Disentangling the contributions of anthropogenic climate change, greenhouse gases, and aerosols to heat-related mortality in Great Britain: a climate change impact attribution study

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Summary

Background Anthropogenic aerosols are a critical contributor to climate change and their net cooling effects can partially counter the warming effects of greenhouse gases, but they are rarely considered in health impact attribution studies of climate change. The aim of this study was to attribute heat-related deaths in Great Britain to anthropogenic climate change and individual forcings of greenhouse gases and aerosols.

Methods Using a special suite of climate simulations, past and future heat-related deaths in Great Britain attributable to the relative contributions of anthropogenic greenhouse gas and aerosol forcings were estimated under the Shared Socioeconomic Pathway SSP2-4.5. Empirical confidence intervals were quantified combining uncertainties from climate models and health risk functions.

Findings Emergence of heat-related mortality associated with anthropogenic climate change was partially counteracted by the cooling effects of aerosols, with the time of emergence being approximately four decades later compared with the greenhouse gas-only simulation. We estimate that around 700 annual heat-related deaths during 1961–1980 were masked by the cooling effects of aerosols. There was a sharp increase in heat-deaths between 1980 and 2020 due to the combined effects of greenhouse gas increases and large aerosol reductions. By the end of the 21st century, a 2–6-fold increase in heat-related deaths due to greenhouse gases is projected, with a negligible counteracting contribution of aerosols.

Interpretation In addition to greenhouse gases, the potential contributions of aerosols should be considered when assessing climate change risks and mitigation pathways. This is crucial due to their opposing temperature effects, diverging future emission trajectories, and varying geographical scales. Separate attribution of climate change impacts to the global effects of greenhouse gases and local effects of aerosols can enhance transparency and equity, and can inform loss and damage funding models. Such impact attribution assessments can help to optimise health co-benefits and prevent unintended negative consequences of environmental policies on heat-related and air pollution-related health outcomes.

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Introduction

There is increasing interest in climate change impact detection and attribution studies that investigate changes to natural and human systems and the extent to which they can be explicitly attributed to anthropogenic climate change.[1] Such impact attributions are critical to demonstrate the present and growing threat of climate change, requiring stronger policy actions on climate change adaptation and mitigation as well as potentially informing loss and damage funding models providing financial assistance to the most climate-vulnerable countries.[2]

Attribution studies have been conducted on heat-related mortality, but only considering impacts since the 1990s rather than earlier periods when a climate change signal was already present.[3,4] Furthermore, previous studies only estimated the contribution of climate change or anthropogenic climate change as a whole.[1] To the best of our knowledge, no health impact attribution study has characterised the individual contributions of anthropogenic greenhouse gas and aerosol forcings, even though attribution to individual climate forcings is a key research area in climate science.[5]

Anthropogenic aerosols (ie, small solid particles or droplets of human origin suspended in the atmosphere) have a net cooling effect on the global climate due to scattering of incoming solar radiation and effects on

Research in context

Evidence before this study

Anthropogenic aerosols play an important role in climate change, with their net cooling effects partially offsetting the warming caused by greenhouse gases. However, they are seldom accounted for in studies attributing health impacts to climate change. We searched Web of Science Core Collection for papers published from database inception to Nov 22, 2024, using the terms (anthropogenic OR human) AND (climate change OR global warming) AND (aerosol OR black carbon OR organic carbon OR sulphur dioxide OR nitrogen oxides OR ammonia OR carbon monoxide OR volatile organic compound) AND (attribut*) AND (temperature OR heat) AND (health OR mortalit* OR death OR morbidit* OR disease OR hospital*). No previous study attributing temperature-related health impacts to anthropogenic aerosols was identified.

Added value of this study

This study provides new evidence quantifying the relative contributions that anthropogenic aerosols and greenhouse gases have made to heat-related mortality. It demonstrates that anthropogenic climate change has significantly contributed to heat-related deaths in Great Britain since the early 21st century, while the cooling effects of aerosols partially masked heat-related deaths due to greenhouse gases during the mid-to-late 20th century. Without the aerosol cooling effect, the emergence of heat-related mortality associated with anthropogenic climate change would have occurred up to four decades sooner. Nevertheless, future projections indicate a reduced aerosol cooling potential with heat-related mortality being dominated by greenhouse gases. To the best of our knowledge, this is the first study investigating the individual contributions of anthropogenic greenhouse gases and aerosols to past and future heat-related health burdens.

Implications of all the available evidence

Aerosols have contributed to past reductions in heat-related mortality in Great Britain through net cooling effects. By the end of the century, anthropogenic aerosols will generally decrease whereas greenhouse gases will continue to increase unless stringent mitigation actions are taken, with greenhouse gases predominantly driving climate change and heat-related health burdens under most scenarios. However, under extremely low emission scenarios, the warming induced by reducing aerosols might outweigh the warming due to greenhouse gases, although aerosols are of course associated with substantial adverse health impacts related to air pollution exposure. Policy makers need to consider both air pollution reduction and climate change mitigation strategies to increase the health co-benefits and minimise disbenefits associated with greenhouse gases and aerosol concentrations, particularly the relative health impacts associated with ambient temperature and air pollution exposures. The global reach of the warming effects of greenhouse gases necessitates joint mitigation efforts by the global community, whereas aerosol effects are largely local or regional and hence require country-specific reduction measures. Attributing climate change impacts to individual forcings of anthropogenic greenhouse gases and aerosols is thus essential for equitable decision making in the context of loss and damage funding and international climate policy.

