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ABSTRACT

Increased temperature-related mortality is predicted to be one of the largest contributors to future economic damages from climate change globally, with declines in cold-related deaths in some regions outweighed by increases in heat-related deaths in others. Changes in temperature could also affect non-fatal health outcomes, whose aggregate societal burden is large, yet much less is known about how temperature affects the overall level and distribution of morbidity. Using georeferenced data on emergency department visits, mortality, and daily temperatures across California from 2006-2017, we show that the effect of temperature on mortality differs substantially from its effect on ED visits: mortality increases under extreme heat and cold, whereas ED visits increase under extreme heat but decline under extreme cold. These differential responses fundamentally shape the burden of future climate change: we predict that mortality in California will decrease by 0.32% due to changes in temperatures by mid-century, with declining cold deaths outweighing increasing heat deaths, but that ED visits will increase by 0.46% over the same period in the state, representing a total of 1.9 million excess visits. Our findings suggest that projected impacts of future warming on mortality, including benefits in many areas, might be a poor guide for morbidity impacts.

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1 Introduction

A large body of research has established that exposure to extreme temperatures, both hot and cold, is a cause of substantial excess mortality in the United States and globally.[1–5] This work also establishes that ongoing and expected future climate change is likely to have substantial, if heterogeneous, impacts on mortality. The burden of human-induced warming on mortality is already detectable,[6] and climate change is increasing the frequency and severity of health-damaging heat.[7–10] Recent estimates find that temperature-related mortality is projected to be one of the leading economic costs of climate change,[5, 11–15] with benefits from reductions in extreme cold temperatures outweighed in aggregate by increasing mortality from more frequent heat extremes. The monetized damage from these aggregate impacts is estimated to be the single largest contributor to the social cost of carbon in recent analyses.[15] Estimates also suggests impacts will vary substantially across and often within countries, with cooler regions likely to experience net benefits from future warming (again due to reduced mortality from less frequent cold extremes) and warmer regions likely to experience net damages.[16]

While temperature-mortality relationships are increasingly well understood, the relationship between a warming climate and morbidity – or the overall rate of disease and ill health in a society – remain much less well quantified. While by definition less severe than mortality, morbidity is far more common and represents a massive societal burden. Healthcare spending in the US on chronic disease alone is estimated to exceed $3 trillion annually and accounts for nearly 18% of US GDP.[17] However, unlike mortality, where relatively comprehensive local-level data on outcomes is well recorded in public vital statistics data in many countries around the world, data on morbidity are much less complete. Even in wealthy countries, comprehensive local-level panel data on key morbidity outcomes remain rare, especially for non-elderly populations, inhibiting assessments of how such outcomes might be shaped by a changing climate, among other phenomena.

There are a number of reasons why climate impacts on mortality – which fairly consistently show a characteristic U-shaped relationship with temperature, at least for all-cause mortality – might not provide an accurate guide for morbidity impacts. First, deaths occur disproportionately among older adults, who may have different environmental exposures or underlying responses to environmental insults; in comparison, illness and poor health are more evenly distributed across the population. Second, the 'causes' of morbidity and mortality outcome often differ – many things make us sick that do not kill us – and these different causes could respond differentially to temperature. Third, unlike mortality, which is directly observed, morbidity is typically proxied by some measure of healthcare utilization such as emergency department visits or hospitalizations. These utilization measures can be shaped by a number of factors, including individual decisions about whether to seek care.

Existing work has begun to indicate that extreme temperatures can indeed lead to sub-fatal, yet potentially still severe, health damages.[18–25] This work is somewhat mixed on whether morbidity responses to temperature differ from established U-shaped mortality responses, and which populations and outcomes are most affected. Some studies using US data do not check for non-linear morbidity responses,[21] find roughly linear responses,[19] or find non-linear responses depending on the lag structure.[23] However, many of these studies only examined adults 65 years and older,[21–23] who could plausibly have distinct responses to extreme temperatures as compared to the remainder of the population. Studies in New England and in Japan that were able to assess morbidity and mortality impacts among the same population found that morbidity tended to show more muted increases, or even declines, due to cold extremes than mortality, but that both increased substantially at hot extremes.[26–29]

Here we seek to advance our understanding of the effects of temperature on health by investigating the impact of daily temperature extremes on both emergency department visits and mortality rates using comprehensive, localized data from California, the most populous state in the US. A substantial advantage of our setting is that we can observe the universe of mortalities and the near-universe of emergency department visits among the same population over the same time period, and explore whether responses of these outcomes differ when each is exposed to the same temperature. Our rich data also allow us to explore, for all ages, both all-cause and cause-specific responses to temperature.

Specifically, we joined data on ED visits to all non-federal hospitals in California, data on all deaths in California, and gridded temperature data from 2006-2017. To compare the effect of temperatures on ED visit rates and mortality rates, we constructed parallel datasets and conducted nearly-identical analyses—the only distinction was that ED visit data were available at the zipcode level whereas mortality data were available at the county level. We estimated age- and cause-specific visit rates per 100,000 population, and studied how these monthly ED or mortality rates responded to hourly variation in ambient temperature within that month, using data from the widely-used gridded Parameter-elevation Relationships on Independent Slopes Model (PRISM) data[30] and a flexible binned panel fixed effects model to relate outcomes to temperature. To better understand drivers of changes in our outcomes, we conducted analyses of cause-coded ED visits (in 15 major disease groups) and mortalities (cardiovascular, respiratory, and accidental injuries) based on the International Classification of Diseases. Finally, using these estimated non-parametric models from the historical data, we then projected the impacts of future climate change on ED visits and mortality in California by combining these estimates with data from 33 global climate model simulations run under a 'middle-of-the-road' emissions scenario (SSP2-4.5), assuming that future ED visit and mortality rates will respond to temperatures as they have in the recent past.

Briefly, we find that, in California, emergency department visits and mortality respond very differently to temperature extremes, and that these responses suggest starkly different impacts under future climate change. Whereas we recover the typical U-shaped relationship between temperature and mortality, we find a roughly linear relationship between temperature and emergency department visits. We also find that extreme temperatures have far-reaching effects on emergency department use, with a very broad range of specific outcomes being affected, some substantially.

We then explore whether differences in mortality and morbidity responses can be explained by substantial observed differences in either the age profile of who dies and who visits the ED, and/or by substantial differences in the cause of death or ED visit and how these respond to temperature. Specifically, for age, we estimate age-specific responses of each outcome to temperature, and then conduct a re-weighting exercise in which we estimate what the ED response would have looked like if the age profile of individuals going to the ED reflected the age distribution of mortality. For causes, we estimate cause-specific responses and examine whether the temperature responses of the primary causes of heat-related mortality in our data – e.g., cardiovascular failure – mirror responses in ED visits for the same outcome. Results suggest that both age- and cause-specific responses can jointly explain much of the overall difference in morbidity and mortality responses in our data.

Finally, we project future impacts of morbidity and mortality due to global warming by mid-century in California, and find that responses differ in sign. Consistent with existing work,[16] we find an aggregate annual decline in temperature-related mortality in CA by 2050 of 0.32%, with a reduction in cold-related deaths outweighing an increase in heat related deaths. We find the opposite response for emergency department visits, and project an annual increase in ED visits of 0.46% by 2050 due to rising temperatures, representing 1.9 million cumulative excess ED visits. While we do not observe cost data associated with ED visits, a back-of-the-envelope estimate using average "direct" costs – i.e., the cost to the medical system of each ED visit in CA – suggests that the benefits from reduced mortality, as estimated using a VSL, substantially outweigh the added costs to the medical system from additional ED visits. This comparison does not account for any additional willingness to pay to avoid ED visits, however, and so could substantially understate total ED-related costs. Estimating such a willingness to pay will be critical for accurately estimating the total health related costs and benefits of a warming climate, given the substantial possibility for mortality-morbidity trade-offs we document.

2 Data and empirical approach

Exposures Daily minimum and maximum ambient temperatures were obtained from a modified version of PRISM (Parameter-elevation Regressions on Independent Slopes Model) climate mapping system, generated using the same interpolation approach but using a consistent set of contributing weather stations. These data were developed and made publicly available by Wolfram Schlenker*. These data report daily maximum and minimum temperature and precipitation levels in a 4km x 4km grid across the United States. To calculate the distribution of temperatures within each cell-day, we applied a sinusoidal interpolation between the minimum and maximum temperatures to recover 24 hourly temperature values (See Appendix). We then aggregated exposures within nine equally spaced bins: $<$6°C, [6-10), [10-14), [14-18), [18-22), [22-26), [26-30), [30-34), or $>$34 °C. These hourly bins were then summed at the cell-day level to estimate the duration of time in each bin.

We used resampled gridded population data[31] to calculate the population-weighted average proportion of each day where the ambient temperature was in each bin at the zipcode or county level. These values were then summed within each month of the year resulting in a temperature metric that indicates the population-weighted average number of days in a zipcode-month (or county-month) where the ambient temperature was within a given temperature bin. We selected [18-22°C) as the reference bin.

Outcomes Data on emergency department visit by cause, age, sex, and zipcode of residence came from California's Department of Health Care Access and Information (HCAI). Our data included all ED visits that occurred at non-federal hospitals in California between January 1, 2006 and December 31, 2017. Each record consisted of a single encounter, which covered patients who had face-to-face contact with a provider. For each encounter, we observed the date of admission, patient characteristics (zipcode of residence, age at time of service, self-reported race, sex), primary diagnosis, up to 20 secondary diagnoses, and hospital identifier.

Zipcode-day emergency department visit rates were constructed for total (all-cause) visits and for 15 mutually-exclusive principal diagnosis groups were developed based on groupings used by the

*Data available at `https://www.columbia.edu/~ws2162/links.html`

Department of Health Care Access and Information (Symptoms, Accidental Injuries, Respiratory System, Nervous System, Musculoskeletal System, Digestive System, Genitourinary System, Skin, Mental Health, Pregnancy, Infections, Circulatory System, Poison, Endocrine system, Alcohol); we additionally constructed an 'Other' category for visits for reasons not defined elsewhere. Diagnosis groupings were defined using ICD-9 and mapped to ICD-10 using Centers for Medicare & Medicaid Services General Equivalence Mappings as needed.[32] Monthly ED visit rates were standardized per 100,000 population, using annual population counts from the American Community Survey (ACS).

Data on mortality were obtained from the National Center for Health Statistics. Each record contained individual-level data on the underlying cause of death (ICD-10), age, sex, race/ethnicity, and the county of residence. County-level mortality rates were age-standardized using the direct method and 5-year bins (0-4, 5-9, ..., 85 and over) based on the 2000 US Census Standard Population. We obtained data on all-cause, all-age mortality rates, respiratory-related all-age mortality rates, cardiovascular-related all-age mortality rates, all-cause mortality rates among those under the age of 65 years, and all-cause mortality rates among those 65 years and older. Monthly mortality rates were standardized per 100,000 population.

Fig 1 summarizes the data. Between 2006–2017, we observed a total of 123 million ED visits and 2.9 million deaths. Over this period, ED visit rates increased from an average of 1,936 to 2,531 per 100,000 people per month and death rates increased from 64.5 to 74.4 per 100,000 people per month. Both outcomes and daily temperatures displayed substantial spatial and temporal heterogeneity.

