a delayed and more prolonged impact. A protective effect is observed at very short lags (0–1 days), potentially an effect of mortality displacement. However, mortality risk increases thereafter, peaking around lag days 3–4, and remains elevated for up to three weeks.

The cumulative exposure–response curve for London exhibits the characteristic J-shape, with elevated risks at both temperature extremes. As expected, the tails of the curve at most extreme temperatures are accompanied by wide confidence intervals due to limited observations. The minimum mortality temperature (MMT) for London is estimated at 19.6°C, indicating the temperature at which mortality risk is lowest.

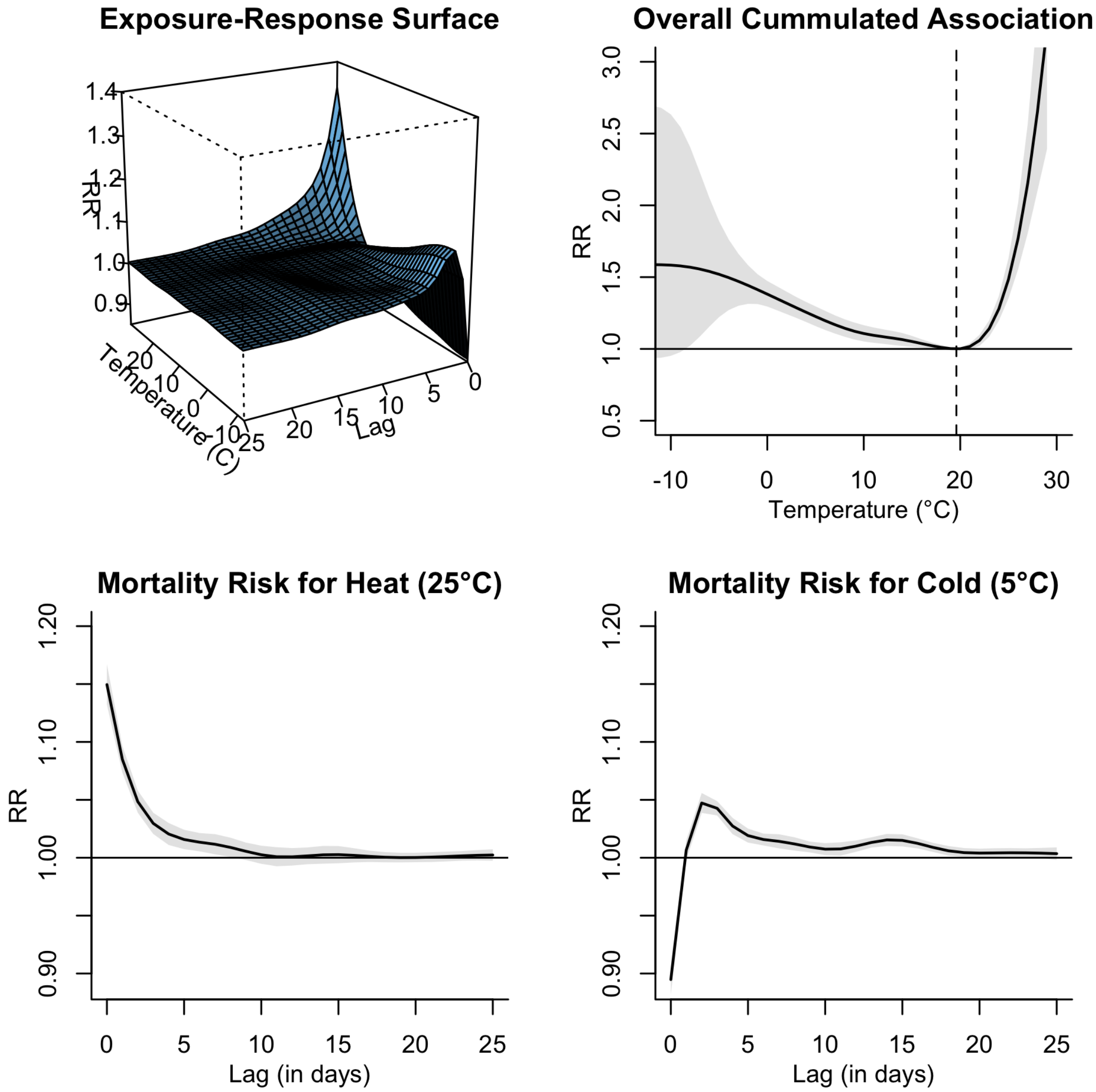

Figure 1: London: Model and Associations from the First-Stage Model

Attributable Fraction per Region: Figures 2, 3 and 4 present the attributable fractions of temperature-related, cold-related and heat-related mortality across regions in Germany and in England and Wales. Overall, cold-related deaths account for the largest share of temperature-related excess mortality. Substantial regional variation is evident: the highest cold-related attributable fractions are observed in England and Wales, while Germany, a modest north-south gradient.

In contrast, heat-related mortalityis more pronounced in Germany. In England and Wales, the highest heat-attributable mortality is found in London. In Germany, elevated heat mortality are located in densely populated regions such as Berlin, North Rhine-Westphalia, Baden-Württemberg and Saarland.