cloud formation and characteristics.[6] The warming caused by greenhouse gases since the pre-industrial period was, therefore, partially masked by such aerosols in the atmosphere. However, aerosols have been decreasing globally since the early 2000s and will generally decline further by the end of the century under all trajectories of climate change due to air quality improvement and climate change mitigation policies.[7] Despite the massive health benefits associated with improved air quality, the reduction in aerosols is expected to accelerate global warming and hence is an important process to consider in heat-health attribution assessments of climate change.[8]

By capitalising on daily mortality datasets spanning almost 40 years, we estimate heat-related deaths in Great Britain between 1850 and 2100 under Shared Socioeconomic Pathway SSP2-4.5 using a special suite of climate simulations. For the first time, we quantify the relative contributions made by greenhouse gas and aerosol forcings to heat-related mortality. Furthermore, by applying a multi-member approach, we disentangle projected climate change signals from underlying natural climate variability.

Methods

Climate data and bias adjustment

We considered data under four different climate forcing agents from the Detection and Attribution Model Intercomparison Project (DAMIP[9]): one factual simulation including all climate forcings and three counterfactual simulations isolating natural forcings, anthropogenic tropospheric aerosols, and anthropogenic well mixed greenhouse gases (appendix p 1). All simulations followed their respective historical path (1850–2014) and projections under SSP2-4.5 (2015–2100). Two climate models met these criteria (ten members per forcing set) and were selected for our study: CanESM5[10] and MIROC6.[11]

The climate data were statistically downscaled to a 0·5° grid and bias-adjusted using non-parametric quantile mapping. GSWP3-W5E5 was used as the reference climatology for 1901–1950; this is a gridded dataset provided by the Intersectoral Model Intercomparison Project (ISIMIP) that combines data from the Global Soil Wetness Project Phase 3a dataset (GSWP3[12]) and the WATCH Forcing Data over land merged with the European Centre for Medium-Range

Weather Forecasts Reanalysis version 5 (ERA5) over the ocean (W5E5 version 2.0[13,14]; appendix pp 2–3).

Mortality and demographic data

Daily all-cause mortality counts (1981–2019) for three age groups (0–64, 65–74, and ≥75 years) were obtained from the Office for National Statistics (ONS) for England and Wales and the National Records of Scotland. Mortality data were only available at the Government Office Regions level (figure 1) for the full study period (1981–2019). Time-series and descriptive statistics of summer mortality are shown in the appendix (pp 5–6). Annual population estimates (1981–2019) were obtained from the ONS.[15]

Epidemiological analyses

Time-series quasi-Poisson regression with distributed lag non-linear models[16] were used to characterise temperature–mortality relationships during summer months (May to September) between 1981 and 2018 (see appendix p 4 for model specifications). GSWP3-W5E5 temperature data served as the observed temperature (appendix pp 5–6).

Climate change risk assessment and impact attribution

The population in 2011 and the average temperature–mortality relationship and annual cycle of mortality rate in 1981–2019 were applied to estimate the heat-deaths in the whole period of 1850–2100.

Daily heat-deaths (HD) were calculated as below,[17] and this calculation was repeated for individual age group (a) and region (r).

$$\mathrm{HD}_{d,f_{me}}=(\mathrm{RR}_{t_{d,f_{me}}}-1)\times P\times \mathrm{BMR}_d$$

$$\mathrm{BMR}_d=\frac{\mathrm{DMR}_d}{\mathrm{RR}_{t_d}}$$

Where RR is the relative risk of mortality at daily mean temperature t for day d against the minimum mortality temperature (MMT). The time-series for t was obtained from the output of ensemble e of climate model m for the forcing f. The RR corresponding to t was obtained from the age-specific, region-specific temperature–mortality relationships. P is the population of age group a in region r. BMR is the baseline daily all-cause mortality rate, which was calculated from the daily mortality rate (DMR) in 1981–2019 excluding deaths attributed to heat. Annual heat-deaths were calculated by summing daily heat-deaths during May to September each year.

The attributable number (AN) of heat-deaths to anthropogenic climate change, greenhouse gases, and aerosols was estimated by subtracting the heat-deaths under the natural-only simulation ($\mathrm{HD}_{\mathrm{nat}}$) from the all-forcing, greenhouse gas-only, and aerosol-only simulations, respectively. The attributable percentage (AP) was estimated by dividing the AN of anthropogenic climate change, greenhouse gases, and aerosols by the heat-deaths under the all-forcing simulation ($\mathrm{HD}_{\mathrm{all}}$).

