Anomalously warm temperatures are associated with increased injury deaths

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Temperatures which deviate from long-term local norm affect human health, and are projected to become more frequent as the global climate changes.[1] There is limited data on how such anomalies affect deaths from injuries. Here, we used data on mortality and temperature over 38 years (1980-2017) in the contiguous USA and formulated a Bayesian spatio-temporal model to quantify how anomalous temperatures, defined as deviations of monthly temperature from the local average monthly temperature over the entire analysis period, affect deaths from unintentional (transport, falls and drownings) and intentional (assault and suicide) injuries, by age group and sex. We found that a 1.5°C anomalously warm year, as envisioned under the Paris Climate Agreement,[2] would be associated with an estimated 1,601 (95% credible interval 1,430-1,776) additional injury deaths. 84% of these additional deaths would occur in males, mostly in adolescent to middle ages. These deaths would comprise of increases in deaths from drownings, transport, assault and suicide, offset partly by a decline in deaths from falls in older ages. The findings demonstrate the need for targeted interventions against injuries during periods of anomalously high temperatures, especially as these episodes are likely to increase with global climate change.

Anomalously warm and cold weather events are an important public health concern in today's world, and one of the key drivers for seeking adaptation measures against anthropogenic climate change.[3–5] Current assessments of the health effects of weather and climate, and by extension of global climate change, largely focus on parasitic and infectious diseases and cardiorespiratory and other chronic diseases.[3–8] Less research has been conducted on injuries,[9–12] especially in a consistent way across injury types and demographic subgroups of the population. There are two reasons to investigate a potential role for temperature anomalies on injury mortality. First, death rates from injuries vary seasonally and the seasonality varies by age group,[13,14] which motivates investigating whether temperature contributes to their pathogenesis. Second, there are plausible behavioural and physiological pathways for a relationship between temperature and injury – for example changes in alcohol drinking,[15] driving patterns and performance,[12,16–24] and levels of anger[25–27] – which motivates testing whether injury deaths are affected by temperature anomalies. Our aim was to evaluate how deaths from various injuries in the USA might be affected by anomalously warm and temperatures that occur today and are expected to become increasingly common as a result of global climate change.[1]

We used vital registration data on all injury deaths in the contiguous USA (i.e., excluding Alaska and Hawaii) from 1980 to 2017, with information on sex, age at death, underlying cause of death and county and state of residence. From 1980 to 2017, 4,145,963 boys and men and 1,825,817 girls and women died from an injury in the contiguous USA, accounting for 9.3% and 4.2% of all male and female deaths respectively. 95.7% of male injury deaths and 94% of female injury deaths were in those aged 15 years and older, and over half (52.3%) of male injury deaths were in those aged 15-44 years (Figure 1). By contrast with males, there was less of an age gradient in females after 15 years of age.

Injuries from transport, falls, drownings, assault, and suicide accounted for 78.6% of injury deaths in males and 71.8% in females. The remainder were from a heterogeneous group of "other injuries" (Figure 1), within which the composition of injuries that led to death varied by sex and age group. Transport was the leading injury cause of death in women younger than 75 years and in men younger than 35 years. Between 35 and 74 years of age, more men died of suicide than any other injury. Above 75 years of age, falls were the largest cause of injury-related death in both men and women.

There was a decline in age-standardised death rates of three out of five major injuries (transport, drownings and assault) from 1980 to 2017, although assault deaths have more recently (since 2014) increased (Figure 2). By contrast, age-standardised death rates from falls increased over time while those from suicide initially decreased followed by an increase to surpass 1980 levels. The largest overall decline over time was for transport deaths in both sexes and for deaths from drownings in men, which declined by more than 50% from 1980 to 2017. Age-standardised death rates for transport injuries and drownings peaked in summer months but deaths from other major injuries did not have clear seasonal patterns.