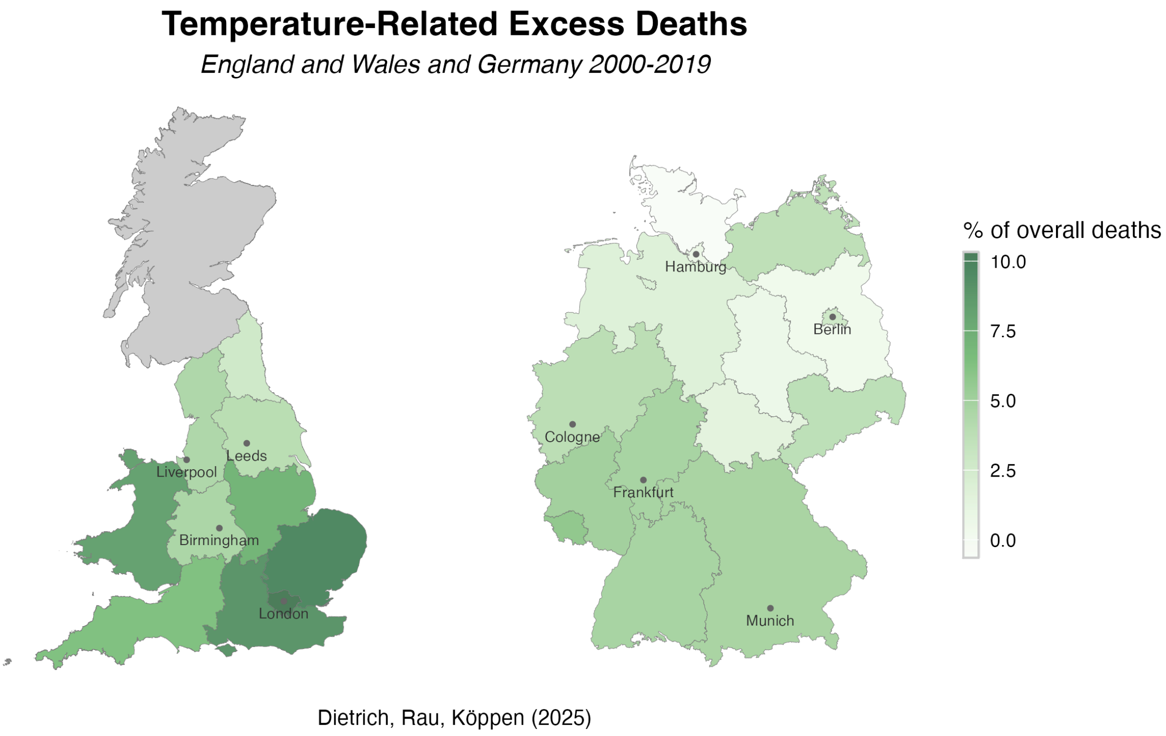

Figure 2: Regional Attributable Deaths to Non-Optimal Temperatures

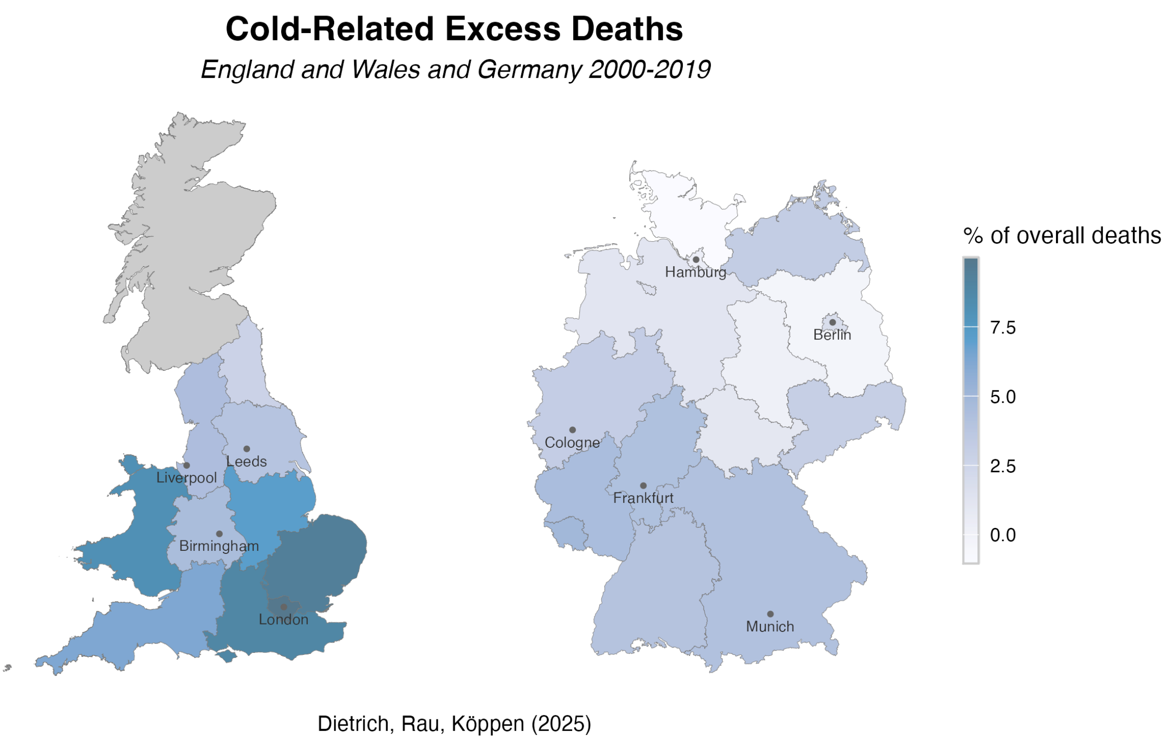

Figure 3: Regional Attributable Deaths to Cold

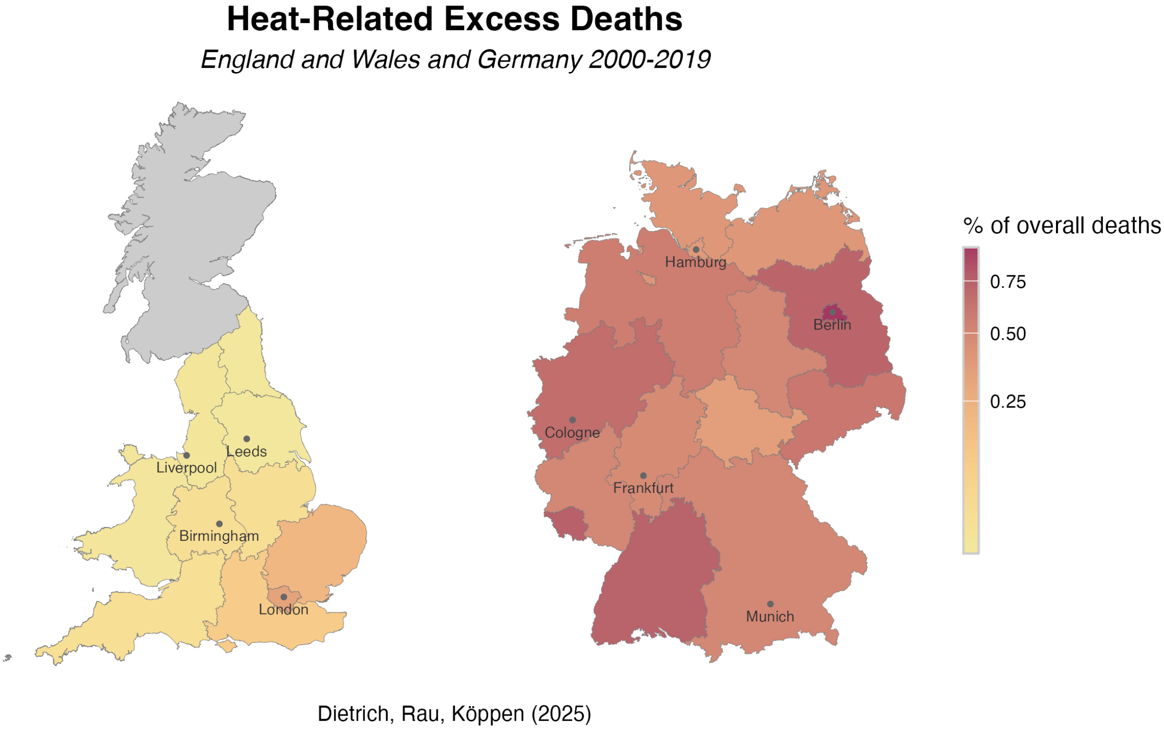

Figure 4: Regional Attributable Deaths to Heat

Pooled Estimates: The pooled exposure-response relationships for Germany and England and Wales (Figure 5) exhibit similar J-shaped patterns. At extreme cold temperatures, the relative risk is lower in Germany than in England and Wales. However, Germany shows higher relative risks at heat extremes. While differences in heat-related risk between the two countries are evident, confidence intervals overlap on the upper end of the distribution. The weighted mean minimum mortality temperature is 17.9°C in Germany and 19.4°C in England and Wales.

The meta-analysis attests both regions a significant heterogeneity between subregions (Q-Test). The I^2 value for the German meta-regression explains that 70.8% of the observed variance is due to heterogeneity between regions. In England and Wales, this is only 52%. Indicating stronger differences in climate, geography and socio-economic factors in Germany.