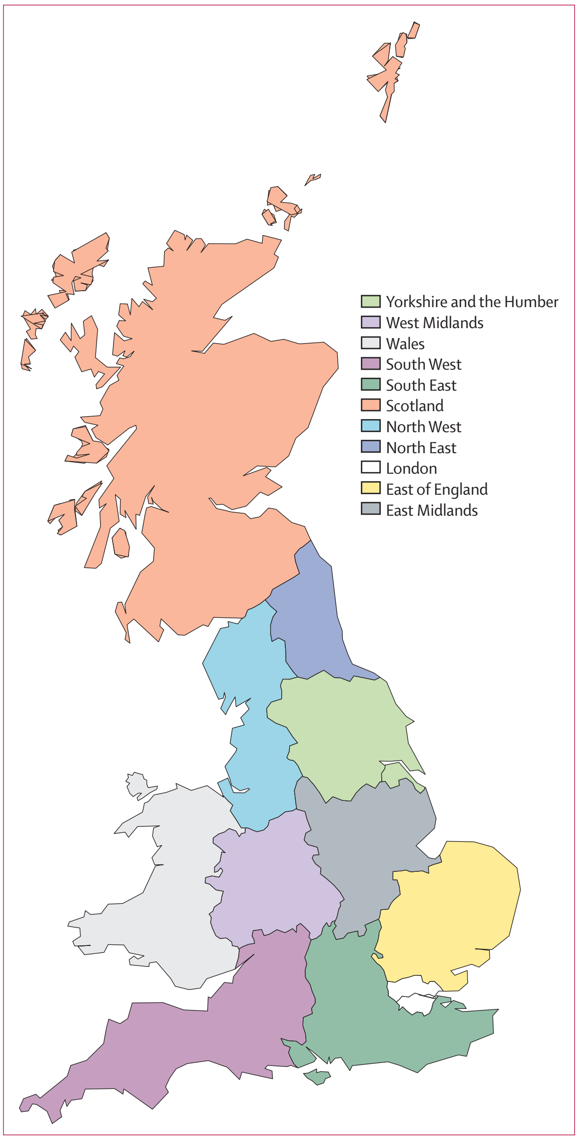

Figure 1: Regions of the epidemiological analysis

$$\mathrm{AN}=\mathrm{HD}_f-\mathrm{HD}_{\mathrm{nat}}$$

$$\mathrm{AP}=\left(\frac{\mathrm{AN}}{\mathrm{HD}_{\mathrm{all}}}\right)\times 100$$

We quantified the combined effects of two main sources of uncertainty—the health risk function of the temperature–mortality association, and the temperature variability from climate models. Monte Carlo simulations were used to estimate the 95% empirical confidence interval (eCI) for AN and AF (appendix pp 8–9). Due to the temperature difference between climate models, heat-deaths and uncertainties were quantified separately for each model.