We defined a measure of anomalous temperature for each county and month, which represents the deviation from the county's average temperature in that month over the entire analysis period (Extended Data Figure 1). County-level anomalies were aggregated to state level with use of population weights. This generated a number for each state and month that measured deviation from long-term average of the state in that month. Average size of anomaly over the study period (1980-2017), a measure of how variable temperatures are around their state-month long-term average, ranged from 0.4°C for Florida in September, to 3.4°C for North Dakota in February (Extended Data Figure 2). Taken across all states and months, the average size of anomaly had a median value of 1.2°C. Temperature anomalies were largest in January and December and smallest in August and September. Additionally, they were larger in northern and central states than in southern and coastal ones.

We analysed the association of monthly injury death rates with anomalous temperature using a Bayesian spatio-temporal model, described in detail in Methods. We used the resultant risk estimates and the age-sex-specific death rates from each injury in 2017, to estimate additional deaths if each month in each state were +1.5°C above its long-term average as envisioned under the Paris Climate Agreement.[2] We present additional results, based on +2°C, which is the upper bound of the Paris Climate Agreement as Extended Data. Based on this analysis, there would be an estimated 1,601 (95% credible interval 1,430-1,776) excess injury deaths, equivalent to 0.75% of all injury deaths in 2017, in a year in which each month in each state was +1.5°C warmer than its long-term average (Figure 3). The number of excess injury deaths would increase to 2,135 (95% credible interval 1,906-2,368), equivalent to 1.0% of all injury deaths in 2017, in each year in which each month in each state was +2°C warmer than its long-term average (Extended Data Figure 3).

Deaths from drowning, transport, assault and suicide would increase, partly offset by a decline in deaths from falls in middle and older ages and in winter months (Figure 3). Most excess deaths would be from transport injuries (739; 650-814 in the +1.5°C warmer scenario) followed closely by suicide (540; 445-631). 84% of the excess deaths would occur in males and 16% in females. 92% of all male excess deaths would occur in those aged 15-64 years, who have higher rates of deaths from transport and suicide. In those aged 85 years and older, there would be an estimated decline in injury deaths, because deaths from falls are expected to decline in a warmer year.

Proportionally, deaths from drownings are estimated to increase more than those of other injury types, by as much 13.7% (12.5, 15.2) for a +1.5°C anomaly in men aged 15-24 years (Figure 4). The smallest proportional increase was that of assault and suicide (less than 3% in all age and sex groups). There was a larger percent increase in transport deaths for males than for females, especially in young and middle-ages (e.g., 2.0% (1.6, 2.6) for 25-34 year old men versus 0.5% (-0.3, 1.4) for women of the same age) (Figure 4). We present additional results, based on +2°C, as Extended Data (Extended Data Figure 4).

That anomalously warm temperature influences deaths from drowning, although not previously quantified, is highly plausible because swimming is likely to be more common when temperature is higher. The higher relative and absolute impacts on men compared with women may reflect differences in their behaviours. For example, over half of swimming deaths for males occur in natural water, compared to about one quarter for females.[28] The former may rise more in warmer weather. Similarly, deaths from falls declined more in older ages because falls in the elderly are more likely to be due to slipping on ice than those in younger people.[29–31]

The pathways from anomalous temperature to transport injury are more varied. Firstly, driving performance deteriorates at higher temperatures.[20–23] Further, alcohol consumption increases in warm temperatures,[15] which also provides an explanation for why teenagers, who are more likely than other age groups to crash while intoxicated,[32] could experience a larger proportional rise in deaths from transport when temperatures are anomalously warm than older adults. Lastly, warmer temperatures generally increase road traffic in North America;[12,16–19,24] coupled with more people outdoors in warmer weather,[33] this increase could lead to more fatal collisions.