Econometric approach Given the different level of aggregation for the ED data (zipcode) and mortality data (county), we estimated separate but parallel panel FE models that in both cases regress monthly outcomes in rates on bins of temperature exposure and use fixed effects to flexibly account for a range of area, seasonally-varying, and time-trending unobservables. Specifically, we estimated regressions of the form:

$$y_{amy} = \sum_b \beta_b Tbin^b_{amy} + \alpha_1 ppt_{amy} + \alpha_2 ppt^2_{amy} + \delta_{am} + \theta_{ay} + \varepsilon_{amy} \quad (1)$$

where y_{amy} is the ED visit rate per 100,000 population (or mortality rate per 100,000 population) in zipcode (county) a, month of year m, and year y modeled as a Poisson to enable estimates as a percent change in the presence of zeros.[33] $Tbin^b_{amy}$ is the number of days (i.e., number of hours divided by 24) where the temperature in area a (zipcode or county) in month m in year y fell into the range of bin b, i.e., one of either $<$6°C, [6-10°C), [10-14°C), [14-18°C), [22-26°C), [26-30°C), [30-34°C), or $>$34 °C. We included a quadratic in zipcode (county) monthly precipitation levels (αppt_{amy}), as well as fixed effects for zipcode-month (county-month) and zipcode-year (county-year) to flexibly control for local seasonality in both ED visits and temperature, average differences in baseline temperatures and public health, and long-term trends or year-specific regional shocks to either public health or temperature. Regressions were weighted by average zipcode (county) population to generate population-averaged effect estimates, and standard errors were clustered at the zipcode (county) level. We also estimated this model separately across age groups to better understand heterogeneity in age-stratified responses. We estimated Equation 1 with poisson regression, meaning coefficients can be interpreted as the percent change in monthly ED visit (mortality) rates per additional day (24 hours) spent in a given temperature bin, relative to additional day where the temperature was between [18-22°C).

We estimated Equation 1 separately for all-cause mortality or ED-visits, as well as separately for a number of cause-specific outcomes observed in the data, using cause-specific groupings to facilitate interpretation. Similarly, we estimated pooled all-age regression as well as age-group-specific regressions. In settings in which we report outcomes for multiple age groups or causes, we Bonferroni corrected confidence intervals to account for multiple hypothesis testing (all-age all-cause α = 0.05, all-age cause-specific ED visits α = 0.05/16; all-age, cause-specific mortality α = 0.05/3; age-specific all-cause α = 0.05/3; age-specific cause-specific α = 0.05/80).

As additional robustness, we also leveraged the availability of ED visit data at the daily level to model the impacts of daily temperatures on ED visit rates, estimating a binned model similar to Equation 1 and modeling ED visits as a function of temperature on that day and previous days, including lags of up to 28 days.

Climate change projections To estimate the potential impacts of future climate change on temperature-related ED visits and mortality in California, we used climate model projections from the sixth phase of the Coupled Model Intercomparison Project (CMIP6). Specifically, we obtained daily maximum and minimum temperature data from 33 global climate model simulations under the middle-of-the-road SSP2-4.5 scenario, which is broadly consistent with current emissions policies.[34] We used only 12 unique models, given the requirement for daily maximum and minimum temperature data in the SSP2-4.5 simulation, but used multiple realizations for a given model where available (up to as many as 5). As a result, our simulations capture uncertainty due to both inter-model differences as well as internal variability as represented by initial-condition uncertainty.

Climate models are spatially coarse relative to zipcode and county boundaries. Here we calculated zipcode- and county-level values from the model by assigning each zipcode (or county) the value from the model grid cell in which the zipcode's centroid falls. For each zipcode and county in each simulation, we conducted the same sinusoidal interpolation as described in Section 2 to obtain estimates of the proportion of each day spent in each temperature bin. We then summed these daily estimates to the monthly level. To calibrate the projections to our study period, we calculated the average number of days in each bin in each month of the year in our projections' data between 2006–2017 for each zipcode (county). For each month between 2018 and 2050, we then subtracted off this area-level month of year average from each projected temperature bin, yielding a 'delta' between the projections and the projections' baseline. To generate future projections calibrated to our observed data, we then added each 'delta' to the observed data's county level month-of-year average temperature bins. This now-standard procedure avoids relying on absolute temperatures from the climate models and instead only uses changes between the historical and near-future periods, and implicitly bias-corrects the model output by ensuring that model baselines match observations.

County-level population estimates from 2020–2050 were obtained from the California Department of Finance [†]. To estimate zipcode level future populations, we calculated the ratio of estimated county level populations in each future year to 2017 populations and then estimated zipcode level population-weighted averages of intersecting counties. Future populations were then estimated by multiplying 2017 zipcode populations by these ratios.

To estimate the effect of future warming on mortality and ED visits, we then multiplied our estimated effects of an additional day in a daily temperature bin by the change in the days per month in that given temperature bin, which yielded the change in our outcome in percentage change terms in that given zipcode (county). We then applied these rate changes to baseline ED and mortality rates, calculated by averaging rates over the most recent three years in our data 2015–2017. Multiplying these two estimates together, along with estimates of future population, generates estimates of excess ED visits (or deaths) in each future month.

In addition to our use of 33 climate model simulations, we additionally quantified uncertainty in our historical temperature - health relationship by randomly sampling at the area level with replacement 100 times and re-estimating the relationship in our calculation of historical rates and future changes. Thus we produced 3,300 estimates of future changes in ED visits and mortalities,

[†] Data available at `https://dof.ca.gov/forecasting/demographics/projections/`

which we aggregated to the month of sample level and then summarized. This resulting distribution accounts for uncertainty in the historical response of public health to temperature, uncertainty due to climate model structure, and uncertainty due to the initial-condition sensitivity of climate model projections.

Valuation of changes in mortality and ED visits To value deaths, we use the US Environmental Protection Agency central estimate of the value of a statistical life (VSL) in 2024 of $11.11 million. Economically valuing non-fatal health impacts is less straightforward because they can include a variety of difficult-to-monetize factors, including discomfort from illness, medical costs related to healthcare, loss of wages, and costs related to mitigating adverse health effects. In the absence of comprehensive estimates of willingness to pay data to avoid emergency department visits, we used public data on the average cost of an emergency department visit. According to the Healthcare Cost and Utilization Project (HCUP), based on data from the National Emergency Department Sample (NEDS), the average cost of an ED visit in the US in 2017 was $530.[35] There are differences in costs according to age (visits among older populations are on average more expensive) and by the severity of visits (more severe visits are more expensive), for example. In the absence of California-specific data, we use the average ED visit cost in western US states (Montana, Idaho, Wyoming, Colorado, New Mexico, Arizona, Utah, Washington, Oregon, California, Alaska, Hawaii): $650. Here, costs refer to "actual expenses incurred in the production of hospital services, such as wages, supplies, and utility costs" and were estimated based on charges ("the amount a hospital billed for the case") using HCUP hospital-specific cost-to-charge ratios.

3 Results

We found distinct differences between how all-cause ED visit and mortality rates respond to daily temperatures. Whereas we recovered the typical U-shaped temperature-mortality relationship in which all-cause mortality rates increase under both anomalously hot and cold temperatures, we found a roughly linear response of all-cause ED visit rates to daily temperatures. Relative to an additional day where the temperature was between 18-22 °C, monthly ED visit rates increased in response to both moderately warm days (i.e., 22-26 and 26-30°C) and hot days (i.e., 30-34 °C and $>$34 °C), but declined in response to moderately cold and cold days (Fig 2a). Monthly mortality rates increased in response to an additional day at $>$34 °C, did not meaningfully change due to moderately warmer days, and increased due to moderately cold and cold days relative to the reference (Fig 2b).

To assess robustness of these findings, we tested the sensitivity of our results to alternative temperature bin specifications, omitting population weights, lagging our exposures by one month, dropping individual months or years, and modeling outcomes in an ordinary least squares (OLS) regression and dividing by average rates to generate percent change estimates. Figure S7 shows these alternative specifications for ED visits and Figure S8 shows them for mortality rates. No meaningful differences are observed for omitting population weights (with the exception of larger standard errors) or for modeling the outcome in OLS regressions. Lagged results are shown in Figure S10. Modeling ED visits at the day level instead of at the monthly level, and including up to a month's lag of temperatures, gives similar results S11. Results are robust to dropping individual years or months (Figure S12,S13).

We tested alternative bin specifications that include lower minimum temperatures (e.g., instead of the lowest bin being <6°C the lowest is 4 or <0) and also higher maximum temperatures (e.g., instead of > 34 the highest bin is >36). For ED visits, alternative bin specifications indicate that temperatures below the cutoff of the lowest bin in our preferred specification have no effect on ED visit rates (rather than a negative effect), but confidence intervals are wide because these days are so infrequent in our sample. On the other side of the temperature spectrum, modeling days to include 'hotter' temperature days indicate larger ED visit rate increases. For mortality, lower bins also increase mortality rates and higher bins increase mortality rates relative to our baseline specification. For mortality, we also re-estimate our main analyses using age-standardized mortality rates as opposed to raw rates, which we select for our primary specification to facilitate the closest comparison to raw ED visit rates (Fig S9).

Age-stratified responses to daily temperatures

To understand why ED visits respond so differently to daily temperatures as compared to moralities, we explored two related potential mechanisms: (1) differences in the ages of the affected populations and (2) differences in the causes of ED visits versus causes of death.

More than 70% of observed deaths were among those older than 65 years of age, but this group made up only 5% of ED visits. In contrast, children under the age of 5 years visited the ED at a higher rate than any other age group but had the lowest mortality rates. Given the distinct age profiles of those that visit the ED as compared to those that die, it is useful to examine age-stratified effects.

We found that mortality rates increase at high and low temperatures among those aged 65 years and older, consistent with the all-age pooled response. The highest and lowest temperatures also increased mortality rates among those under 65 years, but, whereas moderately cold temperatures increased mortality rates among those 65 years and older, such days had no impact on mortality rates among those under 65 years. Confidence intervals for effect estimates for each temperature bin overlapped across these two age groups. Daily temperatures had no meaningful impacts on deaths among those under 5 years of age, though confidence intervals were wide (Fig S1).

Changes to ED visit rates from daily temperatures also largely overlapped across age groups, with some exceptions. Warmer days increased ED visit rates for both those under 65 years of age and those 65 years and older. However, whereas the coldest days decreased monthly ED visit rates among those under 65 years of age, we found that an additional cold day increased monthly ED visit rates among those over 65 years of age. Adults aged over 65 years accounted for about 12% of the population in California during our study period and contributed proportionately to increased visits from days >30 °C. Changes in ED visits were disproportionately driven by variations in ED visit rates among children under the age of five years (Fig S2), in large part because this group uses the ED much more than other groups. Despite children under 5 years accounting for just 6% of California's population, they accounted for 12% of ED visits on average and we found that changes in visits among children under the age of five years accounted for 40% of excess visits on the hottest days and 35% of the fewer visits on the coldest days (Fig S3).