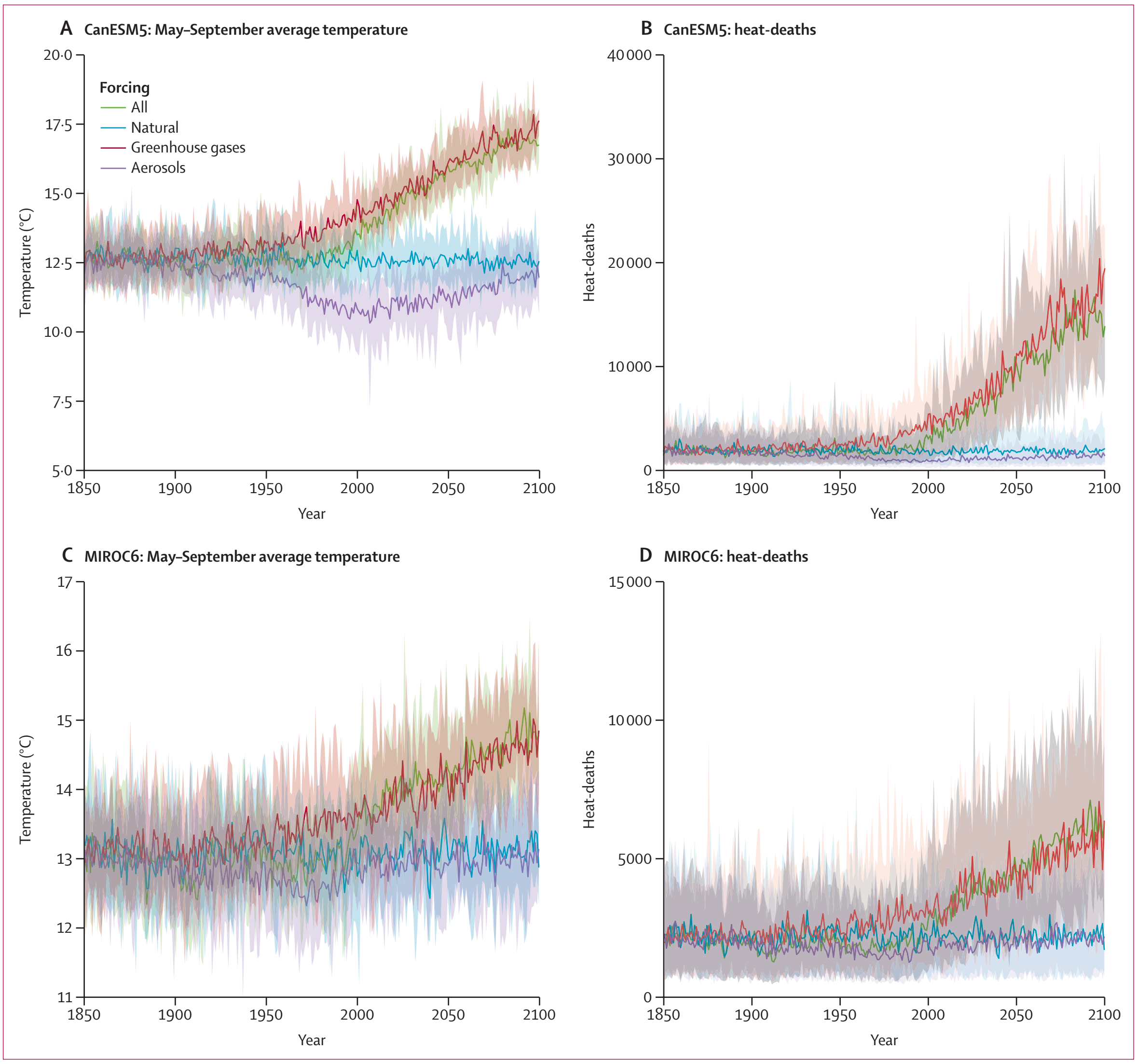

Figure 2: **Summer temperatures and heat-related mortality in Great Britain, 1850–2100**

Average summer temperature in May to September (A and C; shade represents temperature range across ten members of each climate model ensemble) and heat-related mortality (B and D; shade represents 95% empirical confidence interval combining the uncertainties from both the health risk function and from internal climate variability, see Methods) in Great Britain under the four forcing schemes since 1850 and in future periods up to 2100 under SSP2-4.5 (see appendix p 9 for values; see appendix p 3 for temperature anomaly under the all-forcing, greenhouse gas-only, and aerosol-only simulations compared with the natural-only simulation). Note, y-axis scales are different between upper and lower graphs.

Time of emergence (ToE) analysis and SMILEs

Climate change signals were disentangled from natural variability using single model initial-condition large ensembles (SMILEs), which quantify climate variability using multiple simulations with slightly different initial conditions (ie, members) of the same climate model.[18]

ToE marks when climate change signals significantly deviate from natural variability. A two-sided Kolmogorov–Smirnov test (5% significance) was applied.[19] The natural-only simulation of the respective SMILE and member served as the reference covering 1850–2100 for better statistical representation. A 20-year moving window for 1859–2091 centred at each year of the period was used (first year is 1859 covering 1850–1869), with ToE assigned to the first year where differences remain significant. ToE marks the time when the temperature time-series moves to a new climate state.

Sensitivity analysis

GSWP3-W5E5 temperature data were used for both bias adjustment of climate model temperature outputs and the epidemiological analyses, minimising potential systematic biases. Because this dataset captures orographic and urban heat island (UHI) effects only to a limited extent, an alternative temperature–mortality