Pathways linking anomalously high temperatures and deaths from assault and suicide are less established. One hypothesis is that, more time spent outdoors in anomalously warmer temperatures leads to an increased number of face-to-face interactions, and hence arguments, confrontations, and ultimately assaults.[34,35] These effects could be compounded by the greater anger levels linked to higher temperatures.[25–27] However, further research on the association of temperature and assault, and the factors mediating it, is needed.[36] Regarding suicide, it has been hypothesised that higher temperature is associated with higher levels of distress in younger people.[37] Nonetheless, the mechanisms for the links between temperature and mental health requires further investigation, including whether the relationship varies by age and sex, as indicated by our results. Future research should also investigate the extent to which the increased risk of injury death as a result of anomalous temperature depends on community characteristics such as poverty and deprivation, social connectivity and cohesion, quality of roads and housing, public transportation options, emergency response, and social services.

The major strength of our study is that we have comprehensively modelled the association of temperature anomaly with injury by type of injury, month, age group and sex. Our measure of temperature anomaly internalises long-term historical experience of each state, and is closer to what climate change may bring about than solely examining daily episodes, or average temperature to which people have adapted. To utilise this metric, we integrated two large disparate national datasets on mortality (vital statistics) and meteorology (ERA5), and developed a bespoke Bayesian spatio-temporal model. A limitation of our study is that, like all observation studies, we cannot rule out confounding of results due to other factors. As described above, our statistical model by design adjusts for factors related to month, state and state-month that are either invariant over time or that change linearly. Rather, the confounding factors would be those with anomalies that are similar to those of monthly temperature in each state, such as air pollution. However, to our knowledge, there is currently no evidence of an association between air pollution and injury mortality. We analysed the associations between anomalous temperature and injury mortality at the state level because the small number of events and computational demands made county-level analyses unfeasible. Analyses at finer spatial resolution, such as county or district,[50] would be ideal because the impacts of anomalously warm and cold temperature on deaths from injuries may depend on socioeconomic (e.g., poverty; social connectivity and cohesion; availability of guns), environmental (e.g., availability of swimming pools; distance to bodies of water), infrastructure (e.g., quality and safety of roads; public transportation options), and health and social services (e.g., counselling and mental health services; emergency response). We used categories of injuries that are relevant for public health purposes and for designing and implementing interventions. It may be possible to further split each category. For example, 92% of all transport injuries in males and 96% in females are from road traffic injuries, with the remainder being classified as other transport injuries (Extended Data Figure 5). Similarly, suicides can be classified based on the means of suicide. To the extent that these sub-categories are relevant for interventions, they should be separately analysed in future studies. Finally, as with any Bayesian model, choices of prior distributions and hyper-parameters are necessary. There are alternatives to the priors we used. For example, our weakly informative gamma priors could have been replaced with penalised complexity priors[51] or uniform priors on the standard deviation scale.[52] We tested a limited number of alternatives and found that our results were robust to such specifications.

Our work highlights how deaths from injuries are currently susceptible to temperature anomalies and could also be modified by rising temperatures resulting from climate change, unless countered by social infrastructure and health system interventions that mitigate these impacts. Though absolute impacts on mortality are modest, some groups, especially men in young to middle-ages, experience larger impacts. Therefore, a combination of public health interventions that broadly target injuries in these groups – for example targeted messaging for younger males on the risks of transport injury and drowning – and those that trigger in relation to forecasted high temperature periods – for example additional targeted blood alcohol level checks – should be a public health priority.

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Methods

Data sources

We used data on deaths by sex, age, underlying cause of death and state of residence in the contiguous USA from 1980 to 2017 through the National Center for Health Statistics (NCHS) (https://www.cdc.gov/nchs/nvss/dvs_data_release.htm) and on population from the NCHS bridged-race dataset for 1990 to 2017 (https://www.cdc.gov/nchs/nvss/bridged_race.htm) and from the US Census Bureau prior to 1990 (https://www.census.gov/data/tables/time-series/demo/popest/1980s-county.html). We did not include Alaska and Hawaii, (which together made up 0.5% of the US population in 2017) because their climates and environment are distinct from other states due to their substantial physical distance. We calculated monthly population counts through linear interpolation, assigning each yearly count to July.