Do differences in affected ages explain the differences we see in the response functions? To evaluate this hypothesis, we re-weighted our observed age-stratified response functions for ED visits by the proportion of deaths in each age group, thus asking the question: if the age profile of ED visits looked like the age profile of deaths, does the temperature-ED response function look more like the mortality response function? For instance, instead of those over 65 years accounting for 5% of ED visits, we reconstruct the pooled ED-temperature response but now weight the over-65 temperature response at 73%, reflecting the group's share of mortality. We then did the reverse process for mortality, reconstructing the mortality response by re-weighting the age-stratified mortality responses to reflect the younger age distribution observed for ED visits.

The resulting response functions are shown in Figure 3d,e. Weighting the age-stratified all-cause ED visit response by the mortality age distribution in our sample flattens, and even reverses, the cold-temperature ED visit response, indicating that at least some part of the observed all-cause ED visit response is due to differences in the age distribution. The mortality response is relatively unchanged by re-weighting, though the increase in cold-temperature related mortality risks is somewhat attenuated.

Differences in cause-specific responses to daily temperatures

ED visits and mortality differ in both severity and cause. Nationwide, 10% of visits to the ED result in hospitalization and 0.6% result in death, and studies estimate that between 35-50% of all ED visits in the US are non-urgent conditions,[36,37] i.e., those for whom a delay of several hours would not increase the likelihood of an adverse outcome. Causes of each outcome also differ. For instance, heart disease and cancer account for between 40-50% of all deaths in the US, but only 3% of ED visits (Fig 4).

However, unlike our age-stratified analysis, the large differences in causes that lead to death and those that lead to ED visits renders a re-weighting procedure impracticable. For example, 28% of deaths in the US are from cancer, but less than 1% of ED visits are related to cancer; re-weighting ED cancer visits by their share in mortality would require dramatically upweighting a response with very few observed outcomes. Nevertheless, visual inspection reveals several key insights. Fig 4 shows relatively strong agreement in the response of circulatory, respiratory, and accidental injury ED visits and deaths to daily temperatures, suggesting that the harms of temperature on both fatal and sub-fatal outcomes in these categories could act through somewhat similar social and biological pathways.

Our data on ED visits provide additional detail on cause-specific responses. We find substantial influence of temperature extremes on a remarkably broad range of cause-specific outcomes (Fig 5). One very cold day (for California anyway, <6°C) reduces monthly ED visits for injuries, respiratory conditions, musculoskeletal conditions, genitourinary conditions, skin conditions, mental health conditions, poison visits, and alcohol visits all by between 0.5% and 1%. One reasonably hot day (30-34°C) increases monthly visits for general symptoms, injuries, nervous system conditions, mental health conditions, genitourinary visits, and poison visits by the same amount. Proportionally, the largest increases in ED visits from hot days were from general symptoms and the largest declines from cold days were from accidental injuries, musculoskeletal conditions, and skin conditions.

Even further decomposition is possible. For example, we find that the circulatory response at higher temperatures is a combination of a decline in hypertension-related ED visits and an increase in visits for dysrythmias (Fig S4), and that respiratory-related visits are comprised of fewer visits for acute respiratory infections and chronic obstructive pulmonary disorders at higher temperatures but more visits for asthma at moderately warm temperatures (Fig S5).

Future temperature-related health burdens under climate change

Future temperature-health burdens under climate change will depend both on how exposures change and how effectively adaptation can mitigate impacts associated with the changing exposure profile. While adaptation can in theory mitigate future impacts, existing work finds mixed evidence that adaptation has been taking place as temperatures have risen in recent decades.[38] Here, we investigate future health burdens under the assumption that future ED visits and mortalities will respond to changes in daily temperatures as they have in the recent past, at least over the next few decades. We calculated an increase in ED visits of 0.46% in California by 2050 (95% CI, 0.16%–0.65%) representing 1.9 million cumulative excess visits between now and 2050 (95% CI 0.6–2.6 million) (Fig 6b,e). In contrast, we project a *decline* in temperature-related mortalities of 0.32% (95% CI, -0.74% to 0.14%), representing 28,000 fewer cumulative deaths, (95% CI 63,700 fewer to 11,700 additional deaths) over the same period in the state. These estimates are the aggregates of both heat- and cold-related changes. For mortality, we estimate that declines in cold-related deaths will outweigh increases in heat-related deaths in the coming decades (Fig 6c,d). For emergency department visits, given the roughly linear shape of the their relationship to temperature, we found that warming temperatures would increase ED visits at all parts of the temperature distribution in California in the coming decades (Fig 6c,d).

How large are the monetized damages and/or benefits of these projected changes in health outcomes? Under the very conservative assumption of no change in VSL or increase in healthcare costs through 2050, we estimate that (non-discounted) annual mortality damages by 2050 would decline by $17 billion, while ED visit costs would increase by $68 million due to projected warming relative to 2006-2017. We again emphasize that this is an imperfect comparison, as our mortality valuation captures willingness to pay but our morbidity valuation does not.

One might be concerned that our estimates of fewer temperature-related mortalities due to a changing climate is a function of some specific features of our California-specific mortality response function. To address this concern, we re-estimate our same binned mortality response in a sample that includes all counties in the US; unfortunately, we do not have comparable US-wide data for ED visits. We find that mortality responses do differ somewhat between the CA and the US sample, with larger responses to very high and very low daily temperatures in California as compared to the remainder of the US (Fig S6). In other words, California appears to handle temperature extremes worse than US on average in terms of mortality. Nevertheless, applying the full US response rather than the CA mortality response function to estimate the effect of climate change on deaths gives a very similar answer (overall negative cumulative deaths due to climate change by 2050), suggesting at least our excess mortality estimates are not driven substantially by any sort of idiosyncracies in the CA data or sample (Fig S6). However, because the CA-specific response function is meaningfully different from the rest of the US, we would urge some caution in any extrapolation of our response functions to the remainder of the country.

4 Discussion

Our longitudinal data offer a unique opportunity to study the impacts of temperature on morbidity and mortality across the same population and time period, using the same exposure and statistical models. Using longitudinal data on both ED visits and mortality across all of California over 12 years, we provided a comprehensive characterization of the associations between daily ambient temperatures and cause-specific ED visit rates and mortality rates. By examining the effects of daily temperatures on mortality and morbidity in an overlapping population and study period using parallel statistical analyses, we were able to directly compare and contrast their aggregate responses, and decompose these responses by age group and principal causes. The remarkably different responses of mortality and morbidity we observed have large implications for anticipating the health impacts of increasing temperatures under climate change.

We add to a large literature showing that both anomalously low and high temperatures increase all-cause[2,39–41] and cause-specific (especially for cardiovascular[3,39,41] and respiratory[39]) mortality, and a growing body of literature studying the effects of daily temperatures on all-cause and cause-specific healthcare utilization.[19–21,42–47] We contribute specifically to the much smaller set of studies that analyze both mortality and morbidity jointly in overlapping populations, many of which focusing on single rather than multiple causes.[26–29,48–51] Our results are most consistent with studies that have found that the temperature at which there is the smallest health risk is lower for measures of healthcare utilization than for mortality.[26,49] As in ref.,[27] we identify no such minimum risk temperature for our ED visits response. In our work, this lack of a minimum risk temperature could be a function of the relative temperate climate of California, where temperatures below 6 °C occurred less than 10% of the time during our study period; alternative models with a colder lowest bin (i.e., $<$0 °C) suggested no meaningful change in ED visit rates on these very cold – and in California, very rare – days (Figure S7), suggesting further work is needed to assess response functions in regions more frequently exposed to extreme cold.

We find that ED visit rates for a large range of cause-specific outcomes are responsive to daily temperatures. These results indicate that prolonged periods of hot or cold weather can be expected to have meaningful impacts on emergency department utilization for a range of outcomes.

Cause-specific investigations into the different responses of ED visits and mortality to temperatures in parallel analyses remain rare; most studies have focused on all-cause, cardiovascular, and respiratory related causes as we do here. Given that ED visit ICD code assignments can reflect somewhat subjective assessments, that we only analyze the first (primary) of up to 20 visit diagnosis codes, and that heat-related ICD cause codes are rarely used, it is plausible that daily temperatures lead to more ED visits for heat-related conditions, but that the heat-related conditions are not recorded as the primary visit diagnosis. For example, imagine that an individual with a preexisting neurological disorder comes to the ED on a very hot day with a heat-related headache. If a common symptom of the neurological disorder is headaches, then regardless of whether the heat stress caused the headache, the patient may receive a primary diagnosis code related to the underlying condition. In other words, it is possible that the associations between temperatures and cause-specific outcomes are not entirely mediated by heat-related physiological responses. We are therefore cautious not to overinterpret our cause-specific results, particularly for conditions without well understood links to heat.

Our finding of a mid-century decline in mortality in CA is consistent with a few recent US-wide and global analyses,[16,52] but in contrast to others;[12] other global studies do not report CA-specific numbers.[53] Direct comparison to these other studies is challenging given differences in age groups studied and warming scenarios assumed. Our state-specific response functions and projections are likely to have high internal validity for California specific applications but might not be a good guide for impacts outside the state, given California's unique climate.

We observed more than 40 times the number of ED visits as mortalities in our 12 year study period; and yet, the majority of studies projecting the health damages from climate change focus exclusively on mortality.[18,38,54] This focus on mortality comes in part from data availability, as deaths have long been more systematically documented, and in part because death is the most severe outcome and understanding its determinants and how it will change under future warming is extremely valuable. However, the meaningful differences between morbidity and mortality — namely, the age profiles of the populations affected, the specific causes of interest, and the role of human behaviors that lead to their observation in data (i.e., one may choose to go to the ED or not) — that could yield differences in the temperature-morbidity and temperature-mortality responses warrant future study.

Our study has important limitations. Our projections intend to illustrate the differences in temperature's impacts on mortality and morbidity under future warming, but ignore the potentially substantial impacts of demographic changes and adaptation. Our estimates could overstate impacts if future Californians are better adapted to extreme temperatures, or it could understate impacts if warming temperatures bring new health threats (e.g., vector-borne disease) into the state.[55,56] Additionally, our aggregate estimates of the future burden of a warming climate likely mask substantial spatial heterogeneity. For example, it is likely that Southern California will not benefit from fewer colder-than-usual days (of which it already has few) as compared to northern California. Our exposure measure is potentially subject to misclassification, particularly for zipcodes whose residents typically spend substantial time outside of their home zipcode, although we note that temperatures tend to be very highly correlated across nearby zipcodes. Additionally, given our rich set of area and time controls, our analysis relies on variations in daily temperatures and ED visit rates (mortality) within zipcodes (counties) within the same month of year; however, the possibility of residual confounders that covary with our outcomes and daily temperatures on the monthly time scale remains, for example, humidity, fine particulate matter concentrations, and ozone which are imperfectly correlated with temperature. We examined the overall associations between daily temperatures and morbidity and mortality; however, work has highlighted multiple measures of temperature that negatively impact health, including heat stress,[57] heat waves,[58] nighttime temperatures,[59] and temperature variability,[60] which future work should continue to evaluate.

