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Clair Barnes

`c.barnes22@imperial.ac.uk`

Imperial College London <https://orcid.org/0000-0002-7806-7913>

Pierre Masselot

London School of Hygiene & Tropical Medicine <https://orcid.org/0000-0002-7326-1290>

Di Xi

School of Public Health, Imperial College London

Ben Clarke

Centre for Environmental Policy, Imperial College London

Archie Rayner

School of Public Health, Imperial College London

Xinyi Chen

School of Public Health, Imperial College London

Ruohan Wang

Grantham Institute for Climate Change and the Environment, Imperial College London

Emmanuel Raju

Department of Public Health, University of Copenhagen

Emily Theokritoff

Grantham Institute for Climate Change and the Environment, Imperial College London

Malcolm Mistry

London School of Hygiene & Tropical Medicine

Antonio Gasparrini

London School of Hygiene & Tropical Medicine <https://orcid.org/0000-0002-2271-3568>

Friederike E. L. Otto

Imperial College London <https://orcid.org/0000-0001-8166-5917>

Ana Vicedo-Cabrera

University of Bern

Garyfallos Konstantinoudis

Grantham Institute for Climate Change and the Environment, Imperial College London

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Attributing heat-related mortality to human-induced climate change in 854 European cities during the summers of 2000-2025

Clair Barnes^{1*}, Pierre Masselot², Di Xi³, Ben Clarke¹, Archie Rayner³,
Xinyi Chen³, Ruohan Wang⁴, Emmanuel Raju⁵, Emily Theokritoff⁴,
Malcolm Mistry^{2,6}, Antonio Gasparrini², Friederike Otto¹,
Ana Maria Vicedo-Cabrera^{7, 8}, Garyfallos Konstantinoudis⁴

^{1*}Centre for Environmental Policy, Imperial College London, London, UK.

²Environment & Health Modelling Lab, London School of Hygiene & Tropical Medicine, London, UK.

³School of Public Health, Imperial College London, London, UK.

⁴Grantham Institute for Climate Change and the Environment, Imperial College London, London, UK.

⁵ Department of Public Health, University of Copenhagen, Copenhagen, Denmark.

⁶Department of Economics, Ca' Foscari University of Venice, Venice, Italy.

⁷Institute of Social and Preventive Medicine, Universität Bern, Bern, Switzerland.

⁸Oeschger Center for Climate Change Research, Universität Bern, Bern, Switzerland.

*Corresponding author(s). E-mail(s): c.barnes22@imperial.ac.uk;

Contributing authors: pierre.masselot@lshtm.ac.uk; di.xi20@imperial.ac.uk;

b.clarke@imperial.ac.uk; a.rayner@imperial.ac.uk; xinyi.chen123@imperial.ac.uk;

r.wang1@imperial.ac.uk; eraju@sund.ku.dk; e.theokritoff@imperial.ac.uk;

malcolm.mistry@lshtm.ac.uk; antonio.gasparrini@lshtm.ac.uk; f.otto@imperial.ac.uk;

anamaria.vicedo@unibe.ch; g.konstantinoudis@imperial.ac.uk;

Abstract

Anthropogenic climate change is increasing the frequency and intensity of extreme heat, with major implications for population health. Although previous studies have attributed heat-related mortality to climate change during individual events, the longer-term contribution of human-induced warming to urban mortality burdens across Europe remains poorly quantified. Here we combine probabilistic climate attribution with city- and age-specific temperature–mortality relationships to estimate heat-related mortality in 854 European cities during the summers of 2000–2025 under factual and counterfactual climate conditions. We estimate 463,730 heat-related deaths over the study period, with 251,956 resulting from anthropogenic climate change, indicating that just over half of the observed burden is attributable to human-induced warming. The proportion of estimated heat-deaths attributable to human-induced climate change showing a marked rise over time, increasing from 45% in 2000 to 64% in 2025. The largest burdens occurred in older age groups and in cities in southern and south-eastern Europe. Although summer 2003 remained the deadliest summer in absolute terms across Europe as a whole, summers with similarly large mortality burdens have become more frequent in recent years. These findings show that anthropogenic climate change has already greatly increased heat-related mortality across European cities, underscoring the need for both rapid emissions reductions and targeted local adaptation.

Keywords: Climate change attribution, Heat-related mortality, Urban health, Heatwaves, Climate impacts

062 Main

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064
065 By 2025, human activities had warmed the planet by approximately 1.3°C relative to the pre-industrial
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067 baseline [1]. In 2024, global mean temperature exceeded 1.5°C above pre-industrial levels for the first time,
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069 with an estimated 1.36°C of this attributable to anthropogenic greenhouse gas emissions, primarily from
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071 fossil fuel combustion [2]. One of the clearest and most immediate consequences of this warming is the
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073 increasing frequency, intensity and duration of heatwaves across most inhabited regions [3, 4]. Extreme heat
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075 poses a substantial threat to human health, particularly in urban areas, where high population density, the
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077 urban heat island effect, and social and infrastructural vulnerabilities can amplify exposure and risk [5–14].
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079 As temperatures continue to rise, a central question for climate science and public health is how much of
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081 the current burden of heat-related mortality is attributable to human-induced climate change [15, 16]. Clear
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083 evidence on these trends is needed to understand how risks may develop under future warming.

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085 Previous attribution studies have shown that anthropogenic climate change has substantially increased
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087 heat-related mortality. Analyses of major heat events, including the 2003 European heatwave, summer 2022
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089 in Europe, summer 2023 globally, and the summer of 2025 in Europe, consistently indicate that human-
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091 induced warming has contributed substantially to heat-related deaths [16–22]. However, most of this evidence
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093 is derived from individual extreme events or short time periods. As a result, much less is known about how
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095 the mortality burden attributable to anthropogenic climate change has evolved over time across a large and
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097 diverse set of locations. The only study to date to systematically quantify this contribution over multiple
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099 decades and regions analysed 732 locations worldwide for 1991–2018 and estimated that 37% of warm-season
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101 heat-related deaths were attributable to anthropogenic climate change across all countries [15]. However,
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103 given the rapidly increasing rate of observed warming, this figure likely underestimates the current risk.

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105 In this study, we assess the impact of human-induced climate change on heat-related mortality in 854
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107 European cities during the summers of 2000–2025. We focus on Europe because it is the fastest-warming and
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109 ageing continent and because it offers high-quality epidemiological evidence across a large and climatically
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111 diverse set of cities [23]. A city-scale perspective is especially important because urban populations are highly
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113 exposed and often particularly vulnerable to heat, while evidence remains uneven across Europe, especially
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115 outside the largest metropolitan areas and in parts of Eastern Europe. Using an established probabilistic
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117 attribution framework [24], we quantify temporal trends in heat-related deaths and in the proportion of
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119 these deaths attributable to anthropogenic climate change. We present detailed results for 2003, the hottest
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summer in the study period, and 2025, the most recent summer at the time of writing, and examine how the impacts of anthropogenic warming differ across European cities.