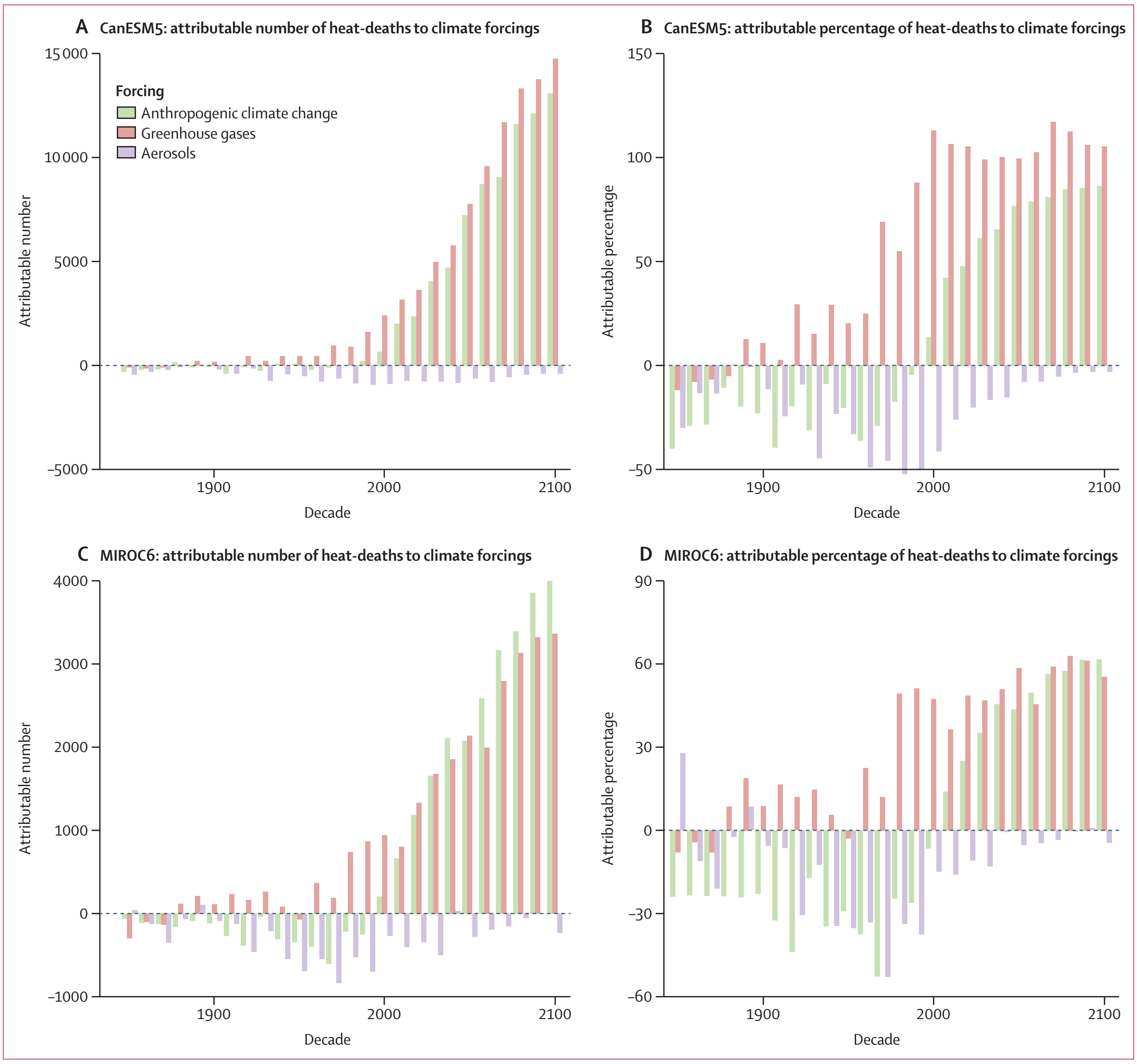

Figure 3: **Annual number and percentage of heat-deaths attributable to anthropogenic climate change, greenhouse gases, and aerosols**
The mean attributable number and percentage of annual heat-deaths in Great Britain to anthropogenic climate change, greenhouse gases, and aerosols in each decade between 1850 and 2100 from two climate model outputs (see appendix pp 9–11 for values). y-axis scales are different between upper and lower graphs. The attributable number and fraction of heat-deaths under the individual forcings are not additive because of the non-linear health risk function. This illustrates the change in annual heat-deaths attributable to anthropogenic climate change and the individual forcings of anthropogenic greenhouse gases and aerosols.

association was derived using temperatures from the ERA5-Land dataset (approximately 9 km spatial resolution) as a sensitivity analysis.

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 British mean summer temperature under the natural-only forcing (1850–2100) is 12·6°C in CanESM5 and 13·1°C in MIROC6 (figure 2A, C). In 1961–1980, summer temperatures increased by 0·8°C (CanESM5) and 0·3°C (MIROC6) under the greenhouse gas-only simulation compared with the natural reference state (pre-industrial conditions). Over the same period, aerosols contributed a similar magnitude of cooling (1·2°C for CanESM5, 0·5°C for MIROC6), offsetting greenhouse gas-induced warming. The appendix shows temperature–mortality associations (appendix pp 6–7) and MMT thresholds (appendix p 8). The results of the sensitivity analyses (appendix p 8) align closely with the main analysis (appendix p 6), confirming the robustness of the health risk functions.

Anthropogenic climate change is projected to result in a 4·3°C (CanESM5) and 1·6 °C (MIROC6) increase by 2100 under SSP2-4.5. Aerosol cooling is projected to