Future studies of the health effects of environmental hazards could again benefit from jointly studying impacts on morbidity and mortality. Here, by analyzing both the mortality and morbidity impacts of anomalous temperatures in the same population, we offer a fuller picture of the potential consequences of climate change. Our results suggest that a very broad range of morbidity outcomes will likely be affected by a warming climate, and that future increases in heat extremes will increase both morbidity and mortality. At the same time, our results suggest that beneficial impact of declining cold extremes for mortality — an expected substantial benefit of climate change in much of the world[16,53] — will be offset, at least partially, by increases in morbidity at those temperatures. A full accounting of the impacts of climate change and their distribution will require understanding these outcome-specific trade-offs.

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Figures

Figure 1: **Distribution of daily temperatures, all-cause emergency department visits, and all-cause mortality rates in California, 2006–2017. a** Average, 25th percentile, and 75th percentile of the monthly zipcode level fraction of all hours where the population-weighted average temperature was greater than 22°C. **b** Average, 25th percentile, and 75th percentiles of monthly zipcode ED visit rates. **c** Average, 25th percentile, and 75th percentiles of monthly county mortality rates. **d** Average zipcode level hours where the population-weighted average temperature was greater than 22°C from 2006–2017. **e** Average monthly zipcode ED visit rates from 2006–2017. **f** Average monthly county mortality rates from 2006–2017.

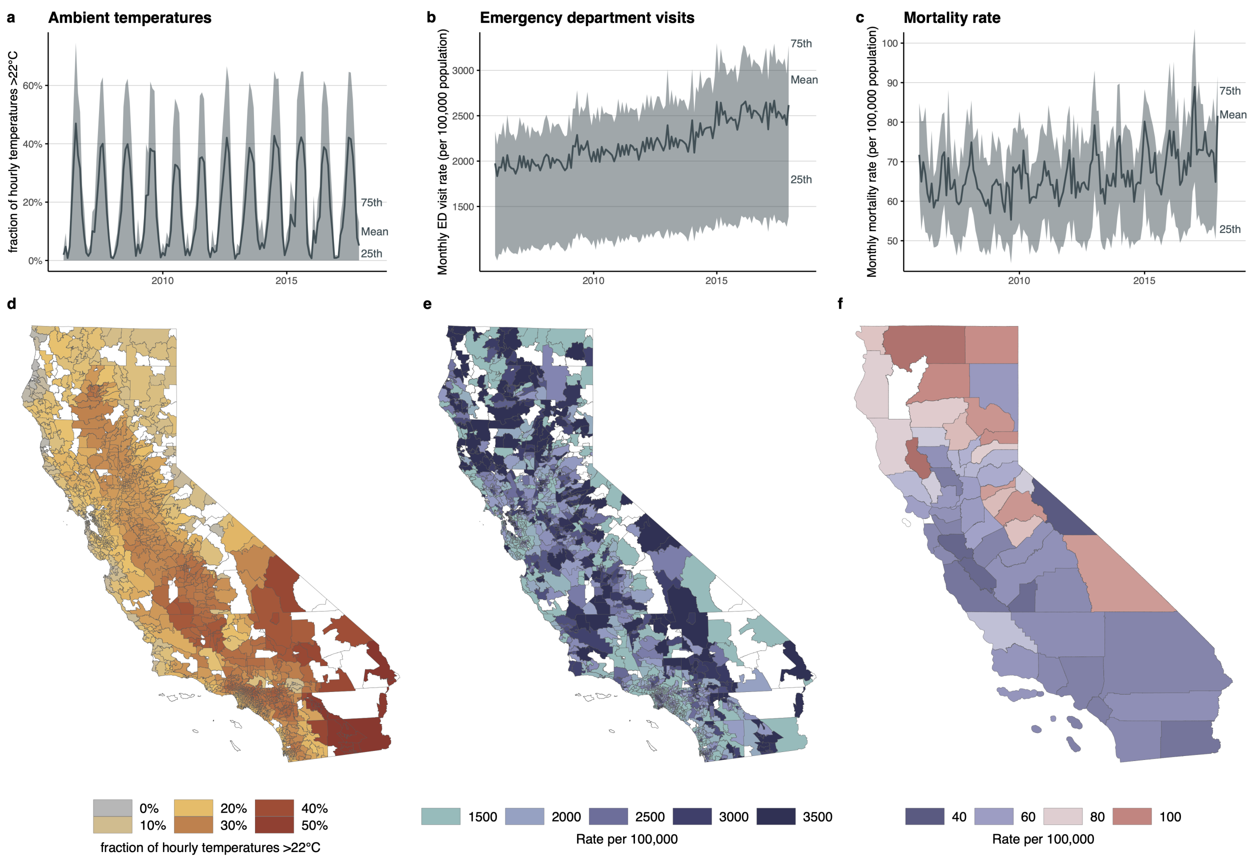


Figure 2: **Effects of daily temperatures on all-cause emergency department visit rates and mortality rates in California, 2006–2017.** Point estimates and 95% confidence intervals of the impact on monthly ED or mortality rates for an additional day spent fully in a given temperature bin relative to an additional day fully in the 18°C-22°C bin. Histograms at bottom show the average days per month in each daily temperature bin. Panels are labeled with the average rates for ED visits and mortality in our zip code (ED visits) or county (mortality) data.

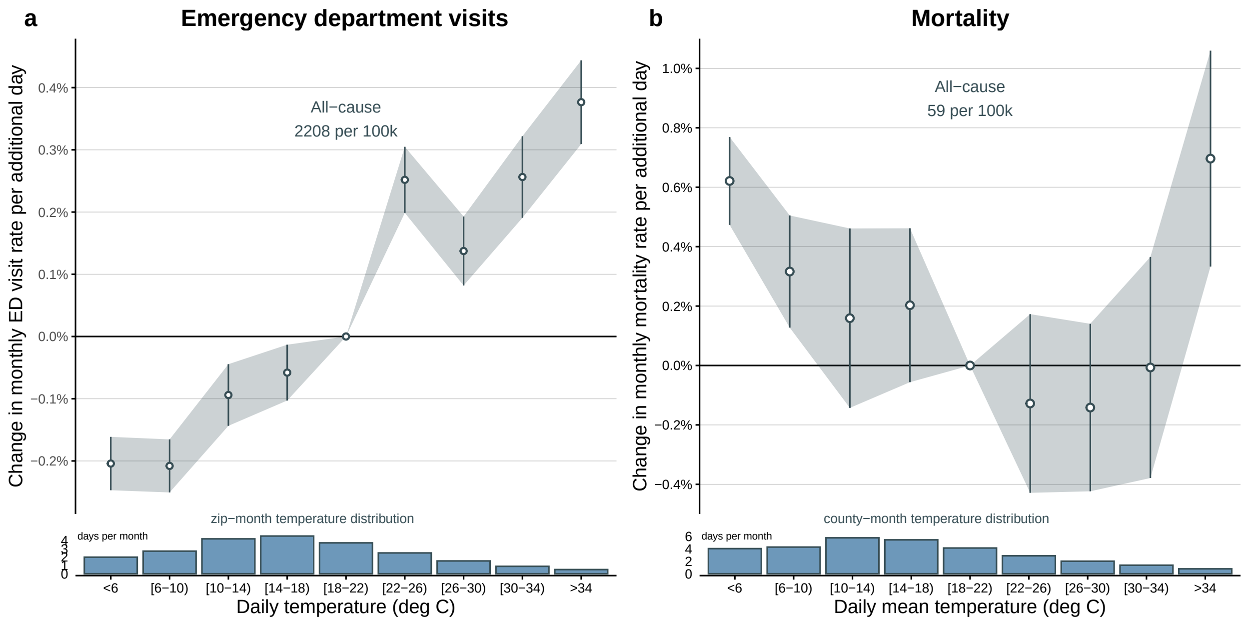


Figure 3: **Age-specific impact of daily temperatures on all-cause ED visit rates and all-cause mortality rates.** Point estimates and Bonferroni-corrected 95% confidence intervals for an additional day spent fully in a given temperature bin relative to an additional day fully in the 18°C-22°C bin. Labels show the average group-specific monthly rates per 100,000 population. Each plot also shows the distribution of temperature bins in days per month. All-cause age-stratified responses increase at moderately-cool temperatures relative to the reference in both age strata, unlike the all-age response, likely due to missing age data (9% data loss).

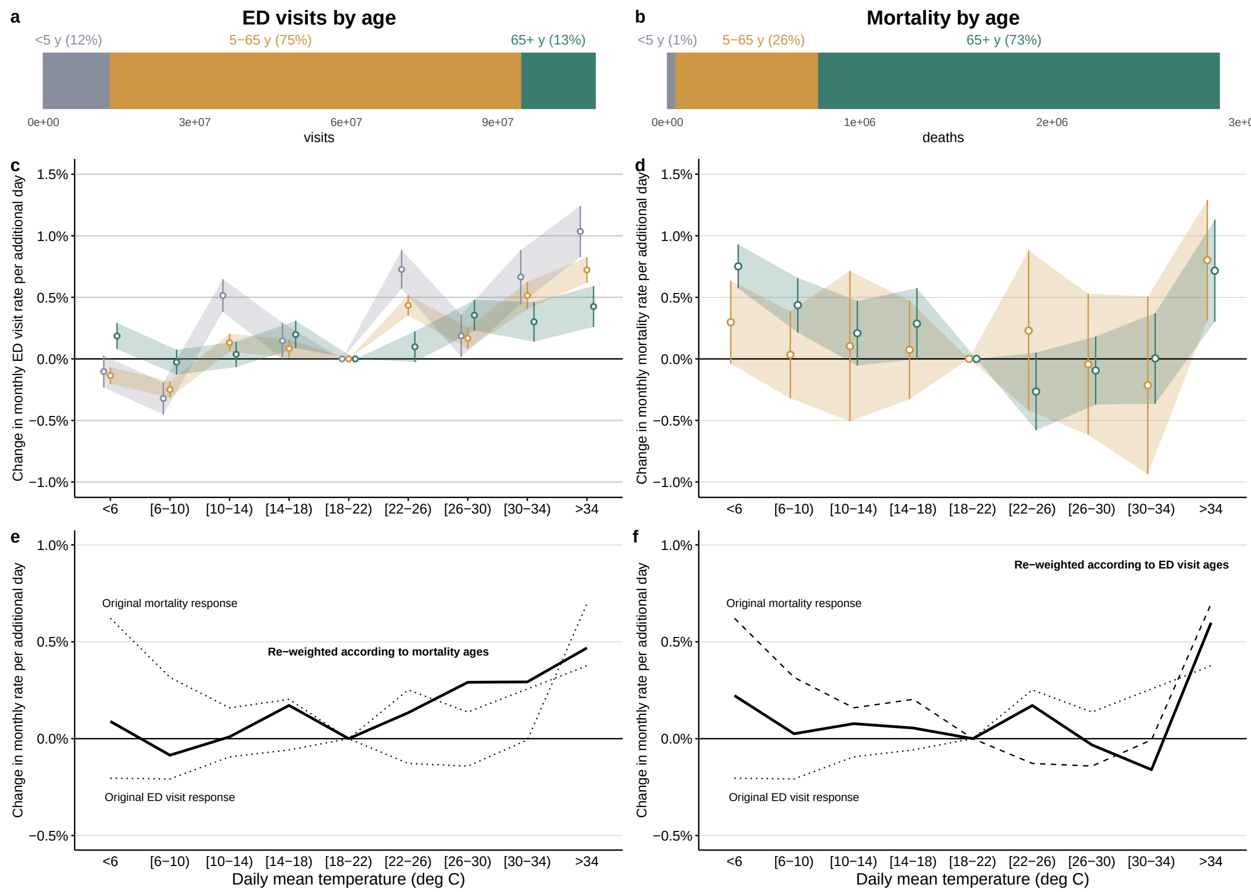


Figure 4: **Cause-specific impact of daily temperatures on all-cause ED visit rates and all-cause mortality rates, for selected causes.** Point estimates and Bonferroni-corrected 95% confidence intervals for an additional day spent fully in a given temperature bin relative to an additional day fully in the 18°C-22°C bin. Labels show the average group-specific monthly rates per 100,000 population. Each plot also shows the distribution of temperature bins in days per month.