Results

We implemented a two-step analysis. First, we obtained factual daily temperature time series for 854 cities across Europe during 2000-2025 and used probabilistic attribution methods to simulate counterfactual temperature series under a world without anthropogenic climate change. We then estimated daily heat-related mortality under both factual and counterfactual conditions by combining these temperature series with publicly available, location-specific exposure-response functions and with population and mortality data for the same 854 cities [23]. We quantified heat-related mortality attributable to anthropogenic climate change as the difference between factual and counterfactual mortality burdens, and as the proportion of factual heat-related deaths attributable to anthropogenic climate change. Because the study focused on heat exposure, analyses were restricted to the summer months of June, July and August. To isolate the contribution of temperature changes due to anthropogenic climate change, the only difference between the factual and counterfactual scenarios is the attributable difference in daily temperatures; exposure-response functions, baseline mortality rates, and population values were held constant. Further details are provided in the Methods.

Attributable trends in temperatures

Panel A of Fig. 1 shows the mean summer temperatures averaged over the 854 cities in the study region since 1950, under both the factual and counterfactual scenarios. Mean attributable summer warming across the 854 cities exceeded 1°C in 2002, and exceeded 2°C in 2024. Panel B shows the change in mean summer temperature in 2025 attributable to human activity (factual versus counterfactual temperatures) across the 854 cities. The highest levels of human-induced warming are observed in northern Italy, central Spain, southern France, and parts of Eastern Europe, with increases of more than 2.5°C attributable to human activities.

Heat-related mortality burden

Across the 854 European cities included in this study, with a combined population of almost 160 million residents, we estimated a factual 463,730 (95% empirical confidence interval (eCI): 406,524, 516,764) heat-related deaths during the summer months over 2000–2025, Table 1. The highest burden was observed among

individuals aged ≥ 85 years, with 181,179 (95% eCI: 161,514, 202,384) heat-related deaths. The annual heat-related mortality burden increased over the study period, from 11,160 (95% eCI: 9,459, 12,733) deaths in 2000 to 24,429 (95% eCI: 21,947, 26,650) in 2025 across the 854 cities (Fig. 2a and Supplementary information Table S1). The largest annual numbers were observed in the summers of 2003 and 2022, with 30,027 (95% eCI: 27,167, 32,672) and 29,957 (95% eCI: 27,046, 32,683) heat-related deaths, respectively.

Among the 30 countries analysed, Croatia, Italy, and Greece exhibited the highest mean standardised excess mortality per million population over 2000–2025 (Table 2). The average annual numbers of heat-related deaths per 1,000,000 people were 365 (95% eCI: 276, 448) in Croatia, 243 (95% eCI: 188, 294) in Greece and 252 (95% eCI: 212, 292) in Italy. Among the 30 capital cities, Rome, Zagreb, and Bern showed the highest mean standardised excess mortality per 1,000,000 population, with an average annual heat-related deaths of 609 (95% eCI: 537, 684), 544 (95% eCI: 413, 672), and 520 (95% eCI: 383, 630) , respectively (Supplementary information Table S2). Over the study period, the highest standardised excess per million population was consistently observed in southern and eastern Europe (Fig. 2b), with the summers of 2003, 2022 and 2024 standing out as particularly dangerous in southern Europe (Fig. 2c).

Heat-related mortality attributable to anthropogenic climate change

Under the counterfactual temperature scenario, we estimated 251,956 additional heat-related deaths (95% eCI: 210,569–288,785) attributable to anthropogenic climate change over the study period (Table 1). This suggests that nearly half of the total heat-related mortality burden observed between 2000 and 2025 can be linked to human-driven climate change (Table 1). The proportion of heat-related deaths attributable to anthropogenic climate was highest among individuals aged ≥ 85 years (0.58; 95% eCI: 0.50, 0.65), Table 1. The trend in estimated excess heat-related deaths under the counterfactual scenario remain constant across the study period, Fig. 3a, whereas the additional excess and the proportion of excess heat-deaths attributable to anthropogenic warming increases substantially, Fig. 3b-c. The proportion of heat-related deaths attributable to anthropogenic climate change rose from 0.45 (95% eCI: 0.38, 0.51) in 2000 to 0.64 (95% eCI: 0.54, 0.72) in 2025, Supplementary information Table S1.

The highest attributable proportions were estimated for Greece 0.65 (95%eCI: 0.55, 0.75), Italy 0.65 (95%eCI: 0.55, 0.73) and the UK 0.65 (95%eCI: 0.51, 0.76), Table ?? . Coastal cities, particularly those along the Mediterranean, Atlantic, and North Sea coastlines, tended to show lower proportions of heat-related mortality attributable to anthropogenic warming, possibly reflecting the moderating influence of maritime climates on temperature trends, Fig. 3d. The proportion of heat-related deaths attributable to

anthropogenic warming varies considerably across both time and geography among the 30 countries studied (Fig. 3e) but in all countries has increased throughout the study period, rising to at least 0.60 in the most recent years of the study period in almost all countries.

Comparison of summer 2003 and summer 2025

Similar geographical patterns were observed in standardised heat-related excess mortality in the summers of 2003 and 2025 (Fig. 4a-b); however, the proportion attributable to anthropogenic climate change was markedly higher in 2025 (Fig. 4c-d). In both summers, the strongest impacts were concentrated in eastern and southern Europe, with Rome showing the highest mean standardised excess mortality among the 30 capitals, Supplementary information Tables S3–S4). In 2003, the heat signal was concentrated in early August and closely mirrored by sharp spikes in daily excess mortality, particularly in western and southern Europe (Supplementary information Fig. S2; box 1). By contrast, summer 2025 was characterised by temperature spikes in June and early July, followed by a shorter heatwave in mid-August (Supplementary information Fig. S2; boxes 2–5). Although summer 2003 resulted in over 5,000 more heat-related deaths than summer 2025, only 42% of those deaths were attributable to anthropogenic climate change. By contrast, 64% of heat-related deaths in 2025 were attributable to human activity, suggesting that while 2003 was deadlier in absolute terms, the role of anthropogenic warming in driving heat mortality has grown substantially and uniformly across the 854 cities (Table S1 and Fig. 4c-d).

