Metadata

Title: Estimating Heat-Associated Mortality in England: Methodological Framework of UKHSA's Heat Mortality Surveillance System

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Abstract

Extreme heat is an escalating public health risk in England, linked to substantial heat-associated mortality. Reliable, timely estimates are essential to monitor impacts, identify vulnerable groups, and evaluate the effectiveness of public health responses. However, existing approaches, such as reliance on heat-specific causes of death or use of statistical models to estimate heat-attributable mortality, risk underestimation or oversimplify the burden on health.

This study presents the UK Health Security Agency's (UKHSA) hybrid surveillance method, which combines estimates of observed all-cause heat-associated deaths during defined heat episodes with modelled expectations based on recent temperature–mortality relationship. Observed estimates provide transparent, episode-specific figures disaggregated by age, sex, setting, cause, and geography, while modelled outputs help to contextualise whether real-world impacts align with recent trends.

Applied to summer 2024, the approach identified four heat episodes and an estimated 1,311 heat-associated deaths (95% CI: 929–1,692), concentrated among older adults. Modelled estimates suggested 1,028 deaths (95% CI: 866–1,155). Although confidence intervals overlapped, observed mortality was consistently higher than predicted, particularly during earlier summer episodes, suggesting that factors beyond temperature may have amplified observed impacts. Later episodes, by contrast, showed closer alignment between observed and expected figures, indicating potential seasonal adaptation or improved preparedness.

By integrating observed mortality with modelled context, UKHSA's approach avoids underestimation, supports evaluation of Heat-Health Alerts, and enables year-on-year monitoring of progress in reducing risks. This dual-method framework provides a practical, reproducible tool for national surveillance and strengthens the evidence base for targeted interventions and climate adaptation planning.

Keywords: Heat-associated mortality, UKHSA, surveillance methodology, public health.

Highlights: *(each 87 characters incl. spaces max)*

- Hybrid method uses observed and modelled heat-related death estimates
- Heat episodes defined using alerts and temperature, with lag days included
- Data disaggregated by age, region, setting, sex, and cause of death
- DLNM modelling allows comparison across years with different heat levels
- Observed deaths validate models, revealing social and health system factors

1. Introduction

Extreme heat presents a growing public health challenge, particularly as climate change increases the frequency, intensity, and duration of heat episodes across the UK.[1, 2] Elevated temperatures have been linked to increased mortality, particularly among older adults and individuals with pre-existing health conditions.[3-7] In response, the UK Health Security Agency (UKHSA) has developed a range of public health and policy interventions aimed at reducing heat-related harm. These include the Adverse Weather and Health Plan (AWHP), the Heat-Health Alert (HHA) system developed by UKHSA, and broader strategic climate adaptation initiatives led by national and local government bodies.[8, 9] However, the effectiveness of these interventions remains difficult to assess without robust, ongoing surveillance of the health impacts associated with heat. Reliable and timely estimates of heat-related mortality are essential to monitor trends, identify at-risk populations, and evaluate the public health response from year to year.

Despite growing attention to this issue, significant challenges persist in quantifying the health burden of heat. For example, in England, two government agencies, UKHSA and the Office for National Statistics (ONS), have previously produced independent estimates of heat-associated mortality using different methodologies, resulting in divergent figures and occasional confusion among statistics users.[10-12] Some approaches being promoted in recent years rely on attributing deaths to heat by modelling the temperature-mortality relationship over a number of years;[12, 13] however, heat impacts are shaped by a wider set of contextual factors, including housing, health systems, behaviour, and social factors that may change between different heat events and years, which models may not fully capture.[7, 14] These limitations constrain efforts to assess trends and evaluate the effectiveness of current public health responses. Similar challenges are noted internationally in a recent European Environment Agency report that found considerable variation in how countries monitor heat-related mortality,[15] with few systems able to disaggregate impacts by age, setting, or cause, and limited ability to link estimates to public health interventions.

This paper describes UKHSA's approach to estimating heat-related mortality in England, which combines episode-based analysis of observed mortality with modelled expectations using a Distributed Lag Non-Linear Model (DLNM) on historic data. We outline the structure and rationale of this hybrid methodology, explore its strengths and limitations, and reflect on how it may evolve to support more responsive and effective public health action in the context of a warming climate. By doing so, we aim to provide a transparent blueprint for national-level heat mortality surveillance and a foundation for future methodological development.

2. Materials and methods

2.1. Data sources

Data on daily deaths was obtained from the Office for National Statistics (ONS) death registrations data for the years 2019 to 2024. Data fields extracted were the date of death, the Lower Super Output Area (LSOA) of the location of death, age at death in years, sex as recorded on the death certificate, place of death (aggregated according to National End of Life Care Intelligence Network guidelines),[16] and underlying cause of death categorised in alignment where possible with groups within OHID Excess Mortality in England reports.[17] Deaths with COVID-19 coded as any cause of death on the death certificate were removed before analysis. Location of death was aggregated up from LSOA to two levels, first English region and second Local Resilience Forum area.

Temperature data was obtained from the Met Office through the UKHSA Environmental Public Health Surveillance System (ephss.ukhsa.gov.uk) for the years 2019 to 2023, for use in the modelling of the historic heat-mortality relationship. We obtained gridded data daily maximum temperatures and daily minimum temperatures at 0.1 degree resolution, using an inverse-distance-weighted mean to calculate temperatures for each grid point. This was processed to produce a daily mean temperature for each English region, calculated as the midpoint of the maximum and minimum for each grid point and then averaged across the region.

For the identification of heat episode days in each summer, UKHSA log data on issuing, updating and cancelling of Heat Health Alerts was used, as well as publicly available data from the Met Office Hadley Centre observations dataset on the Central England Temperature (CET).[18]

2.2. Defining heat episodes

There is no single definition of a heat episode in England. The Met Office defines a heatwave as "a period of at least three consecutive days with daily maximum temperatures meeting or exceeding the heatwave temperature threshold", with thresholds ranging between 25ºC and 28ºC for different areas of the UK.[19] This definition is not suitable for heat mortality surveillance, as increased mortality has been known to occur in shorter and more moderate periods of heat.

The definition used to identify a heat episode in UKHSA heat mortality monitoring has been reported previously,[6, 14] and is a mean Central England Temperature of at least 20ºC, or an Amber Heat Health Alert in at least one region of England. (Prior to 1st June 2023, these were known as Level 3 Heat Health Alerts.) One day before is included to capture the impact of the initial increase in temperatures at the beginning of a heat episode, which may start before alerting thresholds or the 20°C mean CET threshold are reached, and one day before and one day after is also included to account for potential delayed health effects of heat.