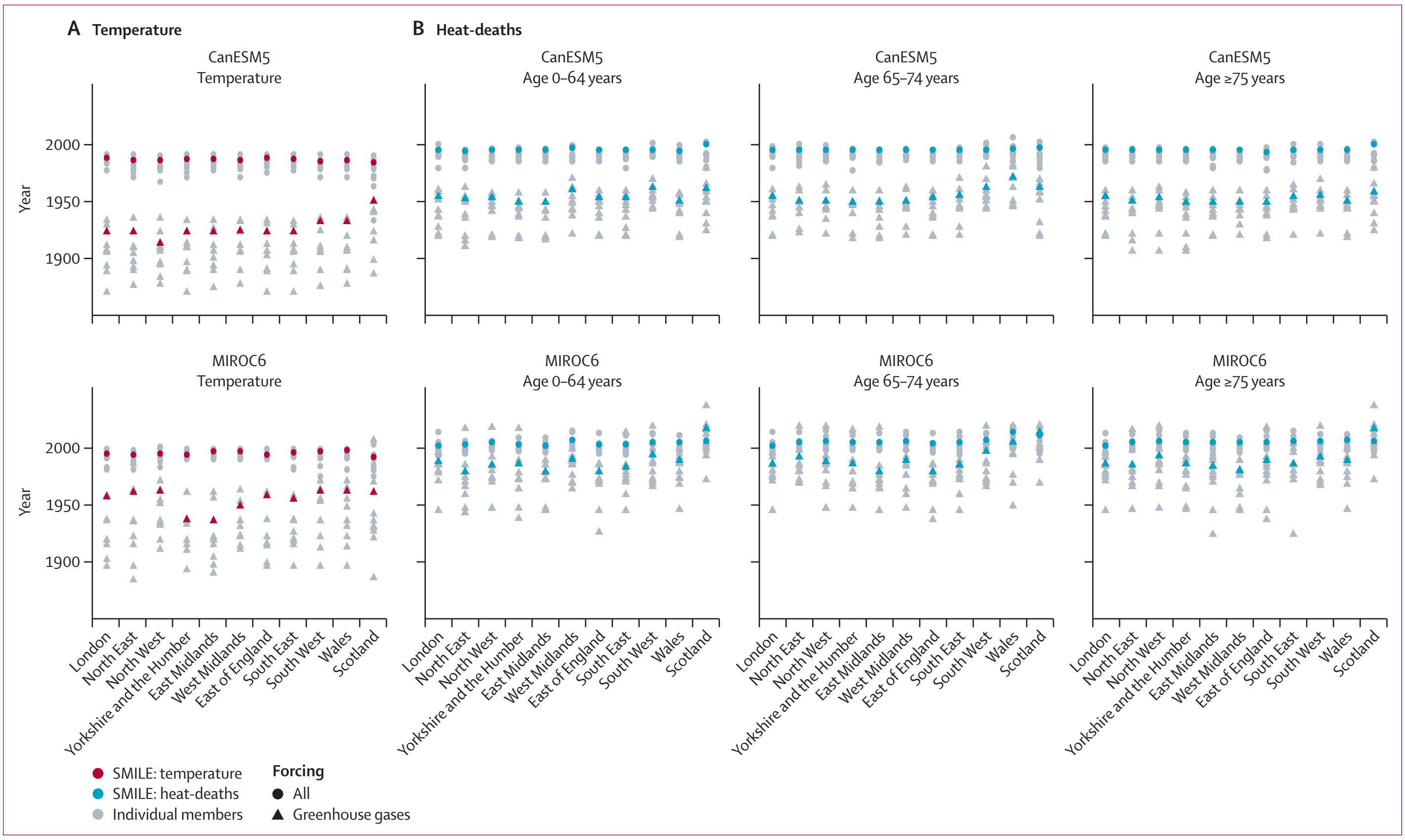

Figure 4: **Time of emergence of temperature and heat-death increases**

The time of emergence of temperature (A) and heat-death (B) increases under the all-forcing (circles) and greenhouse gases forcing (triangles) simulations from individual members (grey) and as consequently derived for each SMILE (red for temperature and blue for heat-deaths; see Methods for details). See appendix pp 11–13 for values. Time of emergence indicates the year from which there is a significant increase in heat-deaths compared with historical periods. SMILE= single model initial-condition large ensemble.

decline, with limited detectability by the end of the century (–0·5°C and –0·1°C in CanESM5 and MIROC6, respectively) compared with natural conditions (appendix p 9). Consequently, future heat-deaths are projected to be dominated by greenhouse gases.

Average annual heat-deaths in Great Britain under the natural-only forcing (1861–2100) were estimated to be 1944 (95% eCI 1096–3416; CanESM5) and 2195 (1267–3792; MIROC6; figure 2B, D). During 1961–1980, greenhouse gases contributed to 936 (408–1724; CanESM5) and 465 (148–990; MIROC6) annual heat-deaths, which were partially or even fully offset by aerosol cooling—746 (318–1452) and 682 (314–1087) in CanESM5 and MIROC6, respectively (figure 3). Aerosol-driven cooling peaked during this period in both models.

In 2001–2020, annual heat-deaths under the all-forcing simulation were 4009 (95% eCI 2452–6271; CanESM5) and 3150 (1926–5075; MIROC6). Anthropogenic climate change accounted for 55% (95% eCI 42–67; CanESM5) and 29% (16–45; MIROC6) of these deaths (appendix pp 9–11). Greenhouse gases resulted in 87% (59–138; CanESM5) and 35% (17–66; MIROC6) additional heat-deaths, whereas aerosol cooling reduced deaths by 19% (6–27; CanESM5) and 12% (7–26; MIROC6).

By 2081–2100, annual heat-deaths are projected to be 14451 (95% eCI 11661–17364; CanESM5) and 6152 (4505–8406; MIROC6) under the all-forcing simulation, with anthropogenic climate change accounting for 87% (95% eCI 79–92; CanESM5) and 65% (52–74; MIROC6) of them, and greenhouse gases contributing to 100% (86–126; CanESM5) and 56% (39–77; MIROC6) of them. Annual heat-deaths (all-forcing) in 2081–2100 are projected to increase by 260% (CanESM5) and 95% (MIROC6) compared with the recent period 2001–2020, and by 649% (CanESM5) and 180% (MIROC6) compared with the natural-only simulation.

Despite minimal temporal change in summer temperature variability (standard deviation 2·7–3·0°C [CanESM5] and 2·3–2·8°C [MIROC6]; 1861–2100), annual heat-death variability is projected to increase (figure 2B, D). During 1961–1980, the difference between the upper and lower 95% confidence bounds of annual heat-deaths under the factual simulation remained stable at up to 2339 (CanESM5) and 2571 (MIRCO6) annual deaths, rising to 5703 (CanESM5) and 3901 (MIROC6) by 2081–2100 (appendix pp 9–11).

Climate change signals emerge earlier for the greenhouse gas forcing than for the combined anthropogenic forcings (figure 4). British summer temperatures under the all-forcing simulation remained near natural state until 1987 (CanESM5) and 1995 (MIROC6), whereas greenhouse gas-induced warming emerged as early as 1927 (CanESM5) and 1955 (MIROC6). Similar patterns were observed in all regions (appendix pp 11–13).