Sensitivity analysis

In a sensitivity analysis we use variable populations and mortality rates across the study period, to test the effect of the assumption of fixed population and mortality rates used in the analysis above. While the number of heat-deaths in 2025 becomes comparable with 2003, reflecting increases in population across the years, the proportion of deaths attributed to anthropogenic climate change is consistent across the approaches (Supplementary information Text S1 and Tables S5–6).

Discussion

In this heat-mortality attribution study of 854 European cities, we estimated the number and proportion of heat-related deaths that would have been avoided in a world without anthropogenic climate change. Overall, we found that more than half of the expected heat-related deaths over the entire period 2000–2025 could be attributed to human-induced climate change. The proportion increased from 0.45 in the year 2000

to 0.64 in 2025, indicating that the ongoing climate crisis has already had a substantial impact on heat-related mortality in European urban populations. The impacts were highly heterogeneous across countries, with the Mediterranean countries (i.e., Italy, Greece and Croatia) bearing the highest heat-related mortality burden. The largest number of expected heat-related deaths was observed during the extreme summer of 2003; however, these numbers are not substantially different from those recorded in summers after 2022. As the climate warms, dangerously hot summer temperatures are becoming increasingly frequent, and with them, a steadily growing proportion of heat-related deaths attributable to anthropogenic climate change.

The analysis builds on the first rapid mortality attribution study published in summer 2025 [21] and extends the results to 854 cities [22] over a 26-year period. We used an established methodology for disentangling the impact of human-induced climate change [24], coupled with state-of-the-art approaches for estimating exposure-response functions [23]. By integrating climate model simulations with large-scale mortality datasets, our analysis provides an unprecedented level of spatial, temporal and age-specific detail for quantifying the health impacts of increasing heat across Europe, with direct relevance for local public health planning and urban climate adaptation policy. Finally, by examining the robustness of the approach and discussing and comparing our estimates with previous studies, we provide further support for its use in future rapid attribution analyses of heat-related mortality.

This study assumes a constant baseline daily mortality rate throughout the study period, derived from historical mortality data [23]. In a sensitivity analysis, we relaxed this assumption and found that the proportion of deaths attributed to human-induced climate change was broadly consistent across methods. However, these results also suggest that our main analysis may underestimate the absolute heat-related mortality burden, particularly in the most recent years. A related assumption is that baseline mortality remains constant within summers. Since mortality tends to rise during heatwaves, the underlying death rate on very hot days likely exceeds the constant rate assumed here, which may further contribute to an underestimation of the absolute heat burden. The exposure-response relationships used in the attribution analysis were derived from health data spanning 2000–2019 and are assumed to remain constant throughout the study period. As a result, we do not explicitly account for potential changes in population vulnerability over time. On one hand, adaptation, through improvements in public health preparedness, housing, urban planning, and healthcare systems, may have attenuated local heat–mortality associations over time [25–27]. On the other hand, our analyses do not capture potential maladaptation, demographic ageing, or increases in the prevalence of chronic conditions, all of which could heighten local vulnerability [28]. Importantly,

assuming constant baseline mortality and exposure-response relationships allows us to isolate the contribution of temperature exposure and evaluate heat-mortality across varying summer conditions. Finally, two further limitations merit mention. These results are characterised at the city level and may not be representative of conditions across entire countries, limiting the extent to which our findings can be extrapolated to national scales. Additionally, the attributable warming is likely a conservative estimate, given the tendency of climate models to underestimate long-term warming trends (see Supplementary Information, Text S2).

Our results are broadly consistent with previous studies. In agreement with analyses focusing on summer 2022 in Europe, we estimate that 56% of heat-related deaths in summer 2022 were attributable to human-induced climate change, with the highest proportion in older populations [19, 20] (Supplementary information Table S 1 and Table 1). A global study covering the period 1991–2018 reported that about 37% of heat-related deaths were attributable to climate change, which is comparable to the proportions we observe in the early years of our study period. Another global analysis of the 2023 heatwave estimated that 54% of heatwave-related deaths were attributable to human-induced climate change [16], slightly smaller compared with our estimate of 61% but well within the confidence interval (95% eCI: 51%, 69%). We estimated an annual average of 17,836 heat-related deaths over the period 2000–2025 (95% eCI: 15,636–19,876). This figure is notably higher than the estimate reported by a previous study that used the same underlying exposure-response functions, which found 13,589 deaths per year (13,589; 95% eCI: 11,530–15,475) [23]. The discrepancy is likely driven by the fact that our analysis extends beyond 2019, a period characterized by exceptionally high heat-related mortality not captured in the earlier work. Our temporal estimates of the proportion of deaths attributable to human-induced climate change are broadly consistent with those reported for the summers 2015–2021 [19]. In line with previous studies, we observed higher rates of heat-related mortality in southern Europe [15, 23, 29], with Croatia, Italy, and Greece being the most affected countries. This pattern likely reflects the persistently higher ambient temperatures in these countries, rather than a greater relative risk of heat-related mortality [23].

Our results differ from those of the first mortality attribution study focusing on summer 2003, which estimated that approximately 20% of heat-related deaths in London and 70% in central Paris were attributable to anthropogenic climate change [17]. We estimated 30% (95% CrI: 19%, 44%) in London and 24% (16%, 34%) in Paris in 2003 (Supplementary information Table S3). These discrepancies are likely driven by methodological differences (e.g., the exclusion of summer 2003 in the exposure response functions we

Masselot et al. [23]), including the geographical extent considered (city-wide versus central areas), the exposure metric (apparent temperature in [17] versus daily mean temperature in our study), and the specific implementation of the probabilistic attribution framework.

Official estimates across Europe suggest a mixed picture of summer heat mortality, but they are not directly comparable with our results. For example, for summer 2025, Rome reported 152 less excess deaths in adults aged over 65 years [30]; the UK Health Security Agency estimated 317 heat-related deaths in London (95% CI: 139, 495) versus 460 (95% eCI: 309, 603) here [31]; and Euromomo reported 590 heat-attributable deaths in Madrid versus 417 (95% eCI: 305, 564) in our analysis (https://momo.isciii.es/panel_momo/). These differences partly reflect methodological choices, including the definition of city boundaries and heat periods, but the key distinction is the interpretation. Our approach estimates deaths above the minimum mortality temperature from a parametric temperature-mortality relationship, whereas official estimates typically derive excess deaths relative to recent historical baselines that may already incorporate part of the temperature signal. A Swiss study of summer 2022 using similar historical-baseline methods found that estimates of absolute numbers of deaths were highly sensitive to assumptions about population dynamics and temporal trends, in line with broader methodological reviews showing that excess-mortality estimates depend strongly on counterfactual baselines, model specification and demographic adjustment, underscoring the need for extensive cross-validation and simulation-based evaluation of any estimates derived using similar methodologies [32].