2.3. Estimating observed heat-associated mortality

Heat-associated mortality for each heat episode is estimated as the difference between average daily mortality on heat episode days and average daily mortality in a baseline period, multiplied by the number of days of the heat episode. The baseline period used is the 14 days before and 14 days after the heat episode in the same summer. (If any other heat episodes fall within that period, those days are 'skipped' and earlier or later days are used in the baseline to make up 14 days on either side, within a maximum window of 21 days before or 21 days after.)

This method was applied to all England deaths (excluding Covid-19 deaths) to produce overall estimates of heat-associated mortality. It was then applied to subsets of the data to produce disaggregated estimates according to age group, region, Local Resilience Forum, sex, cause of death and place of death.

There is uncertainty in attributing the difference between heat episode deaths and baseline deaths to heat due to random variation in daily deaths. In recognition of this, 95% confidence intervals are calculated around these estimates and reported as part of the official statistics. These are calculated based on the standard error obtained by assuming daily deaths come from a Poisson distribution with an adjustment for overdispersion. The overdispersion used was common for all analyses, and derived by comparing within-month variance in daily deaths to the within-month mean daily deaths on non-heat-episode days across the summer.

In addition, an estimate was produced for premature heat-associated mortality, within age groups which had statistically significant heat-associated mortality (that is, a positive estimate of heat-associated deaths and confidence intervals not overlapping with zero). The age groups used for stratification were: 0 to 24 years, 25 to 44 years, 45 to 64 years, 65 to 74 years, 75 to 84 years, and 85 and over. Average remaining life expectancy for each age group was calculated using the latest available ONS life tables for England,[20] stratified by sex. The number of heat-associated years of life lost (YLL) was then calculated for each age group which had statistically significant heat-associated deaths by multiplying the number of deaths by the average remaining life expectancy for each sex-age group cohort, then aggregated by age group. Confidence intervals were constructed using the standard error obtained in the mortality calculation, with an adjustment for the additional uncertainty involved in averaging across the ages within an age group.

2.4. Modelling heat-associated mortality

This section of the analysis employed a statistical model used to estimate the historic temperature-mortality relationship in England and generate estimates of the predicted heat-associated mortality in each heat episode based on the actual temperatures which occurred. This approach has previously been described in detail within the literature.[14]

Data on daily mean temperature and daily deaths in England at regional level over the previous five summers of 2019 and 2023 (May to September) were joined based on date and region, and combined into a single England dataset through a population-weighted average. A quasi-Poisson regression model was then fit using the DLNM framework. DLNMs were used as they allow for delayed health effects of heat over a lag period, and for non-linear relationships between temperature and health outcomes.

As described in previous work[14] a natural cubic spline was used to model the temperature-mortality association, with knots at the 50th and 90th percentiles of the summer daily mean temperature distribution. Lags of up to 3 days were considered with an unconstrained parameterisation in the lag-response dimension. The model also included an indicator for day of week, and an interaction of a year indicator and a natural cubic spline function of day of year with four degrees of freedom, to capture seasonal or long-term trends.

This results in a cumulative temperature-mortality association for England across the lag period. This is centred at a ‘minimum mortality temperature’ value for mean temperature, which is constrained to fall within the range of the 50th to 98th percentile of summer mean temperatures.

This association is then applied to a time series of daily expected deaths (average daily deaths on the same day of year over the previous five years) and actual daily mean temperature for the summer of interest, to generate a heat-attributable number of deaths for each date. Heat-attributable deaths were summed for each period identified as a heat episode, in order to compare observed estimates of heat-associated mortality with modelled predictions at heat episode level.

We estimate uncertainty using Monte Carlo simulations to generate 100 additional temperature-mortality associations, assuming that model coefficients follow a multivariate normal distribution. From the resulting distribution of attributable numbers of heat-associated deaths in each heat episode, we report the 2.5th and 97.5th percentiles as the 95% confidence interval.

For each heat episode, the observed and modelled estimates of heat-associated mortality were compared to assess discrepancies and support detection of heat episodes where observed deaths were unusually low or high, given the time of year and the actual temperatures observed. Observed and modelled estimates are judged as statistically significantly different if their respective 95% confidence intervals do not overlap.

2.5 All-cause mortality versus heat related mortality

To help contextualise UKHSA's decision to focus on all-cause mortality rather than heat-specific causes of death, we also examined deaths explicitly attributed to heat on death certificates, using ONS death registrations data. Data fields extracted were the time of year of death, underlying cause of death and other causes of death recorded. Using ICD-10 codes X30 "Exposure to excessive natural heat" and T67 "Heatstroke and sunstroke", we calculated annual counts of deaths where a heat-specific cause was recorded as the underlying cause or mentioned anywhere on the death certificate, covering the period from 2019 to 2024. These figures were then compared with the all-cause observed heat-associated mortality estimates reported in UKHSA's annual heat mortality monitoring reports for the same period.

3. Results

During the study period there were 196,205 total deaths observed across the population in England in 2024. A full breakdown of the mortality data used in the 2024 analysis and the data used for the generation of the DLNMs (2019-2023) is presented in table 1.

Table 1. Descriptive assessment of data on all deaths occurring in England between 1st May and 30th September inclusive, with deaths with a mention of Covid-19 removed. Full description provided for 2024 (year of interest) and total number of deaths over the same months for years used in the DLNM approach used to provide context to observed heat associated mortality.