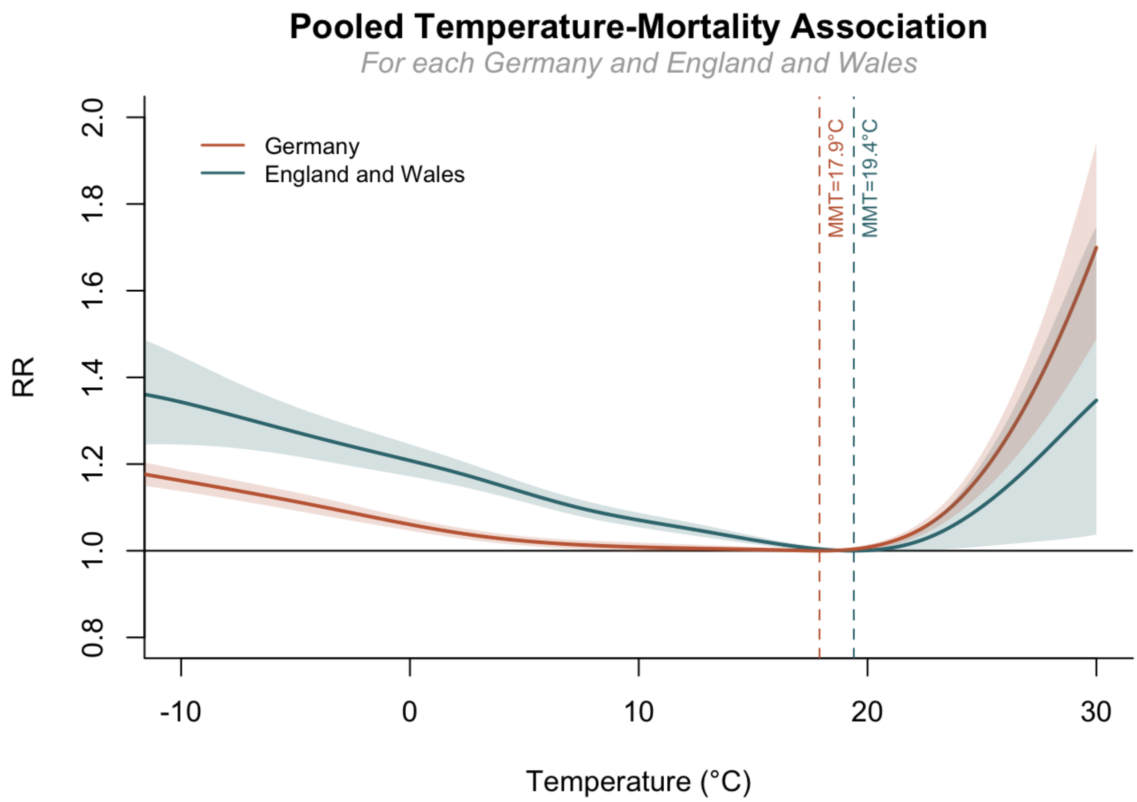

Figure 5: Results of the Second-Stage Meta-Analysis

Changes in periods To assess potential adaptation over time, we modeled and pooled exposure–response relationships separately for two time periods: 2000–2009 and 2010–2019. A flatter exposure–response curve would suggest reduced population sensitivity to non-optimal temperatures, potentially indicating adaptation.

In England and Wales, the curve for the more recent decade is slightly lower at high temperatures and slightly higher at low temperatures. However, the wide and overlapping confidence intervals suggest these differences