Our findings show that anthropogenic climate change has already become a major driver of heat-related mortality in European cities, accounting for more than half of heat-related deaths over the 2000–2025 study period. This burden is unevenly distributed: impacts are greatest in southern Europe and during extreme summers, and appear to be driven primarily by changes in the frequency and intensity of heat exposure rather than by differences in exposure–response relationships alone. With mortality rates and temporal variation of exposure held constant, and allowing variation by age and space, the contribution of anthropogenic warming to heat mortality increased steadily over time, suggesting that summers with mortality burdens comparable to the devastating 2003 heatwave are becoming an increasingly regular occurrence.

These findings carry important policy implications. The pronounced spatial variation in risk underscores the need for locally tailored adaptation strategies, particularly for older and vulnerable populations in southern Europe. Yet adaptation alone cannot be the answer: a substantial share of current heat-related mortality is, in principle, avoidable, since stronger mitigation would directly reduce the likelihood of the

extreme temperatures that drive the greatest death tolls. Without deep and sustained emissions reductions, the capacity to offset the health impacts of continued warming will become increasingly constrained, and the gap between what adaptation can achieve and what the climate demands will only widen.

Methods

Climate attribution

The attribution analysis was carried out using an established probabilistic attribution methodology [24, 33–35]. First, time series of daily mean temperatures in each of the 854 cities during the northern hemisphere summer months (June-August) are retrieved from gridded data products. For each time series, a statistical model is used to estimate the relationship between the monthly mean temperature and the global mean surface temperature (GMST). Results from both observation-based datasets and climate models are combined to estimate the trend in local temperatures as a function of global temperatures, and so to estimate the expected change in temperatures associated with the 1.3°C of human-caused warming that occurred between the preindustrial period (1850-1900) and 2025.

Observed temperatures

For each city we retrieve daily mean temperature data from ERA5-Land and E-OBS (v31.0e + pre1950), selecting the grid cell whose centre is closest to the city centre coordinates. ERA5-Land is a gridded reanalysis dataset that combines historical observations into global estimates using advanced modelling and data assimilation systems, spanning the period from 1950-2025 [36] at a resolution of $0.1^\circ \times 0.1^\circ$, while E-Obs is a land-only product derived from the interpolation of station-derived meteorological observations from 1920-2025 [37], at a resolution of $0.25^\circ \times 0.25^\circ$. For three locations, no data were available from E-Obs because the nearest grid cell is not designated as land, so only ERA5-Land was used. The ‘factual’ temperatures referred to in the study are taken from ERA5-Land.

The annual Global Mean Surface Temperature (GMST) time series is obtained from the National Aeronautics and Space Administration (NASA) Goddard Institute for Space Science (GISS) surface temperature analysis [38, 39]. To reduce variability in the GMST due to the El Nino-Southern Oscillation (ENSO), we use a four-year rolling average of the GMST, centred on the third year.

550 **Climate models**

551
552 The attribution step uses a multi-model ensemble of coupled global circulation models from the CMIP6
553 experiments [40]. For all simulations, the period 1850 to 2014 is based on historical simulations, while the
554 SSP5-8.5 scenario is used to project from 2015 to 2030; the results are not expected to be sensitive to the
555 choice of scenario because all trends are estimated in terms of global mean temperature, rather than time,
556 which controls for the different rates of warming in different models and scenarios. All years from 1850 to
557 2030 were used to estimate the historic warming trend. In an exploratory analysis comparing the spatial
558 climatology of summer temperatures from 1990-2020 with the observed climatology, all models were found
559 to perform well. To avoid using different subsets of climate models in each region, no further selection was
560 carried out based on the local seasonal cycles or parameter fits. However, five model variants were removed
561 from an original ensemble of 43, because they were lower-resolution variants of other models within the
562 ensemble, leaving 38 models each providing one realisation to the multi-model ensemble. Details of the
563 models included in the study can be found in the Supplementary Information, Table S9.

577 **Statistical modelling of trends**

580 For each time series (both observations-based and derived from climate models) we estimate the parameters
581 of a nonstationary normal distribution in which the mean monthly temperature depends linearly on GMST,
582 while the variance remains stationary. This model is used to obtain the change in local temperatures per
583 degree of global warming. 95% confidence intervals are obtained by block bootstrapping of all cities and
584 calendar months (June, July and August), using a sample size of 1000 (ie. by resampling whole years of
585 data for each bootstrap). Trends are estimated independently for each dataset.

593 **Synthesis of trends**

596 For each city and month, the estimated trend parameters from the observational products and climate
597 models were combined into a single estimate of the change in local temperatures per degree of global
598 warming using an established synthesis algorithm [35]. We first pool the observational estimates by taking
599 their mean and inflating the variance with an additional representation-error term (added in quadrature)
600 to capture discrepancies in long-term trends between the observational products. We obtain a separate
601 precision-weighted mean of the model-derived estimates, with a term added in quadrature to account for
602 inter-model spread as well as internal variability. Finally, we take the unweighted mean of the estimates
603 from the observations and the climate models to yield an overall best estimate of the local warming trend

with a corresponding 95% confidence interval. We note that this is a departure from the standard WWA protocol, which would usually use inverse-variance weighting of the estimates from the observations and models; however, climate models are known to produce over-confident underestimates of warming in the region (see Supplementary Information, Section S2), so this approach avoids giving undue weight to the climate models. However, this still results in a lower estimate of attributable warming than the historic warming in observations, and should therefore be interpreted as a conservative estimate.

Calculating counterfactuals

Factual daily mean temperatures for the summers from 2000-2025 were taken from ERA5-Land reanalysis [36]. For each year we calculate the change in GMST since the preindustrial period, and multiply this by the synthesised change in local temperatures per degree of warming for each calendar month, to obtain the local adjustment per year and month.

To obtain a proper quantification of the uncertainty in the mortality estimates arising from uncertainty in the attributable warming, it is necessary to obtain a spatially coherent sample of local warming rates. To achieve this, we use the ERA5-Land ('factual') block bootstrap to estimate the 2562×2562 correlation matrix, $\mathbf{C}$, between the rates of warming in all 854 cities and all calendar months. We then sample 1000 realisations from a multivariate normal distribution with standard normal marginals and correlation matrix $\mathbf{C}$. Finally, the marginal distributions are transformed to have the same mean and variance as the synthesised trends for each city and calendar month. This results in a spatially coherent sample of the local synthesised warming, with the same correlation structure as the observed rate of warming. This adjustment is then subtracted from the daily factual temperatures to obtain an ensemble of preindustrial counterfactual time series, which are used as inputs to the epidemiological model.