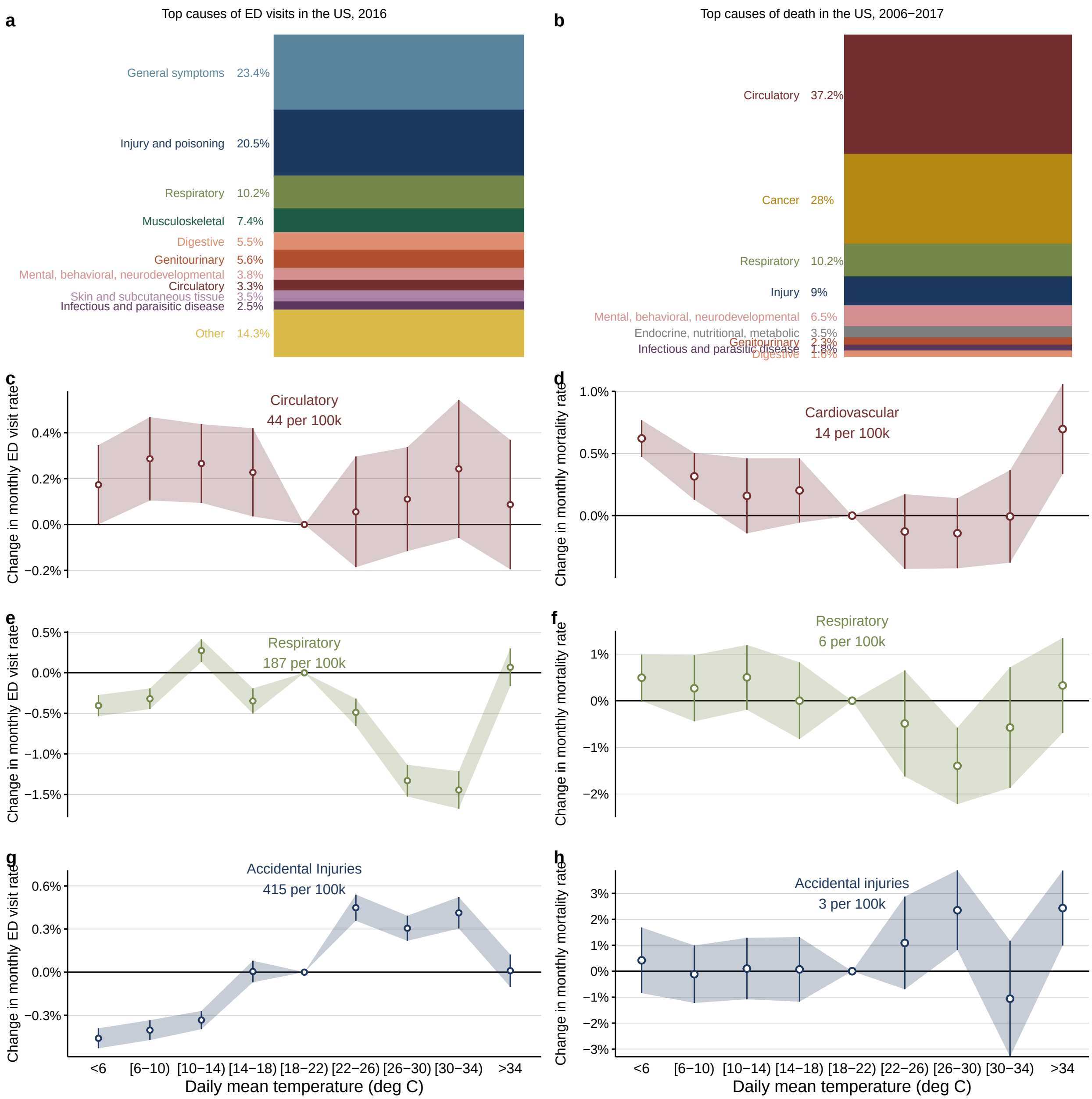


Figure 5: **Effects of daily temperatures on all-cause and cause-specific ED visit rates.** Point estimates and Bonferroni-corrected 95% confidence intervals for an additional day spent fully in a given temperature bin relative to an additional day fully in the 18°C-22°C bin. Below each outcome category are the sample-wide daily ED visit rate for that cause per 100,000 population.

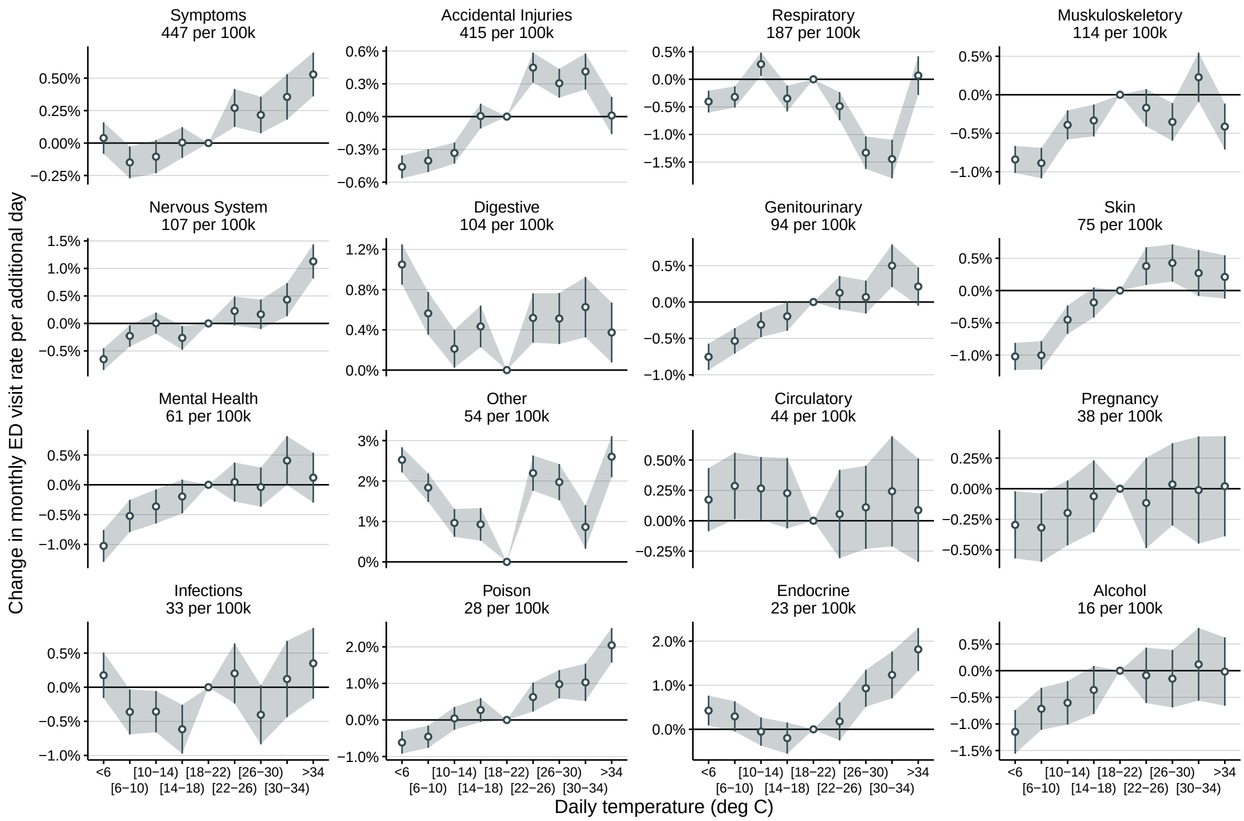
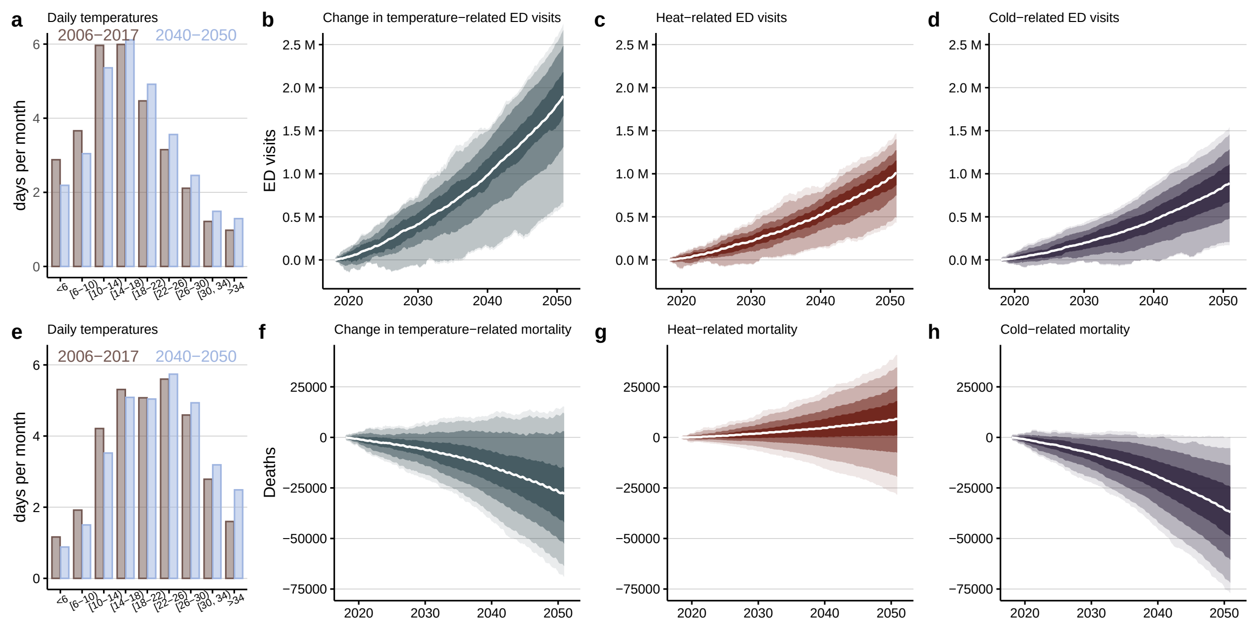


Figure 6: **Projections of changes in temperature-related ED visits and mortality, 2020–2050.** **a,d** Compares the population-averaged baseline-corrected days per day in each temperature bin across the 33 climate models in zipcodes and counties, respectively, in 2006–2017 (study period) to 2040–2050. Panels **b,c,d** illustrate the change in all temperature-related ED visits, heat-related ED visits (ED visits due to daily temperatures above 22°C), and cold-related ED visits (ED visits due to daily temperatures below 18°C). The white line shows the average estimate in every month-year between January 2018 and December 2050 (inclusive) and bands indicate (from darkest to lightest) the 25th percentile to the 75th percentile, 10th percentile to the 90th percentile, 2.5th percentile to the 97.5th percentile, and 1st percentile to the 99th percentile of all estimated changes across the bootstrapped estimates in all climate models (n=3300 estimates). Panels **f,g,h** indicate the same but for mortalities.