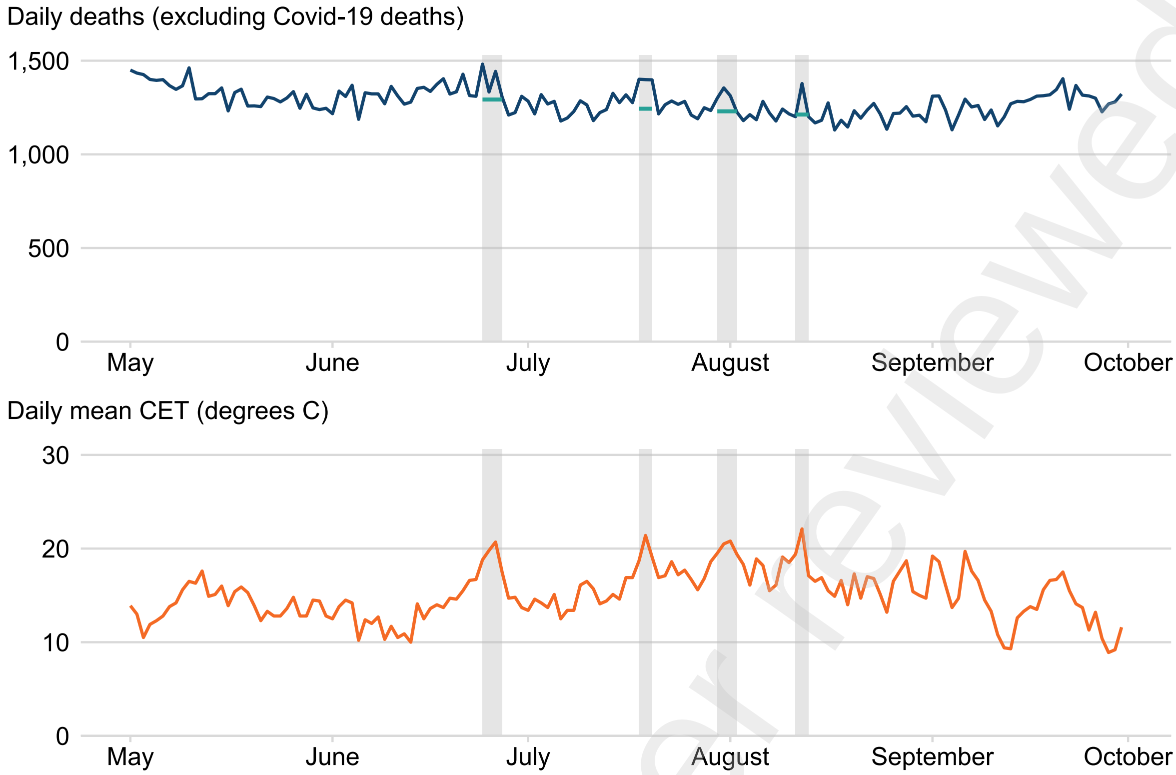
Group	Deaths	Proportion
All deaths (May to Sep 2024)	196205	100.0%
By region		
North West	28914	14.7%
Yorkshire and The Humber	20803	10.6%
South West	22728	11.6%
West Midlands	22326	11.4%
South East	32011	16.3%
East Midlands	17436	8.9%
East of England	22202	11.3%
London	18777	9.6%
North East	11008	5.6%
Sex		
Female	96538	49.2%
Male	99663	50.8%
Other or unknown	<5	0.0%

Age group		
0 to 24	1588	0.8%
25 to 44	4027	2.1%
45 to 64	23205	11.8%
65 to 74	30787	15.7%
75 to 84	58824	30.0%
85plus	77774	39.6%
Place of death		
Own residence	56247	28.7%
Hospital	80690	41.1%
Care home	42821	21.8%
Hospice	11933	6.1%
Other	4514	2.3%
Cause of death		
Chronic lower respiratory diseases (ICD-10 J40 to J47)	9957	5.1%
Cancer (ICD-10 C00 to C97)	57296	29.2%
All other, including unknown	45187	23.0%
All circulatory diseases (ICD-10 I00 to I99)	47650	24.3%
Dementia and Alzheimer's (ICD-10 F01, F03 and G30)	23645	12.1%
External causes (ICD-10 S00 to Y98)	5750	2.9%
Influenza and pneumonia (ICD-10 J09 to J18)	6720	3.4%
Baseline years used in development of DLNM (May to Sep)		
Total deaths (May to Sep) 2019 to 2023	972864	100.0%
All deaths in 2019	190647	19.6%
All deaths in 2020	183939	18.9%
All deaths in 2021	195365	20.1%
All deaths in 2022	204340	21.0%
All deaths in 2023	198573	20.4%

3.1 Application of methodology to summer 2024: headline figures

In the summer of 2024, UKHSA identified four heat episodes that met the definition used for heat mortality analysis. Applying the methodology described in section 2.3, an estimated 1,311 heat-associated deaths were recorded, with a 95% confidence interval (CI) ranging from 929 to 1,692 deaths. Three of the four heat episodes led to statistically significant heat-associated mortality. Figure 1 shows the daily mortality and CET with grey shading marking the four heat episodes. Each episode aligns with a rise in deaths above the baseline (turquoise line), though some variation occurs outside these periods. Mortality was generally higher at the start and end of summer than in the middle. Notably, all four episodes occurred during periods of non-extreme heat, with only yellow Heat-Health Alerts (HHAs) in effect.

Figure 1. Daily deaths and daily mean temperature, England, summer 2024.



3.2 Disaggregation of data

Age Groups and sex

As in previous years, disproportionate impacts of heat were seen in older adults, particularly those aged 75 and above. The detection of significant mortality in these cohorts aligns with longstanding evidence on age-related susceptibility to extreme heat. Individuals aged 85 years and over experienced 521 deaths per million population, while those aged 75 to 84 years experienced 111 deaths per million. These age groups were the only two included in the calculation of heat-associated YLL in 2024. The analysis of premature mortality found a total of 4,087 heat-associated YLLs in those aged 75 to 84, and 2,844 YLLs in those aged 85 and over.

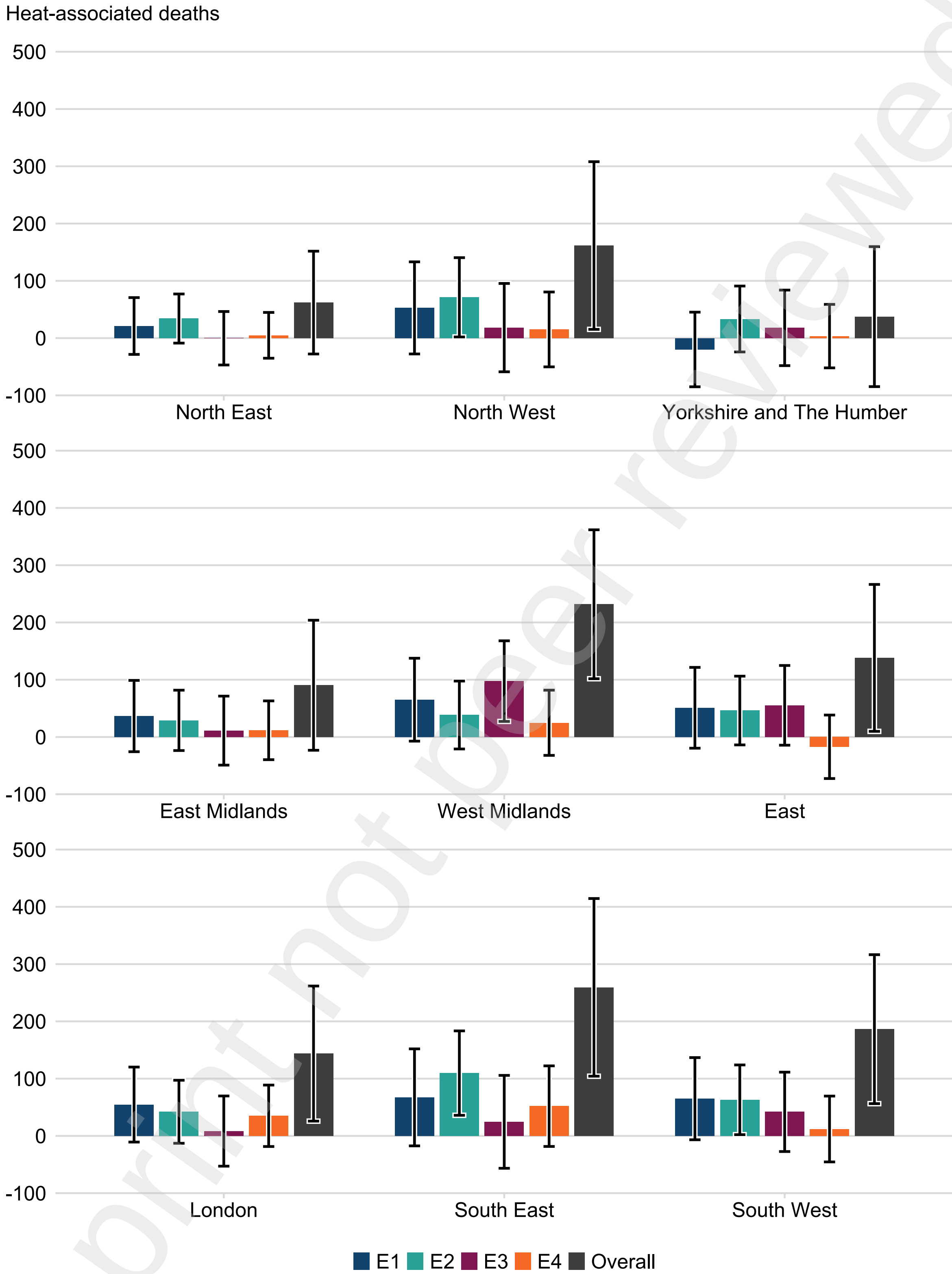
In 2024, heat-associated mortality was slightly higher in females (684 deaths; 95% CI: 417 to 952) than in males (627 deaths; 95% CI: 355 to 899), but the difference was not statistically significant and may simply reflect the larger denominator size for females. Estimates for other or unknown sexes could not be reported due to small numbers. No general trend was observed in differences by sex across the four heat episodes.