Mortality attribution

To quantify heat-related mortality attributable to human-induced climate change, we use a framework that integrates exposure-response functions with temperature time series under factual and counterfactual climate conditions. The approach consists of three main components. First, we derive exposure-response functions by taking age-specific temperature-mortality relationships for 854 European cities from the literature [23]. Second, we apply these city- and age-specific functions to the temperature series under both factual and counterfactual scenarios to estimate the number of heat-related deaths in each case. Third, we attribute mortality to climate change by comparing the excess deaths in the factual and counterfactual worlds.

672 Data

673
674 Exposure-response functions were derived from daily mortality data from the Multi-country Multi-city
675 Collaborative Research Network (MCC; <https://mccstudy.lshtm.ac.uk/>), annual Eurostat statistics, and
676 additional city-specific data from sources including satellite observations (MODIS, Copernicus). Daily mean
677 temperatures came from the ERA5-Land reanalysis dataset for 1990–2019 [36]. The associations were strat-
678 ified by age group (20-44, 45-64, 65-74, 75-84, 85+) and city, capturing variations in vulnerability. This
679 framework also applies pooling of the estimates, providing robust curves in cities where data are sparse [23].
680 Supplementary information Fig. S1 shows the relative risk curves in the 30 European capitals available in
681 the study.

691 Health impact assessment

692
693 Using the retrieved exposure-response function, we calculated attributable fractions for both factual and
694 counterfactual temperatures [19, 20, 41]. Daily deaths during the heatwave were estimated assuming a
695 constant rate based on historical Eurostat data [23]. Applying this rate to the attributable mortality fraction
696 yielded excess deaths in each scenario. As the interest was in estimating the impact of heat, attributable
697 fractions were calculated only for temperatures above the minimum mortality temperature (MMT, defined
698 as the temperature between the 25th and 99th percentiles of the local temperature distribution at which
699 the relative risk is minimised) and for the summer months of June-August. To quantify the impact of
700 human-induced climate change, we compared excess deaths in the factual and counterfactual scenarios and
701 calculated the number and the proportion of heat-related deaths attributable to human activity [21, 22].
702 To propagate uncertainty, we drew 1000 samples from the multivariate distribution of the basis-function
703 coefficients for each location and age group [23]. We combined these with the factual temperature time series
704 and sampled counterfactual time series to obtain a sampling distribution for the attributable fractions and
705 excess deaths in the factual and counterfactual worlds. We summarised the estimates using the median and
706 the 2.5th and 97.5th quantiles, which we report as 95% empirical confidence intervals (eCI).

723 Data availability statement

724
725 The data used in this study is open access. Factual temperatures can be downloaded from ERA5-Land
726 (<https://cds.climate.copernicus.eu/datasets/reanalysis-era5-land?tab=overview>) and E-OBS (<https://cds.climate.copernicus.eu/datasets/insitu-gridded-observations-europe?tab=overview>), the annual global mean

surface temperature from NASA (<https://data.giss.nasa.gov/gistemp/index.v3.html>), and the multi-model ensemble of coupled global circulation models from the CMIP6 experiments (<https://cds.climate.copernicus.eu/datasets/projections-cmip6?tab=download>). The exposure response functions at the 854 cities are available in zenodo: <https://zenodo.org/records/10288665>, mortality data from eurostat (<https://ec.europa.eu/eurostat/data/database>), whereas population data from WorldPop (<https://www.worldpop.org/>).

Code availability

Code used in the attribution step will be made available via GitHub/Zenodo after revisions are complete.

Code for performing the health impact assessment is provided on GitHub: <https://github.com/PierreMasselot/Paper--2023--LancetPH--EUcityTRM>.

Ethics

The study is about secondary, aggregate anonymised data so no ethical permission is required.

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Author contributions

G.K. and C.B. conceived the study; G.K. supervised the work. G.K. developed the initial study protocol in discussion with C.B., P.M., B.C., E.T., M.M., A.G., F.O. and A.M.V.C. C.B. developed the statistical model for climate attribution, and G.K. performed the health impact assessment. P.M. validated and revised the first version of the health impact assessment code. A.R., X.C., D.X. and R.W. collected the data and derived annual mortality estimates for the sensitivity analysis. E.R. contributed to the discussion and the public health implications of the study. All authors read and approved the final manuscript.

794 **Competing interests**

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The authors declare no competing interests.

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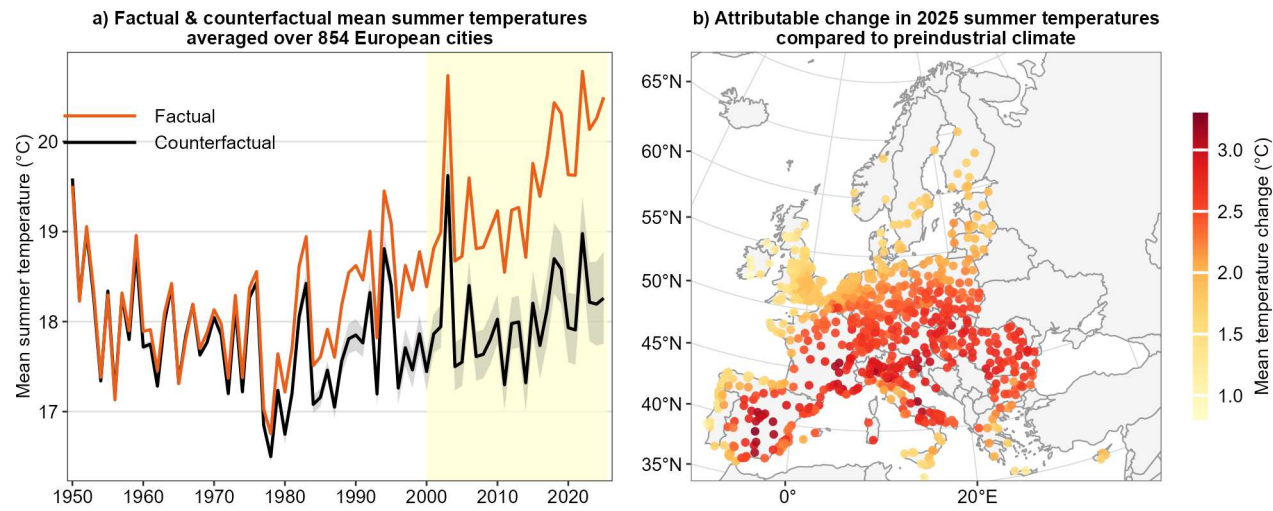
Table 1: Population and median and 95% empirical confidence intervals of number of expected heat-deaths in the factual scenario and the absolute and relative changed due to human-made climate change during 2000-2025 in 854 European cities.