ToE spread was higher for greenhouse gases than the all-forcing simulation (figure 4), indicating a larger contribution of natural variability to the former. Interestingly, the related ToE for heat-deaths occurred with a temporal delay. Across all age groups, mortality ToE under the all-forcing simulation was detected in the 1990s (CanESM5) and early 2000s (MIROC6), whereas for greenhouse gases, ToE occurred 2–4 decades earlier (CanESM5: 1950s; MIROC6: late 1980s).

Discussion

This study demonstrates that anthropogenic climate change significantly contributed to heat-deaths from the beginning of the 21st century and the cooling effect of aerosols masked additional heat-deaths due to greenhouse gases from the mid-to-late 20th century. There was a sharp increase in heat-deaths between 1980 and 2020 due to anthropogenic climate change that will be increasingly driven by greenhouse gases in the future. Heat-deaths increased more rapidly than increases in temperature under climate change, demonstrating the non-linearity of the increase in impacts against the hazard.[20]

During 2001–2020, there were 3150–4009 annual heat-deaths in Britain, with 29–55% attributable to anthropogenic climate change. This is in line with a previous UK estimate of 35·1% heat-deaths attributable to anthropogenic climate change during 1991–2016.[3] Annual heat-deaths in Britain are projected to increase by 260% by 2100 compared with 2001–2020 (SSP2-4.5, CanESM5). This is comparable to a previous finding of a doubling of heat-deaths in the UK by 2090–2099 from 2010–2019 under comparative scenarios.[21] Such health impact assessments of climate change ordinarily compare current heat-health impacts with future burdens and interpret the difference as the additional burden due to climate change.[21] However, this only provides a partial assessment since the climate considered in the baseline period has already warmed compared with pre-industrial times. Our study shows that heat-deaths are projected to increase by up to 649% (CanESM5) by 2081–2100 under the all-forcing simulation compared with the natural-only simulation (pre-industrial conditions), which is more than double the amount when compared with the baseline of 2001–2020.

We further found marked differences in the emergence of climate change signals (ToE) on temperatures and heat-related mortality. The identified temporal lag between the two of several decades makes the case for the consideration of longer time periods in attribution assessments. Given the heterogeneity of global ToE patterns,[19] impact attribution studies should fully account for the contribution of climate change also at the regional scale. The identified large spread of ToE for greenhouse gases highlights the importance of considering natural climate variability.

Although aerosols are associated with reduced heat-health burdens due to their overall cooling effect, their net contribution to health is overwhelmingly negative given the many adverse health impacts associated with air pollution. For instance, there were an estimated 48·6 thousand particulate matter-related premature deaths among UK adults in 2019,[22] in contrast to the approximate 750 heat-deaths prevented from the cooling effects of aerosols as estimated in our study. Furthermore, climate change is increasing the risk of wildfires,[23] with resulting aerosols potentially reaching the stratosphere and causing ozone depletion,[24] which in turn might pose additional indirect health risks through increased exposure to ultraviolet radiation.

We did not control for air pollution in the epidemiological models because some of the temperature effect operates through changes in air pollution and hence air pollution might be on the causal pathway between temperature and mortality, which argues against its control.[25] In any case, particulate matter was not found to have a confounding effect on the temperature–mortality relationship in previous UK studies.[17,26] Nevertheless, this does not discount possible synergistic effects between temperature and air pollution, which likely differ by pollutant type and location. For example, ozone increases at higher temperatures but significant interaction effects in Great Britain were only observed in London.[27] Given such context, it is unlikely that our main findings would affected by this omission.

We also did not consider potential impacts on cold-related mortality burdens. The radiative effects of aerosols are seasonal, with stronger effects in summer when incoming solar radiation is scattered more efficiently than in winter. Reduction in regional aerosol emissions in Europe thus results in increased summer maximum temperature but little change in winter minimum temperature.[28] Therefore, a reduction in aerosols might not directly translate into decreased cold-health impacts. Additionally, the risk of mortality due to cold has broadly decreased in Great Britain,[29,30] complicating any potential health gains of climate change due to milder winters.

This study was conducted under the SSP2-4.5 climate scenario, which represents a middle-of-the-road scenario with a continuation of existing environmental and climate policies in line with the current global warming trajectory. Hence, the findings have high relevance to probable future trajectories.[31] However, aerosol emission pathways are particularly important for low emission scenarios in the near future, under which warming due to aerosol reduction could dominate compared with greenhouse gases.[32] This might even lead to a warmer climate in some locations under Representative Concentration Pathway (RCP) 2·6 compared with RCP4·5 despite lower greenhouse gas emissions.[33]

CanEMS5 and MIROC6 were the only models providing all four forcing agents with multiple members. These two models, however, provide a good estimate of the climate expected under the respective forcing scenarios. Whereas CanESM5 is considered a “hot model” reacting sensitively to greenhouse gas changes,[34] MIROC6 is on the lower bound of climate projections;[19] thus, our results broadly reflect reasonable upper and lower bounds for the potential health impacts. This is also reflected in the warming projected for Great Britain in our study, where CanESM5 yielded higher end-of-century warming than MIROC6. The sensitivity of the two models for the aerosol forcing under the present climate is in a similar range and close to the respective CMIP6 average of similar models.[35] However, aerosol cooling shows different pathways over the second half of the 20th century in Great Britain between the two models. This is partly because the aerosol component of CanESM5 is driven by aerosol emissions whereas MIROC6 uses prescribed concentrations. However, the largest uncertainty source for aerosol forcing sensitivity is aerosol–cloud interactions.[36] Although the general latitudinal cooling patterns are in agreement with observations, they are much less pronounced in MIROC6, which further underestimates the temporal extent of the mid-20th century cooling period.[37] Still, the greenhouse gas forcings contribute primarily to the spread in end-of-century projections, whereas the aerosol responses are similar between the two models.