Regions

The South East recorded the highest number of heat-associated deaths in summer 2024, with an estimated 259 deaths (95% CI: 104 to 414), followed by the West Midlands with 232 deaths (95% CI: 102 to 362), the South West with 186 deaths (95% CI: 56 to 316), the North West with 162 deaths (95% CI: 15 to 308), London with 144 deaths (95% CI: 26 to 262), and the East of England with 138 deaths (95% CI: 10 to 266). The East Midlands, North East and Yorkshire and the Humber regions did not see significant heat-associated mortality. The timing of impacts varied between the regions: mortality peaked in London and the South West during Episode 1, in the North West and South East during Episode 2, and in the West

Midlands and East of England during Episode 3. Notably, the North West experienced significant excess deaths in Episode 2 (71; 95% CI: 2 to 140) despite no Heat-Health Alert being issued during that period.

Figure 2. Heat-associated deaths by region and heat episode, England, summer 2024 with error bars representing 95% confidence intervals.



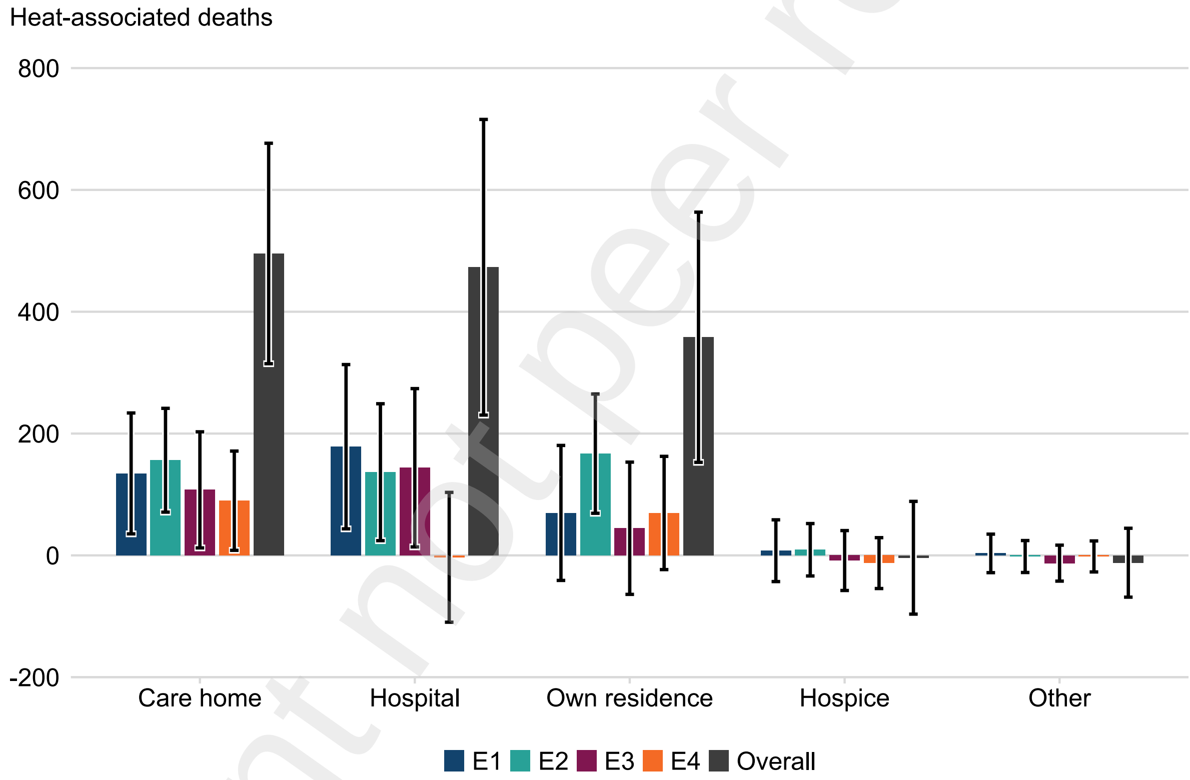
Local Resilience Forum area

In summer 2024, statistically significant heat-associated mortality was identified in London, West Midlands, and Kent LRFs, which all have relatively large populations. While most other LRFs also showed positive estimates of heat-related deaths, these were not statistically significant due to wide confidence intervals associated with smaller population sizes. Cleveland LRF had the highest estimated rate of heat-associated mortality (72 per million), though this was not statistically significant.

Place of death

The largest number of heat-associated deaths occurred in care homes (496 heat-associated deaths), as shown in Figure 3. This was followed by deaths in hospitals (473 heat-associated deaths) and at home (358 heat-associated deaths). Hospices and 'other' places of death did not see significant heat-associated mortality in 2024. This analysis highlights the vulnerability of populations in institutional and residential settings during periods of adverse heat.