Age	Population	Heat-deaths	Difference	Proportion
20-44	66,886,597	12,496 (8,577, 16,577)	4,373 (3,111, 57,35)	0.35 (0.27, 0.46)
45-64	54,059,644	61,766 (50,278, 74,323)	29,001 (23,178, 34,972)	0.47 (0.39, 0.56)
65-74	19,676,737	73,292 (63,138, 83,390)	38,687 (32,010, 45,038)	0.53 (0.44, 0.60)
75-84	12,762,858	133,841 (116,631, 149,422)	74,822 (62,910, 86,060)	0.56 (0.48, 0.63)
85+	5,087,812	181,179 (161,514, 202,384)	105,022 (87,982, 120,565)	0.58 (0.50, 0.65)
Total	158,473,649	463,730 (406,524, 516,764)	251,956 (210,569 288,785)	0.55 (0.46, 0.61)

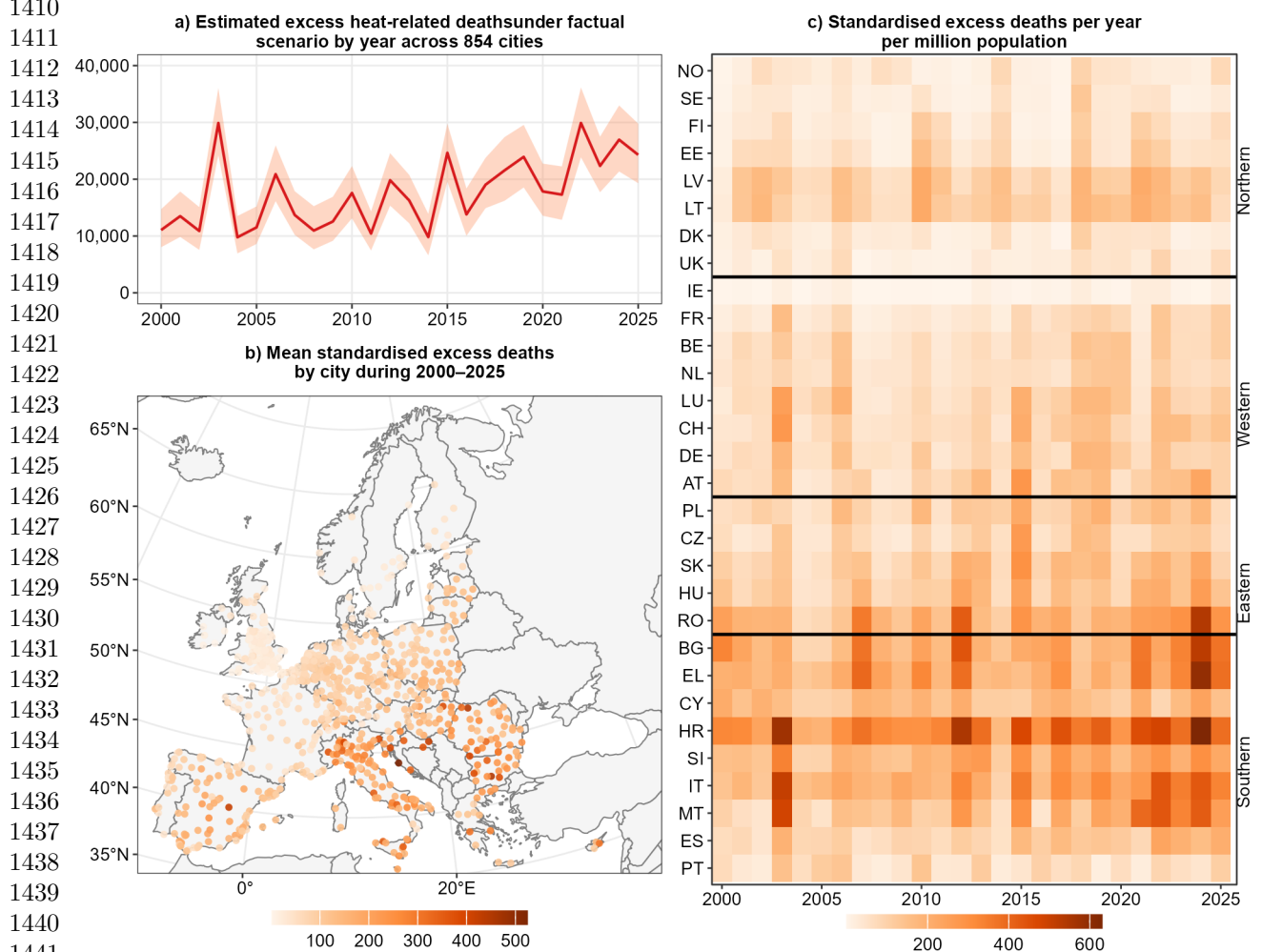
Table 2: Population, and median and 95% empirical confidence intervals for the annual average excess number of heat-related deaths in the factual scenario, age standardised heat-related deaths, and the absolute and relative changes attributable to anthropogenic climate change during 2000–2025 across 854 European cities, by country.