The underlying cause of death was coded according to the international classification of diseases (ICD) system (9th revision from 1980 to 1998 and 10th revision thereafter). The 6 million injury deaths fell into six categories: transport, falls, drownings, assault, suicide and an aggregate set of other injuries (~~Extended Data~~Supplementary Table 1). We report the results of all of these categories except other injuries (1,402,941 deaths or 23% of total injury deaths during 1980-2017), because the composition of this aggregate group varies by sex, age group, state and time.

We obtained data on temperature from ERA5, which uses data from global in-situ and satellite measurements to generate a worldwide meteorological dataset, with full space and time coverage over our analysis period.[38] We used gridded four-times-daily estimates at a resolution of 30 km to generate monthly temperatures by county.

Anomalous temperature metric

With few exceptions,[9,39] current climate change risk assessments extrapolate from associations of daily mortality with daily temperature.[7,8,40–42] Climate change, however, will fundamentally modify weather, including seasonal weather patterns, compared to long-term averages, and hence can disrupt existing forms of adaptation. To mimic the conditions that may arise with global climate change, we developed methodology to examine how deviations from long-term average temperature may impact injury death rates.

We first defined a measure of anomalous temperature for each county and month, which represents the deviation from the average temperature of the county in that month over the entire analysis period. To calculate the magnitude of temperature anomaly, we first calculated average temperatures for each month in each county over the entire 38 years of analysis. We subtracted these long-term average temperatures from respective monthly temperature values to generate a temperature anomaly time series for each month and year in each county (Extended Data Figure 1). The temperature anomaly metric measures the extent that temperature experienced in a specific month, year and county is warmer or cooler than the long-term average to which the population has acclimatised. These values can be different for different months in the same county, and different counties in the same month. Further, a county with higher, but more stable, temperature in a specific month has smaller anomalies than one with lower but more inter-annually variable temperature. County-level anomalies were aggregated to state level with use of population weights for analysing their associations with mortality.

Statistical methods

We analysed the association of monthly injury death rates with anomalous temperature using a Bayesian spatio-temporal model, which leveraged variations over space and time to infer associations. We modelled the number of deaths in each month in each year as following a Poisson distribution:

$$deaths_{state-time} \sim Poisson(death\ rate_{state-time} \cdot population_{state-time})$$

with log-transformed death rates modelled as a sum of components that depend on location (state) of death, month of year, overall time (in months) and temperature anomaly:

$$\begin{aligned}\log(death\ rate_{state-time}) = \\ \alpha_0 + \beta_0 \cdot time + \\ \alpha_{state} + \beta_{state} \cdot time + \\ \alpha_{month} + \beta_{month} \cdot time + \\ \zeta_{state-month} + \\ \psi_{state-month} \cdot time + \\ \nu_{time} + \\ \gamma_{month} \cdot Anomaly_{state-time} + \\ \varepsilon_{state-time}\end{aligned}$$

The model contained terms that represent the national level and trend in mortality, with α_0 as the common intercept and β_0 the common slope with overall time. Death rates also vary by month, which may be partly related to temperature and partly due to other monthly factors; monthly variations tend to be smooth across adjacent months.[13] Therefore, we allowed each month of the year to systematically have a different mortality level and trend, with α_{month} the month-specific intercept and β_{month} the month-specific slope with overall time. We used a first-order random walk prior for the monthly random intercepts and slopes, widely used to characterise smoothly varying trends.[43] The random walk had a cyclic structure, so that December was adjacent to January.