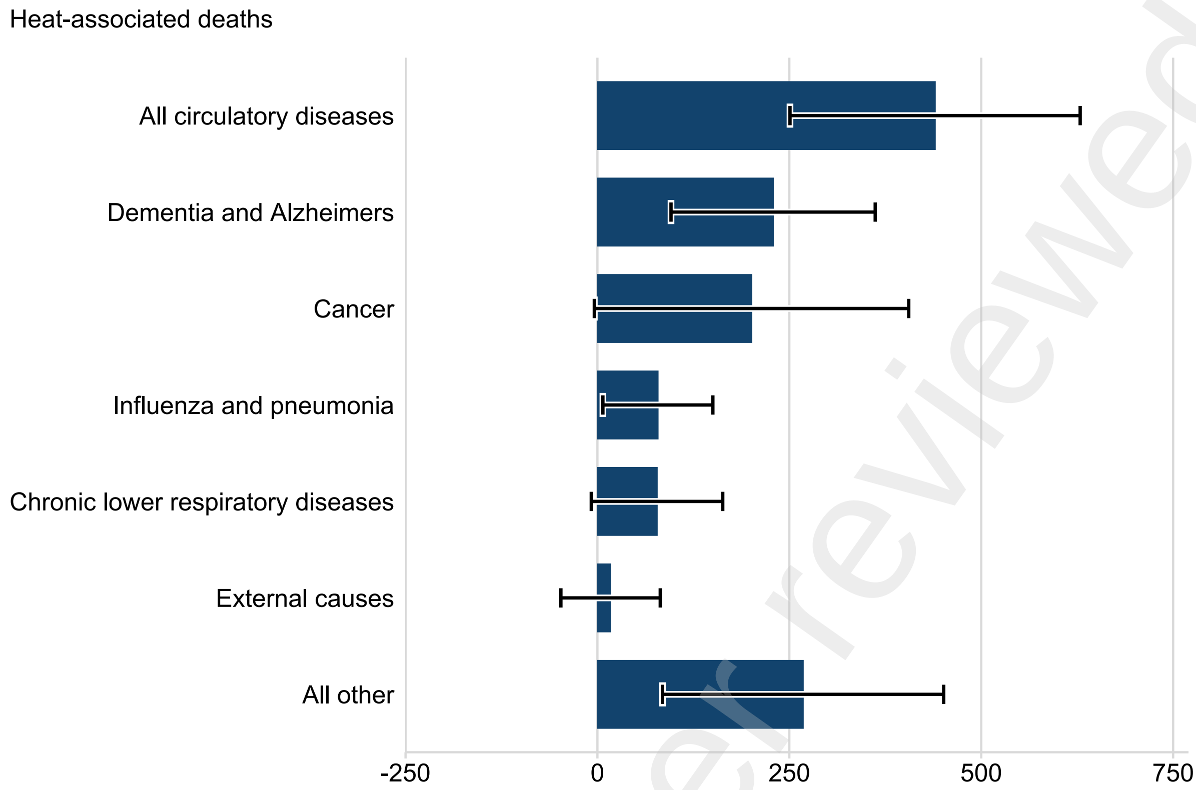
Figure 3. Heat-associated deaths by place of death and heat episode, England, summer 2024 with error bars representing 95% confidence intervals.



Cause of Death

The largest cause of death group for heat-associated deaths were circulatory diseases (440 heat-associated deaths), as shown in Figure 4. This is consistent with the known physiological pathways through which heat exacerbates chronic health conditions. Dementia and Alzheimer's disease (229 heat-associated deaths) and influenza and pneumonia (79 heat-associated deaths) also had statistically significant heat-associated mortality.

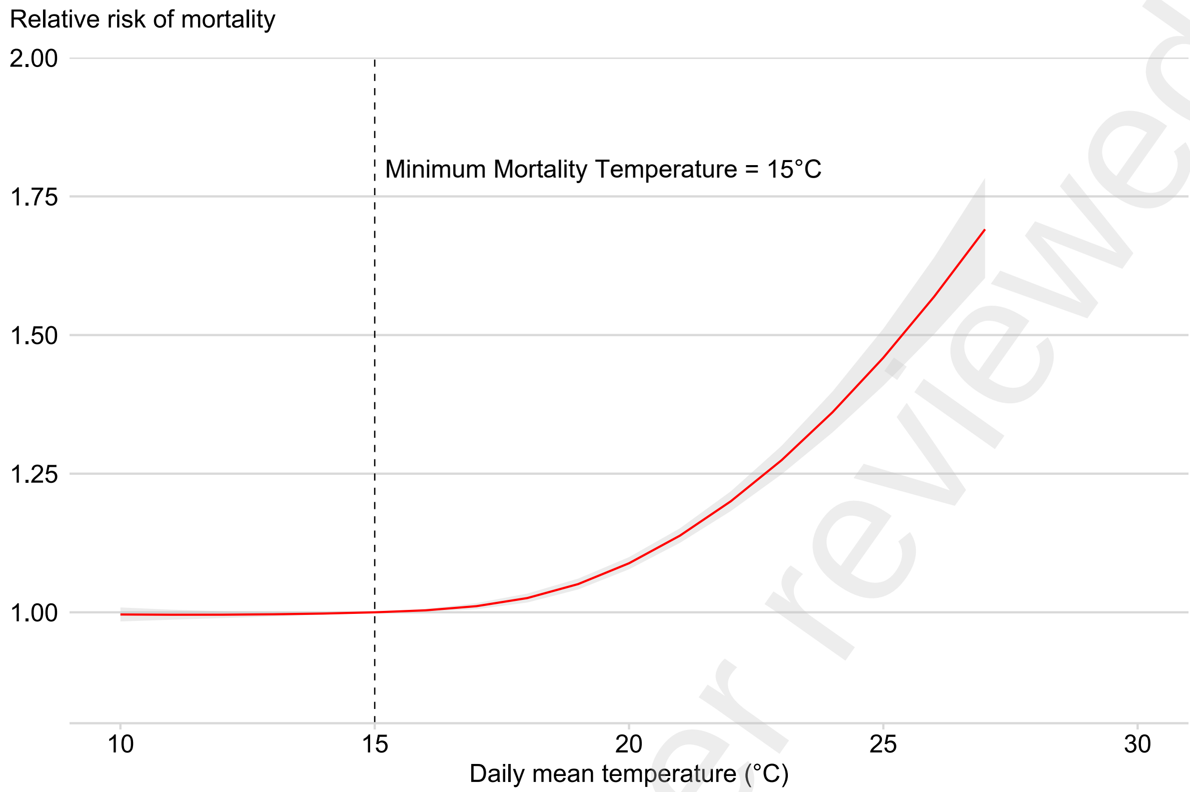
Figure 4. Heat-associated deaths by cause of death and heat episode, England, summer 2024 with error bars representing 95% confidence intervals.