Country	Population	Heat-deaths	Standardised excess	Difference	Proportion
Austria	1,949,160	190 (143, 248)	108 (81, 141)	106 (72, 144)	0.57 (0.42, 0.70)
Belgium	2,455,390	185 (143, 237)	76 (59, 98)	80 (56, 106)	0.45 (0.32, 0.58)
Bulgaria	2,596,877	559 (379, 774)	239 (164, 331)	333 (227, 455)	0.63 (0.50, 0.74)
Croatia	1,101,531	377 (285, 461)	365 (276, 448)	196 (143, 253)	0.54 (0.43, 0.64)
Cyprus	457,113	52 (35, 66)	154 (105, 196)	25 (16, 34)	0.49 (0.34, 0.63)
Czechia	2,522,881	190 (117, 280)	87 (54, 128)	107 (63, 156)	0.59 (0.43, 0.72)
Denmark	917,663	28 (17, 41)	35 (21, 50)	14 (8, 23)	0.56 (0.39, 0.71)
Estonia	440,155	24 (9, 44)	57 (21, 106)	8 (2, 16)	0.40 (0.23, 0.59)
Finland	1,460,602	59 (27, 97)	43 (20, 71)	25 (10, 45)	0.49 (0.31, 0.67)
France	17,962,199	1,090 (877, 1,329)	58 (47, 71)	549 (405, 705)	0.53 (0.39, 0.65)
Germany	23,406,685	2,282 (1,843, 2,743)	94 (76, 113)	1,044 (763, 1,333)	0.48 (0.36, 0.60)
Greece	3,401,064	877 (678, 1,061)	243 (188, 294)	562 (441, 693)	0.65 (0.55, 0.75)
Hungary	2,806,295	349 (215, 524)	134 (83, 201)	163 (89, 244)	0.49 (0.31, 0.64)
Ireland	1,090,316	5 (2, 9)	7 (3, 12)	2 (0, 4)	0.53 (0.01, 0.82)
Italy	17,186,805	5,046 (4,234, 5,834)	252 (212, 292)	3,230 (2,601, 3,835)	0.65 (0.55, 0.73)
Latvia	874,434	102 (22, 193)	116 (25, 219)	27 (3, 61)	0.30 (0.13, 0.47)
Lithuania	1,033,748	121 (24, 234)	121 (24, 231)	39 (2, 84)	0.36 (0.11, 0.57)
Luxembourg	70,074	6 (4, 8)	101 (74, 131)	3 (2, 4)	0.62 (0.46, 0.78)
Malta	170,361	27 (19, 35)	196 (139, 251)	14 (8, 20)	0.54 (0.34, 0.71)
Netherlands	5,644,325	372 (240, 610)	71 (47, 116)	122 (79, 175)	0.33 (0.19, 0.51)
Norway	829,551	22 (9, 35)	35 (15, 54)	10 (4, 18)	0.56 (0.37, 0.71)
Poland	10,396,899	1,042 (673, 1,480)	112 (73, 159)	523 (326, 732)	0.52 (0.38, 0.65)
Portugal	3,457,781	242 (191, 318)	68 (54, 89)	33 (-5, 69)	0.15 (-0.02, 0.31)
Romania	6,010,799	1,150 (756, 1,586)	220 (146, 301)	608 (390, 856)	0.56 (0.41, 0.68)
Slovakia	877,322	84 (51, 126)	129 (79, 192)	41 (23, 62)	0.51 (0.34, 0.67)
Slovenia	308,320	58 (40, 75)	200 (138, 259)	30 (20, 40)	0.53 (0.41, 0.65)
Spain	17,714,878	2,170 (1,724, 2,781)	116 (92, 149)	1,210 (875, 1,568)	0.56 (0.42, 0.67)
Sweden	2,807,484	79 (51, 109)	29 (19, 41)	34 (18, 55)	0.49 (0.30, 0.66)
Switzerland	1,977,029	192 (138, 256)	99 (71, 133)	110 (76, 144)	0.59 (0.40, 0.75)
United Kingdom	26,545,907	721 (557, 885)	31 (24, 38)	413 (286, 556)	0.65 (0.51, 0.76)

Fig. 1: (a) Annual mean summer (June-August) temperatures from 1950-2025, averaged over the 854 cities in the study in the factual (red) and counterfactual (black) climates; grey shaded region represents uncertainty about the counterfactual temperatures. Yellow shaded region indicates the study period (2000-2025). (b) Change in mean summer temperatures in 2025 attributable to human activity in each of the 854 cities.

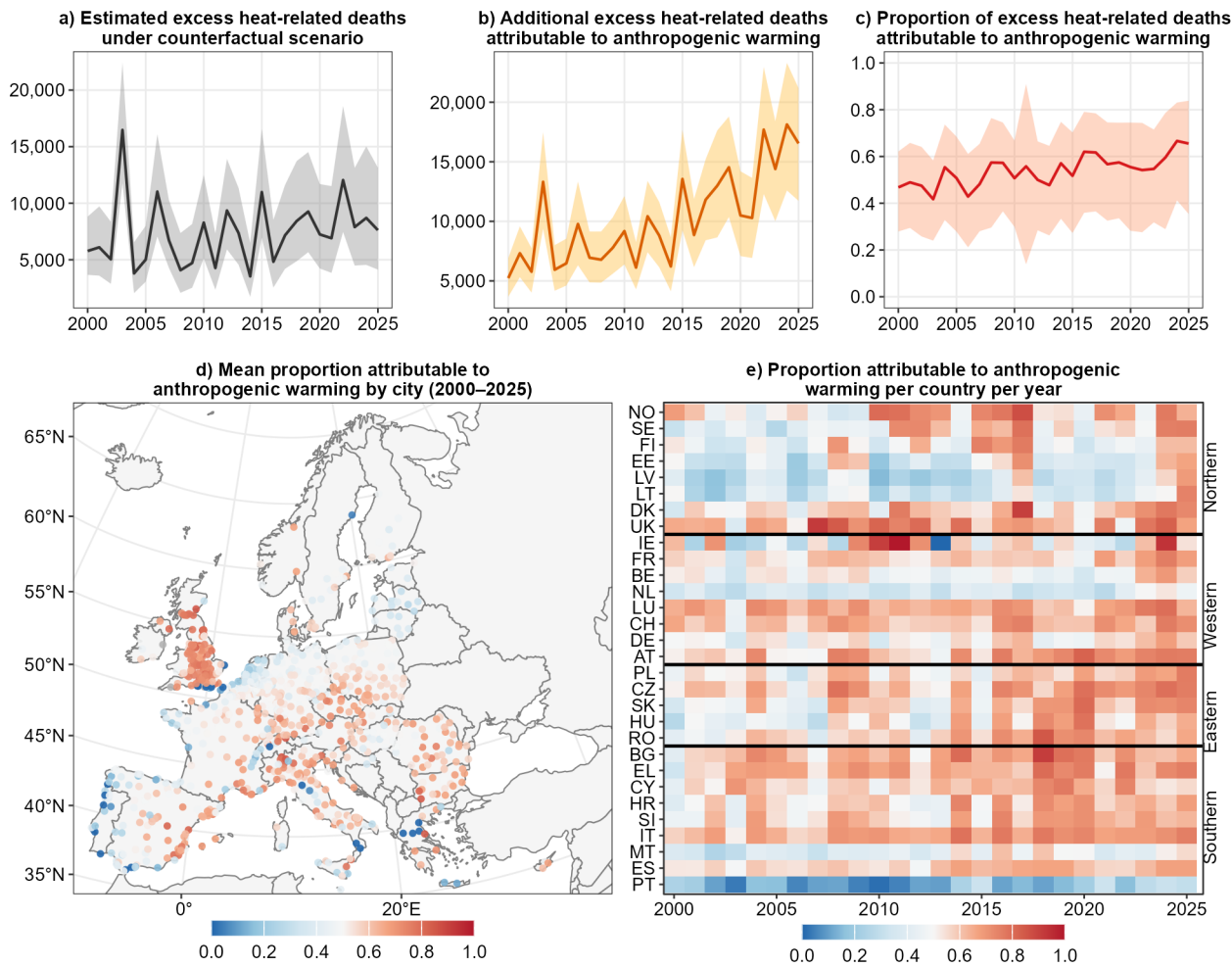


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 1405 **Fig. 2:** (a) Estimated total heat-related excess deaths across the 854 cities under factual scenario from
 1406 2000-2025. (b) Mean standardised excess deaths per 1,000,000 population during 2000-2015 by 854 cities.
 1408 (c) Mean standardised excess deaths per 1,000,000 population by year and country during 2000-2015.