Appendix

Additional detail on temperature exposure

To calculate the distribution of temperatures within each cell-day, we applied a sinusoidal interpolation between the minimum and maximum temperatures to recover 24 hourly temperature values, using the following equation:

$$\text{byhour}_i c(h) = \frac{tMax_{ic} + tMin_{ic}}{2} + \left(\frac{tMax_{ic} - tMin_{ic}}{2}\right) \cdot \sin\left(\frac{\pi \cdot (h-6)}{12}\right), \text{ for } h \in \{1, 2, ..., 24\} \tag{2}$$

where *i* is a day of the year in grid cell *c*.

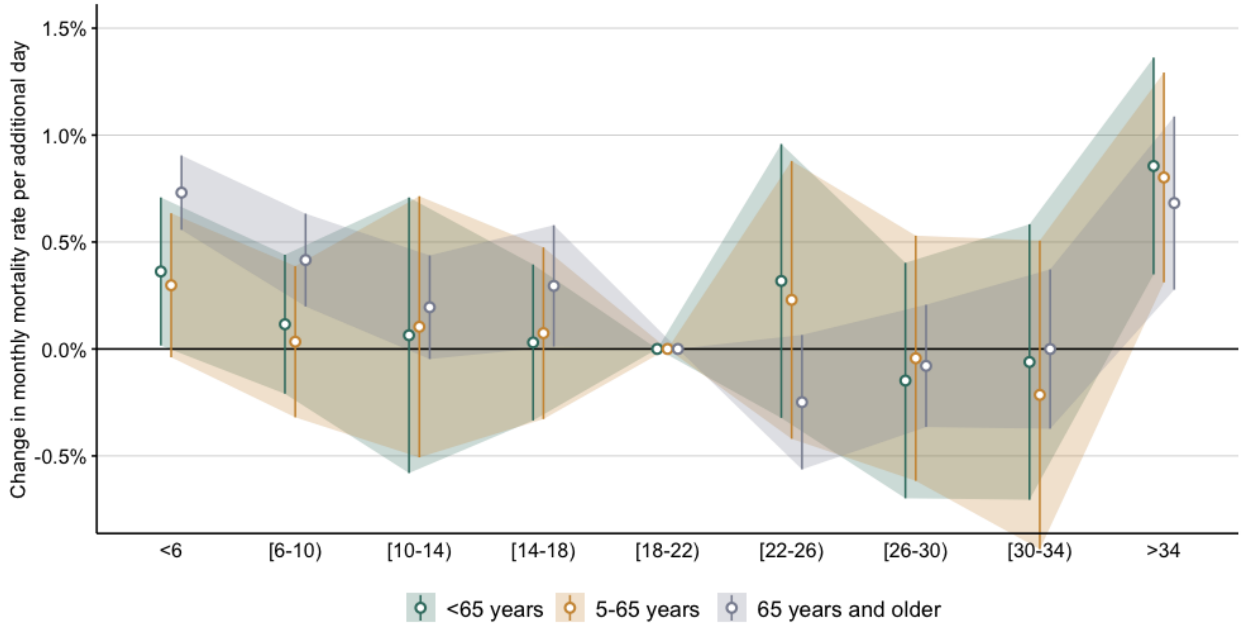
Discussion of cause-specific ED visit responses

Of the 16 groups of causes examined, seven increased from higher daily temperatures and declined from lower daily temperatures (symptoms, accidental injuries, disorders of the nervous system and sensory organs [inflammatory diseases of the central nervous system, disorders of the eye, disorders of the ear], genitourinary [urinary tract, genitals, and kidneys], skin [infections, inflammation], mental disorders [mental disorders due to physiological conditions or psychoactive substance use, mood disorders, pyschoses], and poison [accidental poisonings]). Visit rates for diseases of the digestive system [oral cavity and salivary glands, intestines, colitis], endocrine, nutritional, and metabolic diseases [thyroid, endocrine], and other causes not categorized elsewhere [certain congenital anomalies, encounters for factors that influence health status but are not categorized, certain accidental injuries of external causes] increased from both higher and lower daily temperatures. Both warmer and cooler temperatures reduced respiratory- and musculoskeletory and connective-tissue-related ED visit rates [dorsopathies, rheumatism, arthropathies]. Alcohol-related visits did not meaningfully respond to warmer daily temperatures but fell at lower temperatures relative to a day in the reference bin. Circulatory [hypertension, dysrhythmias, disorders of the veins] and pregnancy-related [pregnancy complications, post-delivery, labor] ED visit rates were not meaningfully affected by daily temperatures.

While positive associations between temperature and cardiovascular mortality have been consistently observed, a number of studies have found no (or even negative) associations between heat and respiratory- and circulatory-related healthcare utilization as we do.[19,21–25] By exploring more granular causes of cardiovascular-related ED visits we provide evidence that these aggregate declines are driven by fewer visits for hypertension-related disorders, consistent with a biological mechanistic hypothesis that fluid losses associated with extreme heat are protective of cardiovascular failure due to high blood pressure.[21] These declines outweigh relatively smaller increases for other outcomes like cardiac arrests and arrhythmias, which may drive increased mortality. Some hypothesize that increased out-of-hospital mortalities for cardiovascular and respiratory-related outcomes outweigh changes in healthcare utilization.[25]

The distinct decline in respiratory-related ED visits with colder temperatures merits further discussion. It stands in contrast to a large body of evidence that finds that colder temperatures are associated with respiratory-related mortality and morbidity, in large part due to higher infection rates. We find the opposite. Observed declines in respiratory-related ED visits in our sample are largely driven by fewer visits to the ED for respiratory tract infections, though we see declines in ED visits for asthma and chronic obstructive pulmonary disorder as well. Stratifying our sample by summer and winter months leaves these results largely unchanged. Furthermore, we see declines for ED visits of similar magnitudes across all ages and in all temperature regions, as well.

Figure S1: **Age-stratified all-cause mortality rate response to daily temperatures.** Models mirror our preferred approach, but include additional age stratified results not presented in the main text, including all deaths among those under 65 years of age and all deaths among those under 5 years of age.



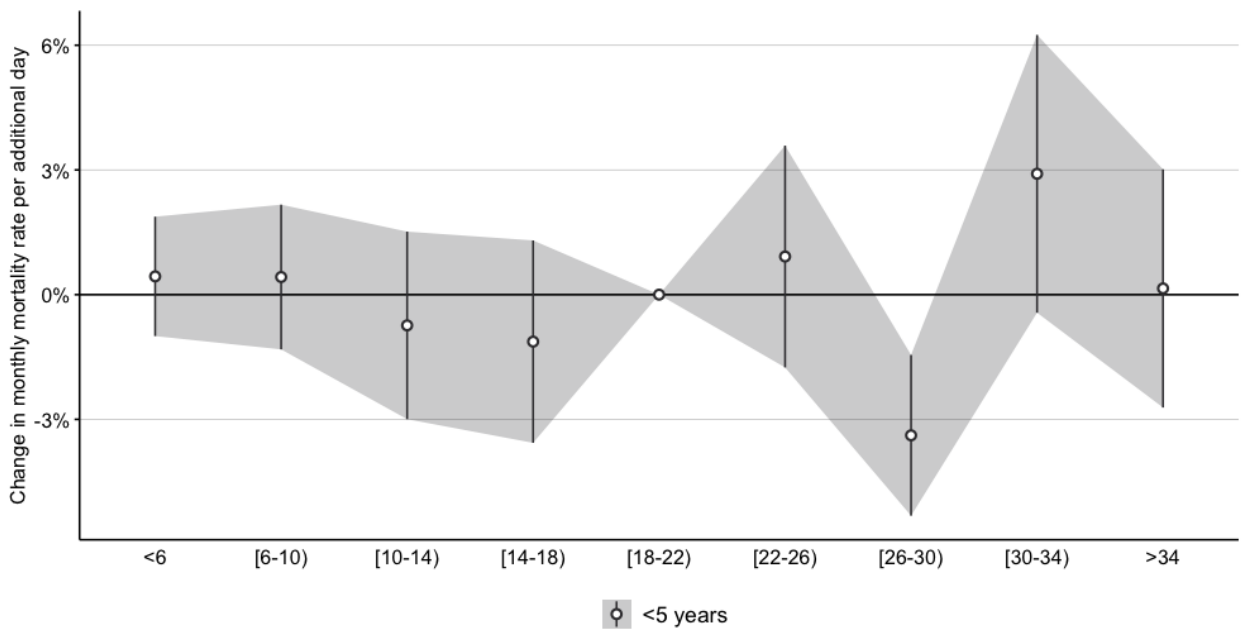


Figure S2: **Heterogeneity of associations between zipcode daily temperatures and monthly age-stratified, cause-specific ED visit rates.** Point-range responses indicate coefficient estimates and 95% confidence intervals for each temperature bin relative to 18-22 °C. Roughly 9% of age-related data were missing.