3.3 Comparison with modelled estimates

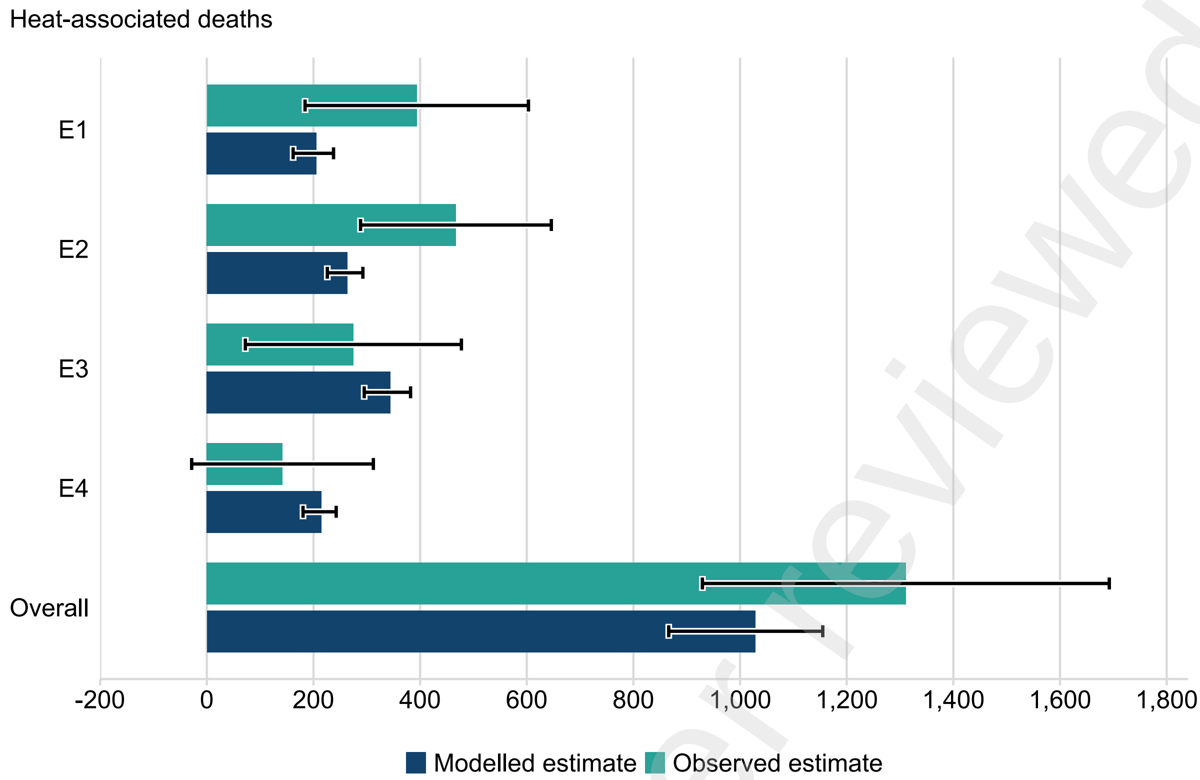
Using the DLNM approach, a cumulative temperature-mortality association was estimated for England across the lag period of up to 3 days, shown in Figure 5. This represents the relationship between heat and mortality in England during the summers of 2019 to 2023.

Figure 5. Relative risk of mortality by daily mean temperature, England, summers of 2019 to 2023 with grey shading representing 95% confidence intervals.



Applying this model to an expected daily deaths series and actual observed temperatures for 2024, we estimated 1,028 heat-associated deaths (95% CI: 866 to 1,155) for England during the heat episodes of summer 2024, compared to 1,311 observed heat-associated deaths. Although observed deaths were higher, the difference was not statistically significant as shown by the overlapping confidence intervals in Figure 6. At the episode level, E1 and E2 had more observed deaths than predicted, while E3 and E4 had fewer, though confidence intervals overlapped between observed and modelled estimates for all episodes.

Figure 6. Observed and modelled heat-associated deaths, England, summer 2024



3.4 All-cause mortality vrs heat related mortality
The numbers of deaths recorded with heat-specific causes of death (ICD-10 X30 and T67) range between <5 and 19. This is significantly fewer than the all-cause heat-associated mortality estimates provided in each year in UKHSA's heat mortality monitoring reports.[11, 21-25] The stark contract in differences in approach for monitoring heat-health impacts is demonstrated in table 2.

Table2 Comparison of all-cause heat-associated mortality to heat-specific causes of death (ICD-10 X30 or T67) as recorded on death certificates in England between 2019 and 2024

Year	All-cause heat associated deaths	Heat-specific deaths as UCD in summer	Heat-specific deaths anywhere on death certificate in summer	Heat-specific death as UCD in winter
2019	892	<5	<5	<5
2020	2,556	9	10	<5
2021	1,634	<5	<5	<5
2022	2,985	13	19	<5
2023	2,295	<5	5	<5
2024	1,311	<5	<5	<5

4. Discussion

4.1 Interpretation of findings

The 2024 results demonstrate that significant heat-associated mortality can occur even in relatively cool summers, where no amber or red Heat-Health Alerts are issued and only four short heat episodes identified. The estimated 1,311 heat-related deaths, particularly concentrated in older adults and institutional settings, underscore the vulnerability of specific population groups. These findings have clear implications for public health planning and response, suggesting that even modest temperature rises can have significant impacts. The tendency towards higher than expected mortality in heat episodes earlier in the summer and lower than expected mortality later in the summer, perhaps due to lower acclimatisation and preparedness, suggests that early-season heat events may warrant particular attention.

The distribution of deaths across place of death and cause of death categories provides further granularity for public health response. The high numbers of heat-associated deaths in care homes and hospitals and the concentration of heat-associated deaths among individuals with cardiovascular, respiratory, and neurodegenerative conditions highlight the need for specific, targeted interventions in both health and social care systems. Additionally, the fact that statistically significant heat-associated mortality occurred during periods of only yellow alerts raises questions about how yellow alerts are being perceived by the public and responding organisations and professionals.

The 2024 comparison between observed heat-associated deaths and modelled estimates highlights the value of using both approaches together. Observed heat-related mortality (1,311 deaths) exceeded modelled estimates based on historical temperature–mortality relationships (1,028 deaths), though the difference was not statistically significant. This slight excess, despite a relatively mild summer, suggests that factors beyond temperature, such as behavioural or social conditions, may have influenced outcomes. Considered alongside findings from previous years[11, 24] and qualitative feedback[26, 27] indicating that yellow alerts are often not perceived as requiring action, these results support the need for clearer communication around yellow alerts and greater emphasis on response, even during less severe heat events.