We also included state random intercepts and slopes for death rates, with α_{state} as the state-specific intercept and β_{state} the state-specific slope with overall time. These terms measure deviations of each state from national values, and allow variation in level and trend in mortality by state. We modelled the state-level random intercepts and slopes using the Besag, York, and Mollie (BYM) spatial model,[44] which includes both spatially-structured random effects with an intrinsic Conditional Autoregressive (ICAR) prior and spatially-unstructured independent and identically distributed (IID) Gaussian random effects. The extent to which information is shared between neighbouring states depends on the uncertainty of death rates in a state and the empirical similarity of death rates in neighbouring states. We also included state-month interactions for intercepts and slopes ($\zeta_{state-month}$ and $\psi_{state-month}$), to allow variation in mortality levels and trends in a particular state for different months and vice-versa. These state-month interactions were modelled as IID and therefore were of Type I space-time interactions.[45] Non-linear change over overall time (in months) was captured by a first-order random walk, ν_{time}.[43] In order to ensure identifiability each set of random walk terms or state random effects was constrained to sum to zero.

Finally, we included a term that relates log-transformed death rate to the above-defined state-month temperature anomaly, $\gamma_{month} \cdot Anomaly_{state-time}$. The coefficients of γ_{month} represent the logarithm of the monthly death rate ratio per 1°C increase in anomaly. There was a separate coefficient for each month which means that an anomaly of the same magnitude could have different associations with injury mortality in different months. As with the month-specific intercepts and trends, we used a cyclic first-order random walk to smooth the coefficient of the temperature anomaly across months. An over-dispersion term ($\varepsilon_{state-time}$) captured the variation unaccounted for by other terms in the model, modelled as $N(0,\sigma_{\epsilon}^2)$. We used weakly informative priors so that parameter estimation was driven by the data. As in previous analyses,[46,47] hyper-priors were defined on the logarithm of the precisions of the random effects, in other words on $\log(1/\sigma^2)$. These were modelled as logGamma(θ, $\boldsymbol{\delta}$) distributions with shape θ = 1 and rate $\boldsymbol{\delta}$ = 0.001. The same hyper-priors were used for all precision parameters of the random effects in the model. For the common slope, we used $N(0, 1000)$ and for the common intercept a flat prior.

In addition to representing the spatial (across states) and temporal (across months and years) patterns of mortality, the intercept terms (α_{month}, α_{state}, $\zeta_{state-month}$) in our statistical model implicitly adjust for unobserved factors that influence mortality at the state, month and state-month level; the slope terms (β_{month}, β_{state}, $\psi_{state-month}$) do so for changes in these factors over time.[46] This means that the only confounding factors would be those that have the same state-month anomaly as temperature.

We fitted the models using integrated nested Laplace approximation (INLA), using the R-INLA software, which is computationally more efficient than traditional MCMC for Bayesian inference[48] The uncertainty in our results were obtained from 5000 draws from the posterior marginal of each month's excess relative risk. The reported 95% credible intervals are the 2.5th to 97.5th percentiles of the sampled values.

Analyses were done separately by injury type, because different injuries can have differing associations with anomalously warm and cold temperature. Analyses were also done separately by sex and age group (0-4 years, 10-year age groups from 5 to 84 years, and 85+ years) because injury death rates vary by age group and sex (Figure 1 and ~~Extended Data~~Supplementary Table 2), as might their associations with temperature. We used the resultant risk estimates and the age-sex-specific death rates from each injury in 2017, to calculate additional deaths if each month in each state were +1.5°C above its long-term average, not only realistic in our lifetimes under current projections of global climate change but an agreed upper bound chosen under the Paris Climate Agreement.[2,49] +1.5°C is also within the range of anomaly size experienced by some states (Extended Data Figure 2). We did similar calculations for +2°C, which is the upper bound of the Paris Climate Agreement, and present these as Extended Data. For these calculations, we multiplied the actual death counts for each month, sex, state and age group in 2017 by the corresponding excess relative risk, which was calculated as the exponential of the coefficient of the temperature anomaly term from the above analysis.

Sensitivity analyses

We conducted sensitivity analyses to assess how much our results might depend on the temperature metric used to generate anomalous temperature. First, instead of building our monthly temperature anomalies based on daily mean temperatures, we used daily maxima and minima. These measures were strongly correlated to those generated from daily means (~~Extended Data~~Supplementary Table 3), and therefore we did not run models using these alternatives.