are statistically uncertain. In Germany, the exposure–response curves for the two decades are nearly identical, offering no indication of a marked change in temperature-related mortality over time.

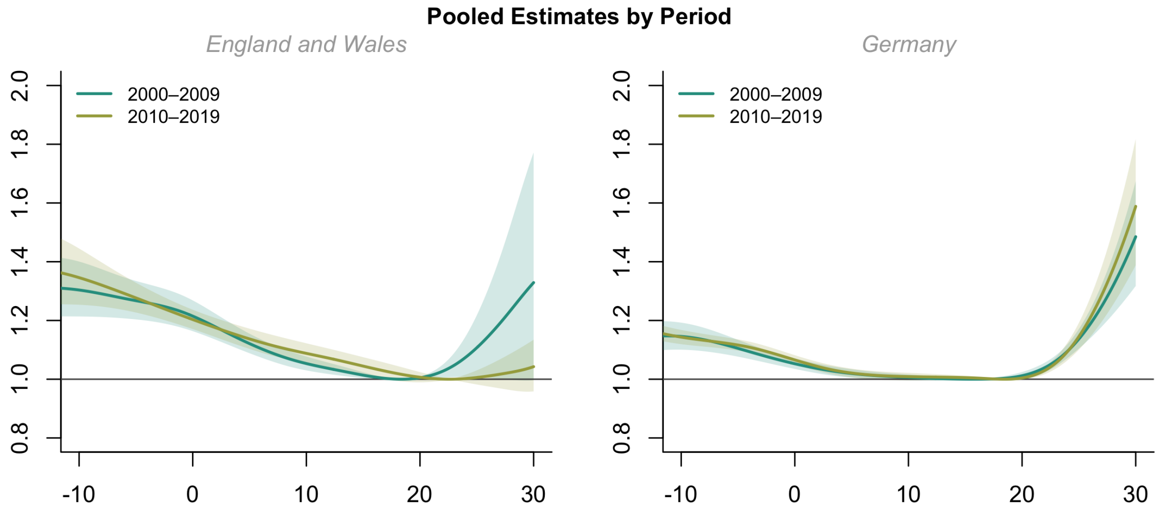

Figure 6: Pooled Estimates for two Periods for each England and Wales and Germany

Conclusion

This study assessed the relationship between temperature and mortality across 16 regions in Germany and 10 regions in England and Wales over the period 2000–2019. A two-stage analytical approach was employed, combining distributed lag non-linear models (DLNM) with multivariate meta-analysis.