Finally, as can be seen within table 2, focusing on heat-specific causes of death in England is an inappropriate approach as it is likely to significantly underestimate the true burden on health, as revealed by excesses in all-cause mortality.

4.2 Comparison with existing literature and methods

Other national systems focus primarily on near real-time estimates of excess mortality based on observed data and predefined heatwave criteria, often without detailed breakdowns by age, cause, or setting.[15, 28] Others incorporate statistical modelling or syndromic surveillance but may lack the clarity around causality or the episode-level granularity that UKHSA provides. Broader European initiatives such as EuroMoMo offer important insights into overall weekly excess mortality[29] but are not specifically designed to assess or identify heat-related impacts, which may occur over shorter timeframes. In the United States the approach has been to focus on heat related mortality as measured through heat-specific causes of death. French heat mortality monitoring reports use a similar approach to UKHSA in calculating both *mortalité en excès* (comparing deaths during heat episodes with a EuroMoMo-generated baseline) and *mortalité attribuable à la chaleur* (using a DLNM approach to attribute deaths to heat), but do not directly compare results from the two approaches.[30]

Focusing solely on heat-specific causes of death presents several risks that can undermine effective public health action. First, it severely underestimates the true health burden of heat, as heat is rarely recorded explicitly on death certificates, even in settings with robust death registration systems, as demonstrated in table 2. In many low-resource or informal settings, collecting death data is already a challenge, and reliance on precise coding exacerbates these gaps. This approach may also distort global comparisons, making countries with stronger reporting systems appear to suffer disproportionately, when in fact they are simply capturing the data more completely. As a result, policymakers may deprioritise investments in essential adaptation measures, such as early warning systems or heat-health action plans, based on misleadingly low estimates. Furthermore, this narrow approach risks deepening health inequities by excluding deaths that occur outside formal healthcare or administrative systems, often affecting rural, displaced, or marginalised populations, thereby reinforcing existing data and health protection gaps.

Many academic studies and statistical reports rely on time series models such as DLNMs to estimate the relationship between temperature and mortality and use this to generate estimates of heat-attributable deaths.[12, 13, 15] DLNMs are powerful tools for characterising and quantifying temperature-mortality associations. They can be used to produce exposure-response curves and relative risks of health outcomes at different temperatures, leading to interesting insights into how the shape or magnitude of temperature-mortality relationships may differ between geographical areas or time periods, and allowing for estimates of heat burden in the future under different climate change scenarios.[14, 31, 32] However, their application as standalone tools for estimating heat-attributable mortality in real-time raises several methodological questions and concerns.

A key limitation of many DLNM approaches is the assumption, in using a temperature-mortality relationship fit from many years of data to generate an estimate for a single shorter period, that the relationship between temperature and mortality remains constant over time.[12, 13] In reality, this relationship is shaped by a wide range of evolving factors, including demographic change, social behaviours, housing quality, and the implementation of public health measures such as heat early warnings. These factors are not always measurable or readily available for inclusion in models. Applying a single, static temperature-mortality relationship based on many years of data to produce estimates for individual years or heat episodes can obscure important changes in vulnerability and resilience over time. This makes it impossible to identify where a particular summer was unusually severe or mild in terms of health impacts, given the temperatures observed. As a result, using multiple-year DLNMs for attribution has limited value for probing the effects of heat on population health in any single year or heat event, which is crucial for surveillance and evaluation of adaptation measures in public health.

In addition, there is often limited reporting of any model validation or evaluation activities when using DLNMs to model impacts of heat on health. Recent findings in UKHSA's mortality monitoring report[11] and previous research[14] have shown significant differences between observed deaths and modelled estimates for certain heat episodes, and suggest that models are not capturing factors which can play an important role in the real-world outcomes observed, such as coordinated governmental response, public awareness or behaviour changes. As an example of how these models may not be able to capture real-world modifiers of risk, there is a growing mismatch in model outputs that suggests the risk at regional level is highest in London[13], even though the observed data as reported by UKHSA is consistently not showing this.[11, 22-24] Despite this, model performance metrics, cross-validation results or sensitivity analyses are rarely reported in academic literature using DLNMs for heat and health estimates[13] or stated to be beyond the scope of the study.[33] This is particularly important where DLNMs are used to estimate attributable deaths at the most extreme and rarely-observed temperatures, where limited training data is available, but which may have outsized effects on the total attributable number reported. Without reporting of model validation, there can only be limited confidence in attributable numbers reported from DLNMs.

In another example, recent studies have claimed to forecast heat-associated mortality in real time during the 2025 heat events in England,[34] drawing national attention. However, these models rely on data from 1 January 2000 to 31 December 2019, omitting the past five years, an especially critical period marked by major shifts in public health. The COVID-19 pandemic altered the UK's mortality baseline and coincided with an aging population, changes in healthcare access (including longer waiting times), and evolving public behaviours as heatwave become more frequent, intense and last longer. These factors, along with rising levels of chronic illness, may have significantly changed the population's vulnerability and response to heat. Therefore, using pre-pandemic models to estimate current heat-related deaths is inappropriate and risks undermining timely public health messaging when Heat-Health Alerts are issued.

The approach used in the UKHSA heat mortality monitoring reports overcomes these limitations by not relying on DLNMs for attribution of heat-associated mortality. The model is used not with the aim of full causal inference, but instead to contextualise the observed heat-associated mortality in each heat episode by providing an expected number of deaths at the observed temperatures based on the temperature-mortality trends of the previous five years. This supports monitoring of changes in the heat-mortality relationship over time and evaluation of public health response during heat events.

4.3 Strengths and limitations

A key strength of the UKHSA method is its hybrid nature, combining transparent, interpretable observed heat mortality estimates for each heat episode with the use of epidemiological modelling to contextualise them. The observed heat-associated mortality method using all-cause mortality quantifies the hidden 'indirect' effects of heat on health, capturing far more of the true burden of heat on mortality than a count of deaths caused by heat-specific conditions such as heatstroke. The ability to disaggregate estimates by age, sex, region, LRF, place of death, and cause of death provides a multi-dimensional view of heat impacts that few other heat mortality monitoring systems currently provide.

Reporting YLL provides a clearer picture of the impact of heat on premature mortality by showing not just how many people died, but how early in life those deaths occurred. This helps highlight the burden of heat on public health more meaningfully than death counts alone. This may be especially useful when comparing burdens across age groups, health conditions or causes of mortality.

Using a 14-day pre- and post-heatwave period to define the baseline, which was established following the COVID-19 pandemic to account for holistic shifts in mortality patterns,[35] offers several advantages to using historical baselines such as the same dates over the previous 5 years, which is vulnerable to long term changes in underlying mortality patterns through changing population structure (including total population and seasonal population variations), and sudden shocks (such as the COVID-19 pandemic). The approach used here captures localised mortality patterns immediately surrounding each event and adjusts for longer-term trends across the entire summer season.