Second, together with temperature anomaly based on daily mean temperatures, we also included a second measure of anomaly in the model. We tested three different measures for this sensitivity analysis: (i) temperature anomaly calculated based on 90th percentile (°C) of daily mean temperatures within a month, compared to the average of 90th percentiles for each state and month; (ii) number of days in a month above the long-term 90th percentile of average temperature for each state and month (adjusted for length of month); and (iii) number of 3+ day episodes above the long-term 90th percentile of average temperature for each state and month (adjusted for length of month). These additional measures were related to more extreme anomalous situations which may be relevant if the impacts on injuries are related to more extreme temperatures and how frequent they are in each month.

The correlations among these variables and anomaly based on mean were between 0.60 and 0.89 (~~Extended Data~~Supplementary Table 4). The estimated rate ratios of temperature anomaly based on daily means (i.e., the anomaly measure used in the main analysis) were robust to the addition of alternative measures of anomaly, while the coefficients of the additional measures were generally not significant and with large credible intervals. Therefore, we did not include the alternative additional measures of extreme anomalous temperature in the main analysis.

Comparison with previous studies

While there are no previous studies of how deviations of monthly temperature from long-term average are associated with injury mortality, our results are broadly in agreement with those that have analysed associations with absolute temperature and for specific injury types. A study of suicide in US counties over 37 years (1968-2004) estimated that 1°C higher monthly temperature would lead to a 0.7% rise in suicides,[9] compared to our findings of 0.7-1.5% in males and 0.5-2.9% in females in different ages for a +1.5°C anomaly. A cross-sectional analysis in 100 US counties found that a 1°C higher temperature would lead to a 1.3% increase in death rates from road traffic injuries,[24] compared to our finding of 0.6-3.1% in males and 0.5-2.0% in females for a +1.5°C anomaly. In a study of six French heatwaves during 1971-2003, mortality from unintentional injuries rose by up to 4% during a heatwave period compared to a non-heatwave baseline.[10] A study of daily mortality from all injuries from Estonia found a 1.24% increase in mortality when daily maximum temperature went from the 75^{th} to 99^{th} percentile of long-term distribution.[11]

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Data availability

ERA5 temperature data are downloadable from https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5. Vital statistics files with geographical information can be requested through submission of a proposal to NCHS (https://www.cdc.gov/nchs/nvss/nvss-restricted-data.htm).

Code availability

The computer code for the Bayesian model used in this work is available at www.globalenvhealth.org/code-data-download.

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Author contributions

All authors contributed to study concept and interpretation of results. RP, GD, RT and ME collated and organised temperature and mortality files. RP, JEB, VK, HT-W and ME developed statistical model, which was implemented by RP, JEB and VK. RP performed the analysis, with input from other authors. RP and ME wrote the first draft of the paper; other authors contributed to revising and finalizing the paper.

Competing interests statement

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Figure 1. Number of injury deaths, by type of unintentional (transport, falls, drownings, and other) and intentional (assault and suicide) injury, by sex and age group in the contiguous USA for 1980-2017.

Figure 2. National age-standardised death rates from 1980 to 2017, by type of injury, sex and month.

Figure 3. Additional annual injury deaths for the 2017 US population in year in which each month was +1.5°C warmer compared with 1980-2017 average temperatures. The top row shows breakdown by type of injury, sex and age group. The bottom row shows the break down by type of injury, sex and month. Black dots represent net changes in deaths for each set of bars. See Extended Data Figure 3 for results for scenario of 2°C warmer.

Figure 4. Percent change in death rates in year in which each month was +1.5°C compared with 1980-2017 average temperatures by type of injury, sex and (A) age group or (B) month. Coloured dots show the posterior means and error bars represent 95% credible intervals, both obtained at the posterior draw level. See Extended Data Figure 4 for scenario of 2°C warmer.