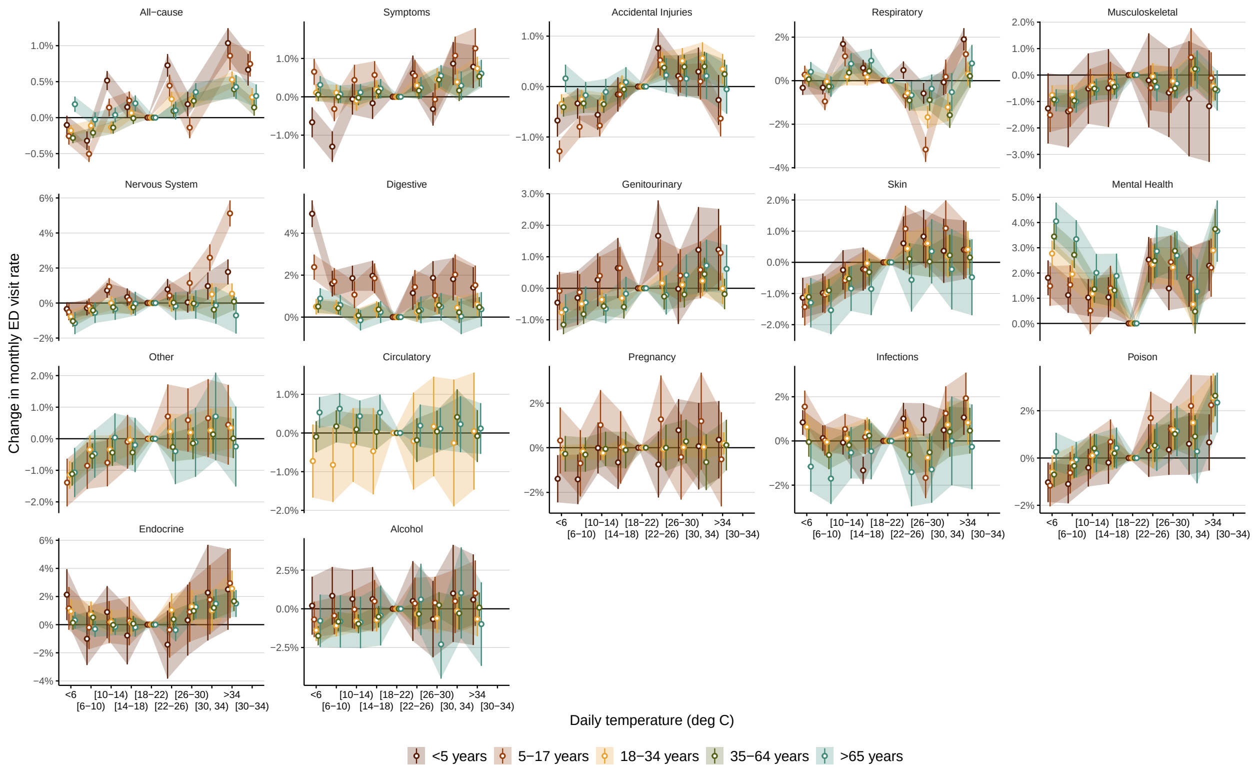


Figure S3: **Breakdown of attributable increases and decreases in monthly ED visits by age group and temperature bin.** For each temperature bin (x-axis), we plot the age-stratified change in ED visit rate per 100,000 population on the y-axis from regressions that use the raw rates as the dependent variable estimated via OLS. Bins are separated by positive and negative impacts. For example, an additional day above 34 °C is estimated to increase the monthly ED visit rate by around 80 visits per 100,000 population, of which 35 are from those under 5 years, 15 from 18-34 years, etc.

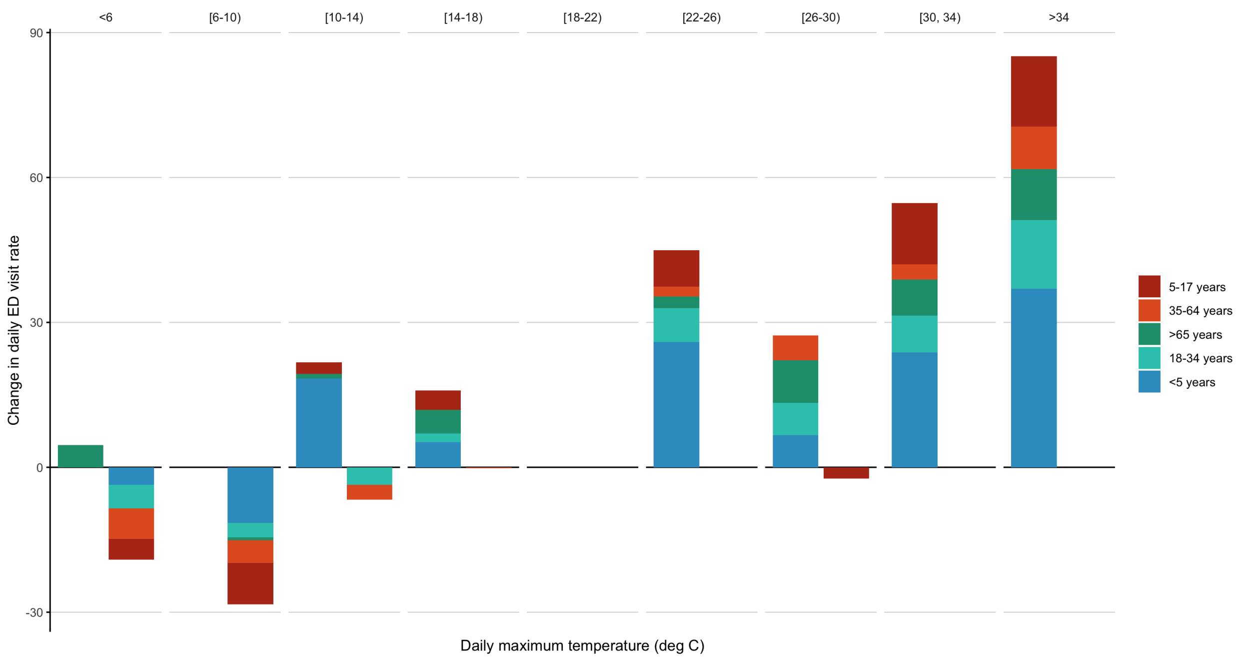


Figure S4: **Associations between daily temperatures and granular circulatory-related ED visits.** These models parallel our main statistical approach.

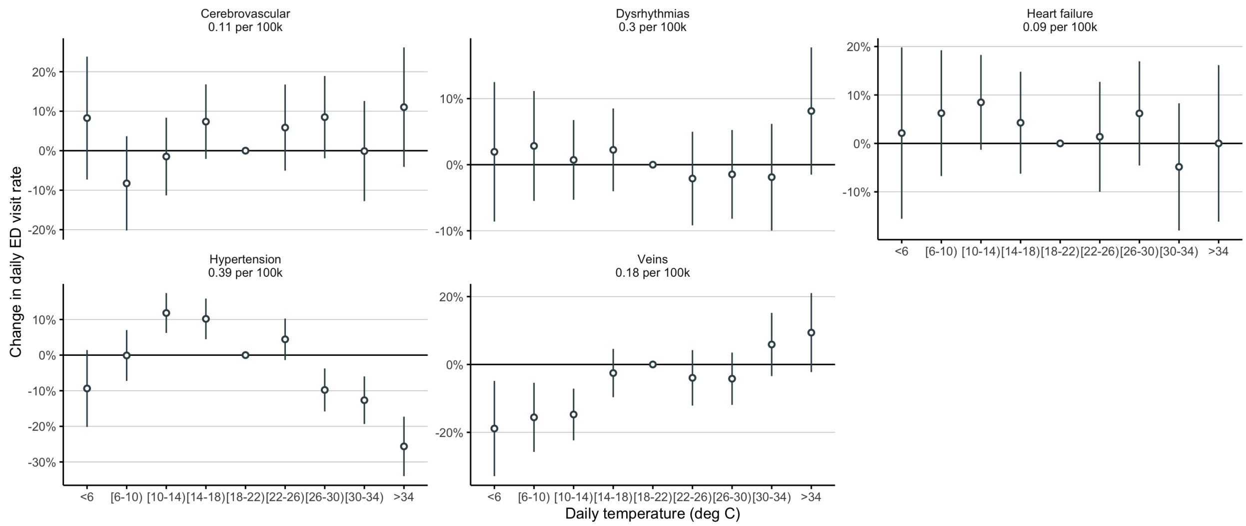


Figure S5: **Associations between daily temperatures and granular respiratory-related ED visits.** These models parallel our main statistical approach.

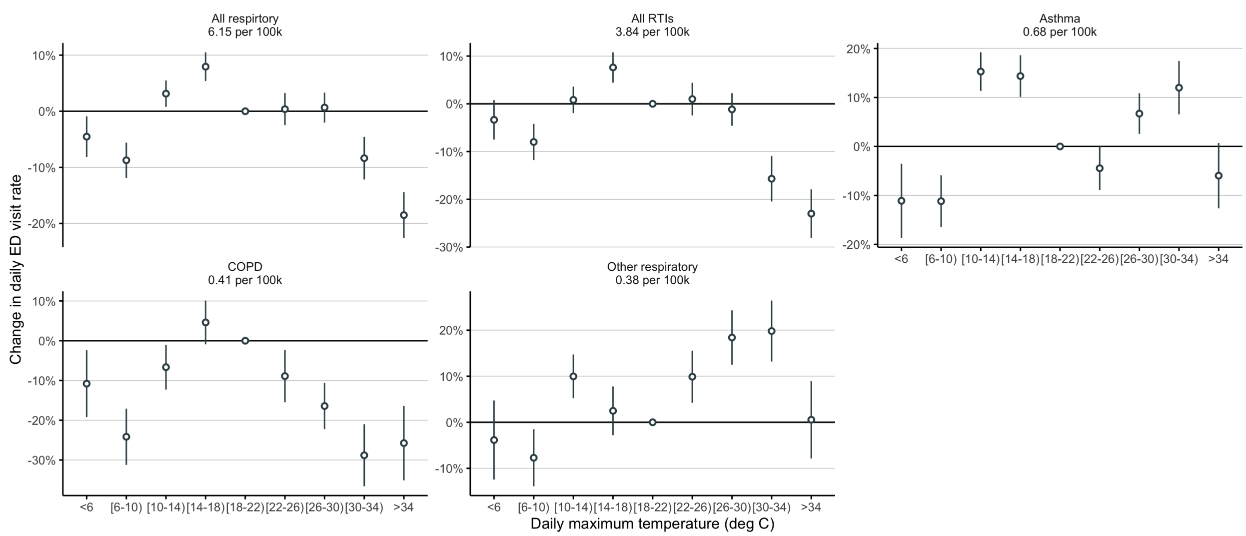


Figure S6: **Comparing the effects of daily temperatures on all-cause mortality rates in California vs. the US.** These models parallel our main statistical approaches, but compare two samples. The first is our California-only sample (red) and the second is the full contiguous US-wide response. Below the main panel we show the distribution of daily temperatures.