Non-optimal temperatures were found to significantly impact mortality risk. Cold-related effects were generally more prolonged, while heat-related effects were more acute. As expected, the overall exposure–response functions followed a J-shaped pattern. Heat-related mortality risks were higher in Germany, whereas England and Wales showed a stronger response to cold. Regional heterogeneity was evident in both countries, with particularly pronounced differences across German regions. The highest fractions of heat-attributable mortality were observed in capital areas and densely populated urban regions.

Despite rising temperatures and increasing public awareness, there was no clear evidence of temporal adaptation in either country. The absence of clear changes in mortality response suggests that adaptive measures, where present, may have been insufficient or unevenly distributed across population subgroups or geographic areas.

These findings underscore the urgent need for localized public health interventions and climate-resilient infrastructure to mitigate the growing health risks associated with temperature extremes. With climate change accelerating, the burden of heat-related mortality is likely to surpass that of cold, positioning heat as an increasingly critical threat to population health.

Future studies should incorporate age-specific analyses to better identify vulnerable populations, as well as gender-sensitive approaches to uncover potential disparities in risk. In addition, finer spatial resolution, at the city or district level, may reveal areas with limited adaptation capacity, helping to guide targeted interventions and inform policy.

References

[1] World Meteorological Organization. Atlas of Mortality and Economic Losses from Weather, Climate and Water Extremes (1970–2012); 2014.

[2] Baccini M, Biggeri A, Accetta G, Kosatsky T, Katsouyanni K, Analitis A, et al. Heat Effects on Mortality in 15 European Cities. Epidemiology. 2008;19(5):711.

[3] D'Ippoliti D, Michelozzi P, Marino C, de'Donato F, Menne B, Katsouyanni K, et al. The impact of heat waves on mortality in 9 European cities: results from the EuroHEAT project. Environmental Health. 2010;9(1):37.

[4] Gasparrini A, Guo Y, Hashizume M, Lavigne E, Zanobetti A, Schwartz J, et al. Mortality risk attributable to high and low ambient temperature: a multicountry observational study. The Lancet. 2015;386(9991):369-75.

[5] Huynen MM, Martens P, Schram D, Weijenberg MP, Kunst AE. The impact of heat waves and cold spells on mortality rates in the Dutch population. Environmental Health Perspectives. 2001;109(5):463-70.

[6] Kovats S. Estimates of temperature-related mortality due to climate change in Europe. Epidemiology. 2004;15(4):S95.

[7] Vicedo-Cabrera A, Sera F, Tobias A, Astrom C, Guo Y, Honda Y, et al. Heat-related mortality impacts attributed to climate change: a global study over historical period. Environmental Epidemiology. 2019;3:414.

[8] Vicedo-Cabrera AM, Scovronick N, Sera F, Royé D, Schneider R, Tobias A, et al. The burden of heat-related mortality attributable to recent human-induced climate change. Nature Climate Change. 2021;11(6):492-500.

[9] Armstrong B. Models for the Relationship Between Ambient Temperature and Daily Mortality. Epidemiology. 2006;17(6):624-31.

[10] Gasparrini A, Armstrong B, Kenward MG. Distributed lag non-linear models. Statistics in Medicine. 2010;29(21):2224-34.

[11] Gasparrini A, Scheipl F, Armstrong B, Kenward MG. A penalized framework for distributed lag non-linear models. Biometrics. 2017;73(3):938-48.

[12] Gasparrini A, Leone M. Attributable risk from distributed lag models. BMC Medical Research Methodology. 2014;14(1):55.

[13] Sera F, Gasparrini A. Extended two-stage designs for environmental research. Environmental Health. 2022;21(1):41.