The ability to report heat-associated mortality for each individual heat episode is crucial for the public health applications of heat mortality surveillance, supporting the evaluation of public health responses implemented in each heat event. Furthermore, the use of the DLNM method to contextualise each heat episode's mortality impacts is a key strength, supporting an assessment of whether observed mortality differs significantly from other recent years when accounting for the temperatures and time of year. For example, in the July 2022 heat episode which saw record-breaking temperatures in England, the statistical model of the historic heat-mortality association predicted 2,160 heat-associated deaths over the period 10^{th}-25^{th} July, while only 1,256 heat-associated deaths were observed.[11] The discrepancy may be partly due to inaccuracy in the model predictions for very extreme temperatures not previously observed, but may also be indicative of the success of the widely publicised heat alerts and warnings, leading to effective action taken across society to reduce the adverse impacts of the hot weather on health.[36] According to a Met Office survey from 2022, 98% of respondents reported that they took some level of protective action during this period of record-breaking heat.[37]

There are also limitations to the data sources and methods. First, the use of death registrations data to monitor health impacts is inherently retrospective and subject to registration delay, limiting its use in real-time decision-making.[38] The approach used to define periods of heat for analysis relies on CET, which is a long-running temperature series that represents the average temperatures across a central region of England.[18] Therefore, it is not representative of all regions of England and could potentially miss some periods of locally significant heat. However, the use of 20°C CET has aligned with periods where HHAs have been issued, and therefore, to date, it is unlikely a new regionally specific definition would have improved estimates.

There are benefits to the simplicity of the calculation for observed mortality as the difference between deaths during heat episodes and deaths during same-summer baseline periods, which produces estimates for deaths associated with heat agnostically to precise causal pathways. However, the method does rely on a sufficient baseline period, which may be unavailable in the event of prolonged periods of heat with few non-heat episode days between them. In addition, the lack of causal attribution means that the method cannot distinguish between the impacts of heat and the impacts of concurrent events significantly and suddenly affecting all-cause mortality. The removal of deaths with a mention of Covid-19 on the death certificate aims to mitigate any confounding from Covid-19 waves, which do not follow a clear seasonal pattern. More research is needed however to fully understand the relationship between temperature and Covid-19.

Related to this, the substantial random variation in daily deaths during summer means there is significant uncertainty when attributing the difference in deaths during heat episodes and baseline periods to heat. This results in wide confidence intervals for the observed estimates. This limits the usefulness of disaggregation to smaller population groups, as seen in the 2024 heat mortality analysis where only three LRFs with large populations were found to have statistically significant mortality. This also means that direct age standardisation techniques (which would be useful to compare between geographic areas or populations with different age structures) are difficult to apply, with small sample sizes leading to wide confidence intervals and difficulty making comparisons.

While disaggregation is a strength of the UKHSA approach, a range of other potentially insightful risk factors are not included. This may be due to their absence from death certificates, such as ethnicity, which was not recorded in England until September 2024[39], or because the analysis focuses solely on death registration data. As UKHSA develops its heat-health surveillance approach, it should consider how to incorporate additional data sources to build a more comprehensive understanding of the inequitable distribution of impacts across the population and improve public health responses to address those.

The comparison of observed with modelled estimates has yielded several useful insights into factors other than mean temperature which may play a role in determining heat-associated mortality in a given episode, such as public behaviour or high night-time temperatures. However, discrepancies may result from methodological differences in the derivation of the modelled and observed estimates (such as the different treatment of lagged effects) or from model inaccuracy for previously rare or unseen temperatures as previously highlighted. As a result, even a statistically significant difference between a modelled and observed estimate should be viewed as a starting point for further investigation and analysis, rather than conclusive evidence of the role of any particular external factor on the observed heat-associated mortality.

Finally, the current approach focuses on heat episodes and is not suitable for detecting the health impacts of more moderate heat, even though the temperature-mortality relationship suggests such effects may exist.[40] During less extreme heat episodes, any smaller increases in mortality may be masked by the normal day-to-day variation in death rates. In addition, some moderately hot days that do not meet the heat episode definition will not contribute towards the heat-associated mortality estimate. As a result, the reported figures may slightly underestimate the total burden of heat. However, they can be meaningfully interpreted as the impact of unusually hot spells on mortality over and above normal summer days, rather than an overall seasonal effect.

4.4 Future directions

There are several avenues for future methodological development. First, expansion into heat-related morbidity, including emergency department admissions, ambulance call-outs, and hospitalisations. This would provide a more holistic picture of the burden of heat and the strain on health services. Integration of such surveillance outputs could enhance early warning capabilities and facilitate dynamic responses during heat episodes.

Second, future development of the methodology could focus on improving how uncertainty is captured and how assumptions are made more transparent. There is also scope to explore approaches that help better understand the drivers of heat-related mortality and the impact of interventions. For example, assessing how public health responses, such as Heat-Health Alerts, affect outcomes, and the cost-benefit remains an important area for further research.

Third, now that the DLNM approach is in use, there may be value in exploring how it could support operational decisions, such as providing an early indication of potential health impacts based on forecast temperatures that could inform early warning decisions by UKHSA. While the estimates would carry the same caveats discussed earlier, they could still offer helpful context to inform decisions around issuing Heat-Health Alerts.

Finally, as the climate continues to warm and heat episodes become more frequent and intense, adapting and stress-testing the methodology for use in more extreme scenarios will be critical. Further collaboration with academic and international partners may help harmonise heat mortality surveillance across countries, improving comparability and enabling shared learning.

5. Conclusions

The 2024 analysis highlights the value of UKHSA's dual-method approach to estimating heat-associated mortality, combining observed excess deaths during defined heat episodes with modelled estimates based on historical temperature-mortality relationships. This hybrid method enables both real-world validation and contextual benchmarking, offering a more complete picture of heat-related health impacts than models alone. Disaggregated data by age, cause, and place of death provide crucial insights into which populations and settings are most affected, allowing for more nuanced understanding of how heat impacts public health.

Importantly, this methodology supports operational decision-making by aligning mortality estimates with specific heat episodes and alert levels. This strengthens the evidence base for refining Heat-Health Alerts, evaluating their effectiveness, and improving public and institutional responses. By linking health outcomes directly to periods of elevated temperature, UKHSA's approach offers a practical tool for targeting interventions, enhancing communication strategies, and prioritising resources - particularly as the climate warms and the need for timely, evidence-based action becomes more urgent.

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Data Availability Statement

The data utilised in this study are publicly available through the UKHSA's official reports:

- Heat mortality monitoring report, England: 2024. Link
- Quality and methodology information: Heat mortality monitoring reports. Link

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