Given the application of global models, our study cannot properly consider the UHI effect. Although the statistical downscaling applied introduces the UHI effect to some extent, the underlying climate model data are not capable of representing effects.[38] However, this should not have substantial impacts on estimated heat-deaths since consistent temperature data were used for deriving health risk functions and were bias-adjusted. Due to the relatively coarse resolution of the climate outputs and the sparse population distribution in Scotland compared with England, Scotland is treated as a single region in the epidemiological analysis to obtain a more stable heat-health risk function. However, the resulting temperature–mortality association is comparable to a previous study for separate Scottish cities and regions.[26]

Demographic factors, baseline mortality rates, and heat response functions were assumed to be static in this study. Such an approach in impact attribution studies allows focus on the contribution of climate change.[39] Integrating acclimatisation or adaptation into heat-health burden estimation remains a challenge due to inadequate empirical evidence.[40] Some studies modelled the effect of housing or land use on heat-health burdens, and projected future burdens based on assumed changes in these factors.[41,42] However, these studies usually focus on a single adaptation mechanism, overlooking the broader, multifaceted nature of population adaptation. Demographic changes can affect future health burdens too, which might contribute to future heat-deaths in the UK more than climate change itself.[43] Notably, changes in life expectancy can have opposing effects on heat-health burdens—increasing the older population while reducing underlying mortality rates.[44] Future research could consider these important aspects.

Our study demonstrates the importance of considering the separate effects of greenhouse gases and aerosols in climate change impact assessments because of their opposing temperature effects, diverging future emissions trajectories, and varying geographical effects. As well as obvious implications for the research community, policy makers must recognise that air pollution and climate mitigation actions have differing impacts on greenhouse gas and aerosol concentrations and associated heat-related and air pollution-related health impacts, which should be a factor when considering different policy options. Both air pollution and climate change mitigation actions are crucial. While many actions clearly contribute to both air pollution and climate change mitigation (eg, switching from fossil fuels to renewable energy), some interventions that target only one factor could have unintended negative consequences on the other. For example, when both aerosols and greenhouse gases are generated by the same source (eg, coal power plants) and only the gases that contribute to aerosols are removed (eg, SO_2, which produces sulphate aerosols, being removed through flue gas desulphurisation), this helps to improve air quality but leaves greenhouse gas emissions unaddressed. Similarly, climate change mitigation policies might be to the detriment of air quality if not carefully planned, such as the UK Government’s doomed policy of promoting diesel vehicles on account of their greater fuel efficiency but which served to increase certain air pollutants. Therefore, it is important to consider health impacts holistically to inform effective air pollution reduction and climate change mitigation actions that can contribute health co-benefits and avoid unintended negative impacts.[45,46]

Furthermore, drawing no distinction between greenhouse gases and aerosols runs the risk that the warming effects of greenhouse gases, and their associated health impacts, are masked by the local or regional effects of aerosols. Whereas the warming effects of well mixed greenhouse gases are largely global regardless of emission source, climate effects of aerosols are regional and geographically heterogeneous.[47] The general effects of aerosol cooling are detectable across the globe, potentially altering climate circulation patterns;[48] however, the specific pathways and magnitudes likely differ across regions, requiring region-specific studies. This has the potential to exacerbate geographical inequalities in emissions in situations where the greenhouse gases are emitted much further afield.

Finally, our study highlights the importance of attribution science in informing more realistic loss and funding models. For example, models based on traditional health impact assessments that take the recent past as the baseline to estimate climate change risk would underestimate impacts since the influences of greenhouse gases might have occurred decades earlier, as shown by our results. Such findings would be particularly important to demonstrate in low-income and middle-income settings, where responding to loss and damage will be a key component of countries developing climate resilience. Such evidence-based information from attribution studies will become increasingly important in international climate policies and loss and damage funding models that promote climate change resilience and health equity.

Contributors

KW: conceptualisation, data curation, formal analysis, investigation, methodology, project administration, software, visualisation, writing (original draft, review and editing). DG: conceptualisation, data curation, formal analysis, investigation, methodology, software, visualisation, writing (original draft, review and editing). SH: conceptualisation, data curation, funding acquisition, investigation, methodology, supervision, writing (original draft, review and editing). KW and SH had full access to the mortality data in the study, and all authors had full access to the climate data in the study. All authors had final responsibility for the decision to submit for publication. KW and SH accessed and verified the mortality data, and DG and KW accessed and verified the climate data.

Declaration of interests

We declare no competing interests.

Data sharing

Mortality data cannot be shared due to confidentiality. The GSWP3-W5E5 temperature data used in this study are open-access and can be accessed through https://www.isimip.org/gettingstarted/input-data-bias-adjustment/details/110/. The applied climate projections with the corresponding variables under historical and SSP2-4.5 are provided by the DAMIP project and available under the Earth System Grid Federation nodes (https://esgf-metagrid.cloud.dkrz.de/search).

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