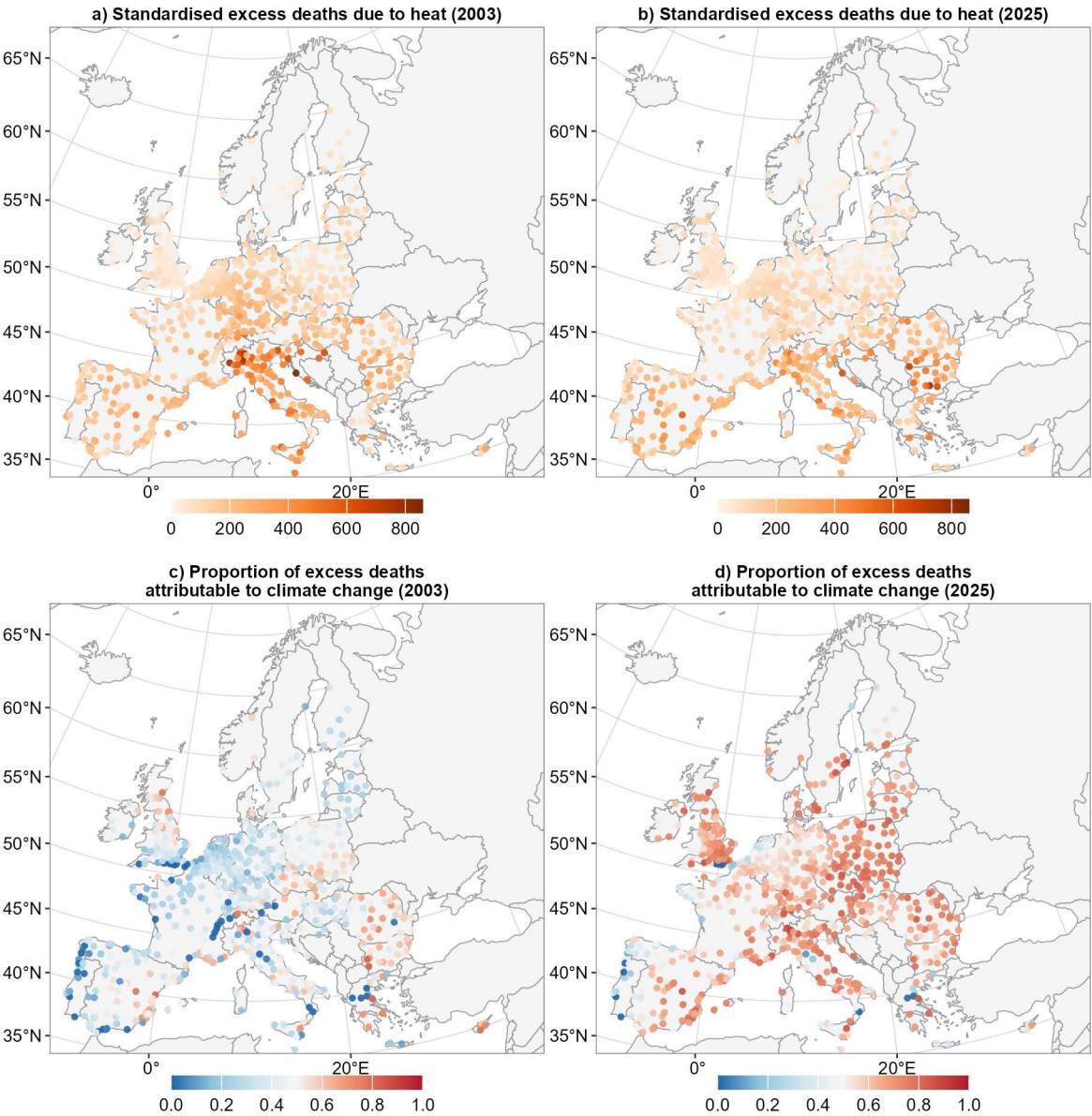
1446 NO: Norway, SE: Sweden, FI: Finland, EE: Estonia, LV: Latvia, LT: Lithuania, DK: Denmark, UK: United
 1447 Kingdom, IE: Ireland, FR: France, BE: Belgium, NL: Netherlands, LU: Luxembourg, CH: Switzerland, DE:
 1448 Germany, AT: Austria, PL: Poland, CZ: Czech Republic, SK: Slovakia, HU: Hungary, RO: Romania, BG:
 1449 Bulgaria, EL: Greece, CY: Cyprus, HR: Croatia, SI: Slovenia, IT: Italy, MT: Malta, ES: Spain, PT: Portugal

Fig. 3: (a) Estimated total heat-related excess deaths across the 854 cities under counterfactual scenario from 2000-2025. (b) Difference between total heat-related excess deaths in factual and counterfactual scenarios. (c) Proportion of heat-related excess deaths attributable to climate change. In all panels, line indicates median estimate and shaded region represents the 95% confidence interval. (d) Mean proportion attributed to human-induced climate change at 854 cities during 2000-2028 (e) Mean proportion attributed to human-induced climate change per country and year during 2000-2028



NO: Norway, SE: Sweden, FI: Finland, EE: Estonia, LV: Latvia, LT: Lithuania, DK: Denmark, UK: United Kingdom, IE: Ireland, FR: France, BE: Belgium, NL: Netherlands, LU: Luxembourg, CH: Switzerland, DE: Germany, AT: Austria, PL: Poland, CZ: Czech Republic, SK: Slovakia, HU: Hungary, RO: Romania, BG: Bulgaria, EL: Greece, CY: Cyprus, HR: Croatia, SI: Slovenia, IT: Italy, MT: Malta, ES: Spain, PT: Portugal

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1527 **Fig. 4:** Map of (top) median of annual age standardised excess deaths due to heat and (bottom) proportion
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1529 of excess deaths attributable to climate change in each of the 854 cities, in (left) 2003 and (right) 2025.



Supplementary Files

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