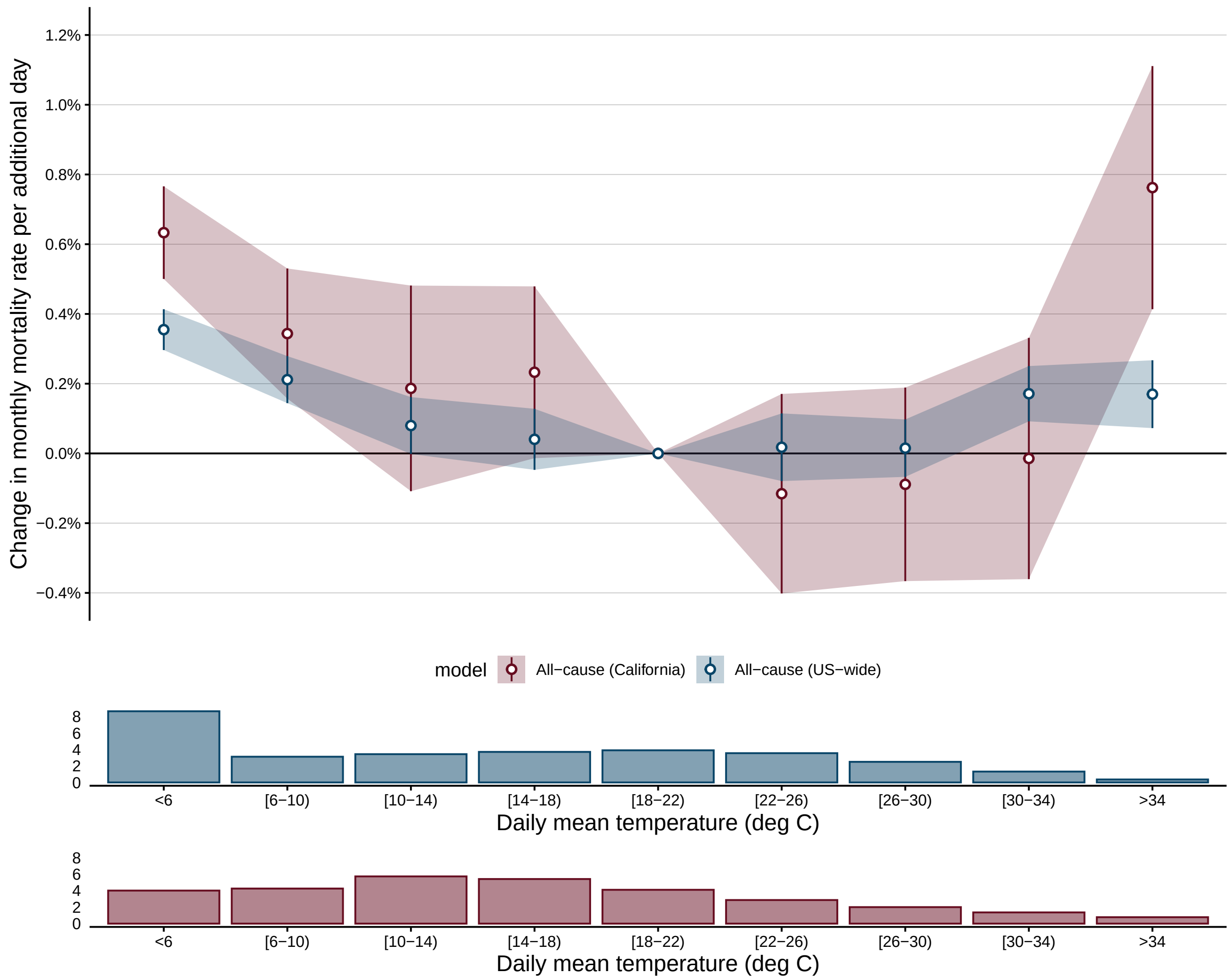


Figure S7: **Alternative specifications for assessing effects of daily temperatures on ED visit rates.** In the top panel, we show our main specification, omitting population weights, estimating the relationship via OLS and dividing by the average rates to generate percent change. In the bottom panel, we estimate our relationship with slightly different temperature bins.

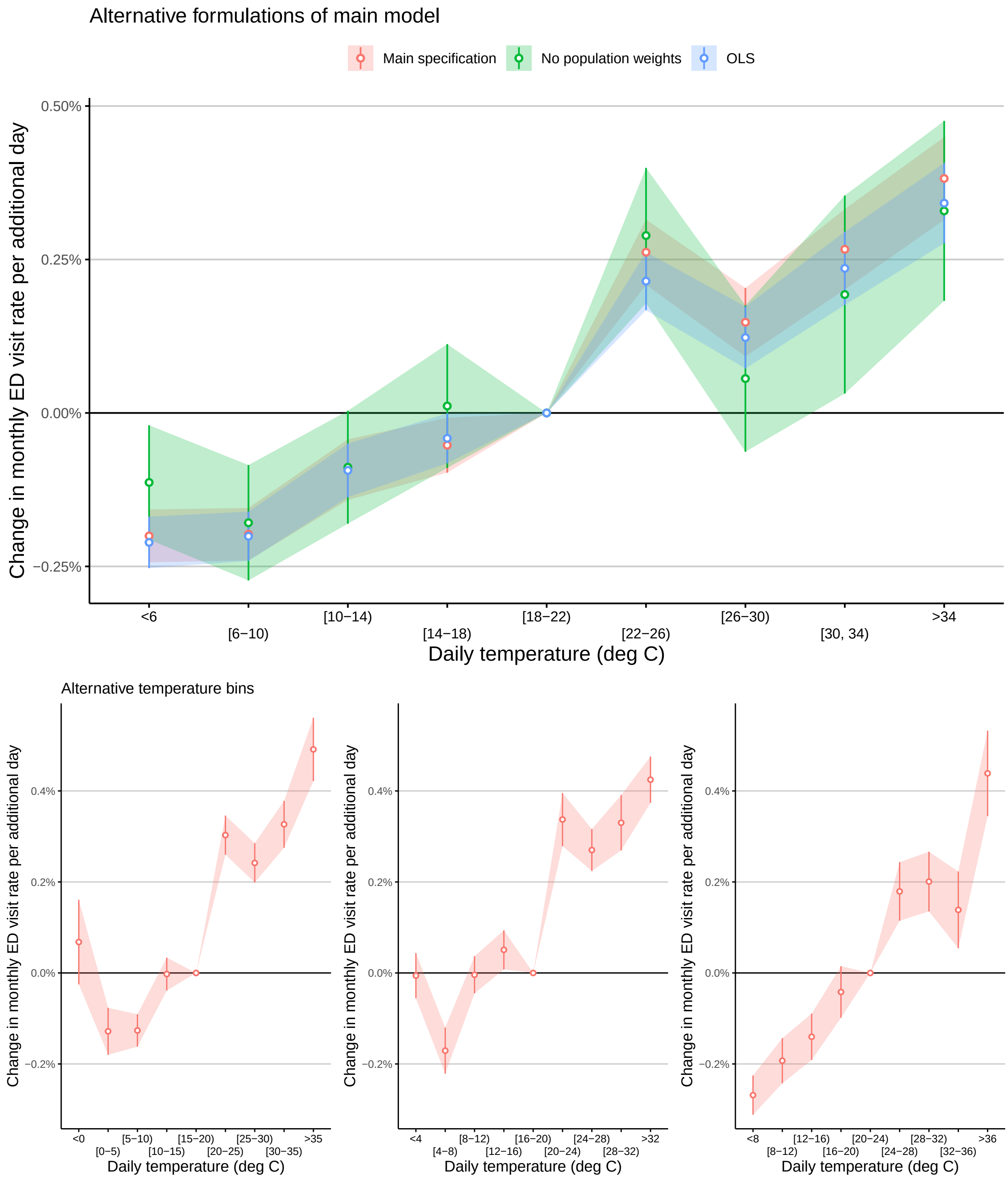


Figure S8: **Alternative specifications for assessing effects of daily temperatures on monthly mortality rates.** In the top panel, we show our main specification, omitting population weights, estimating the relationship via OLS and dividing by the average rates to generate percent change. In the bottom panel, we estimate our temperature-mortality relationship with slightly different temperature bins.

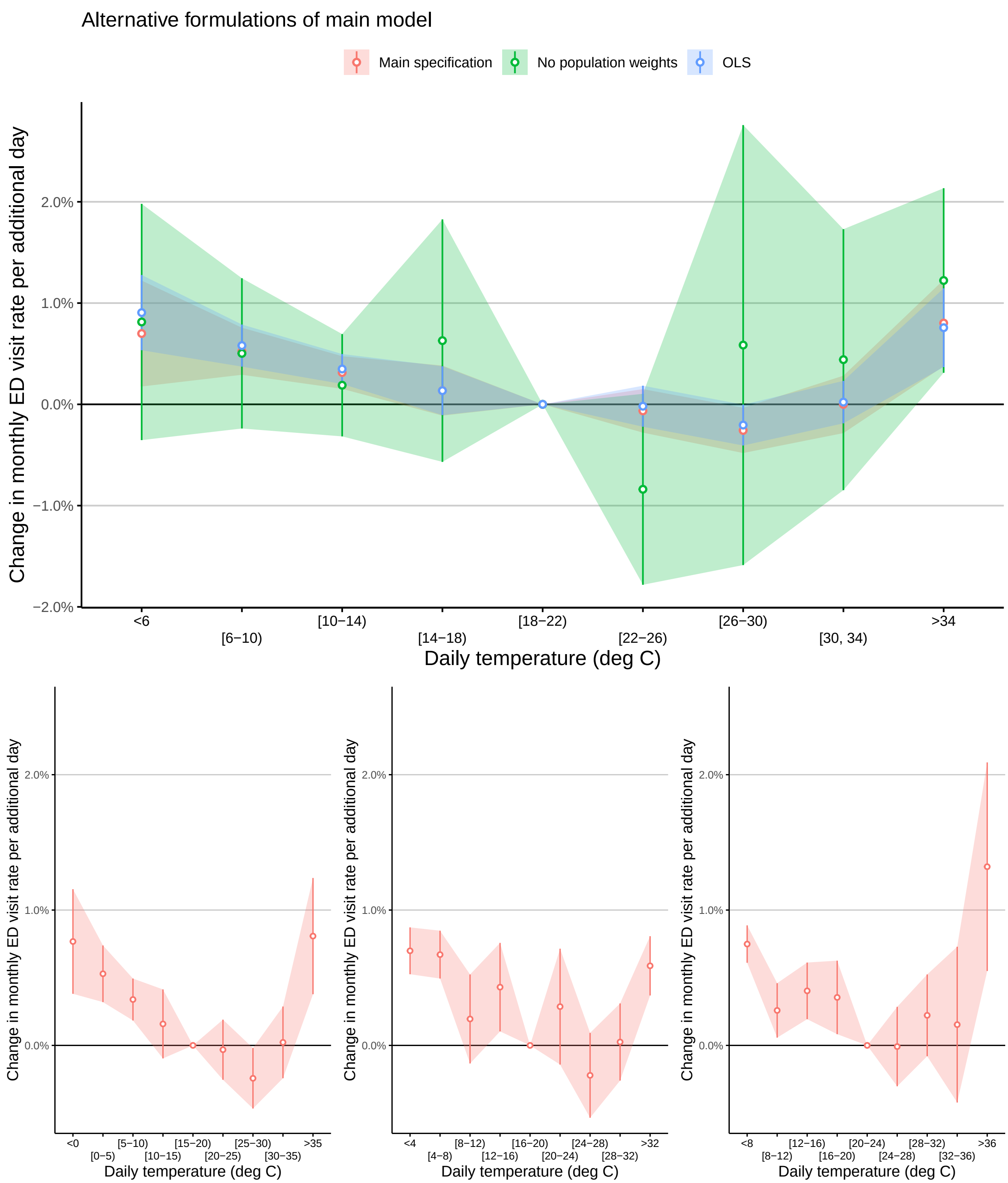


Figure S9: **Effect of daily temperatures on age-adjusted mortality rates.** In the top panel, we replicate our main all-cause and cause-specific analyses (shown in Fig 2 and Fig 4), but instead of raw mortality rates we the outcomes have been age-standardized. In the bottom panel, we replicate our all-cause, age-stratified results (shown in Fig 3 and Fig S1), but instead of raw mortality rates the outcomes have again been age-standardized.

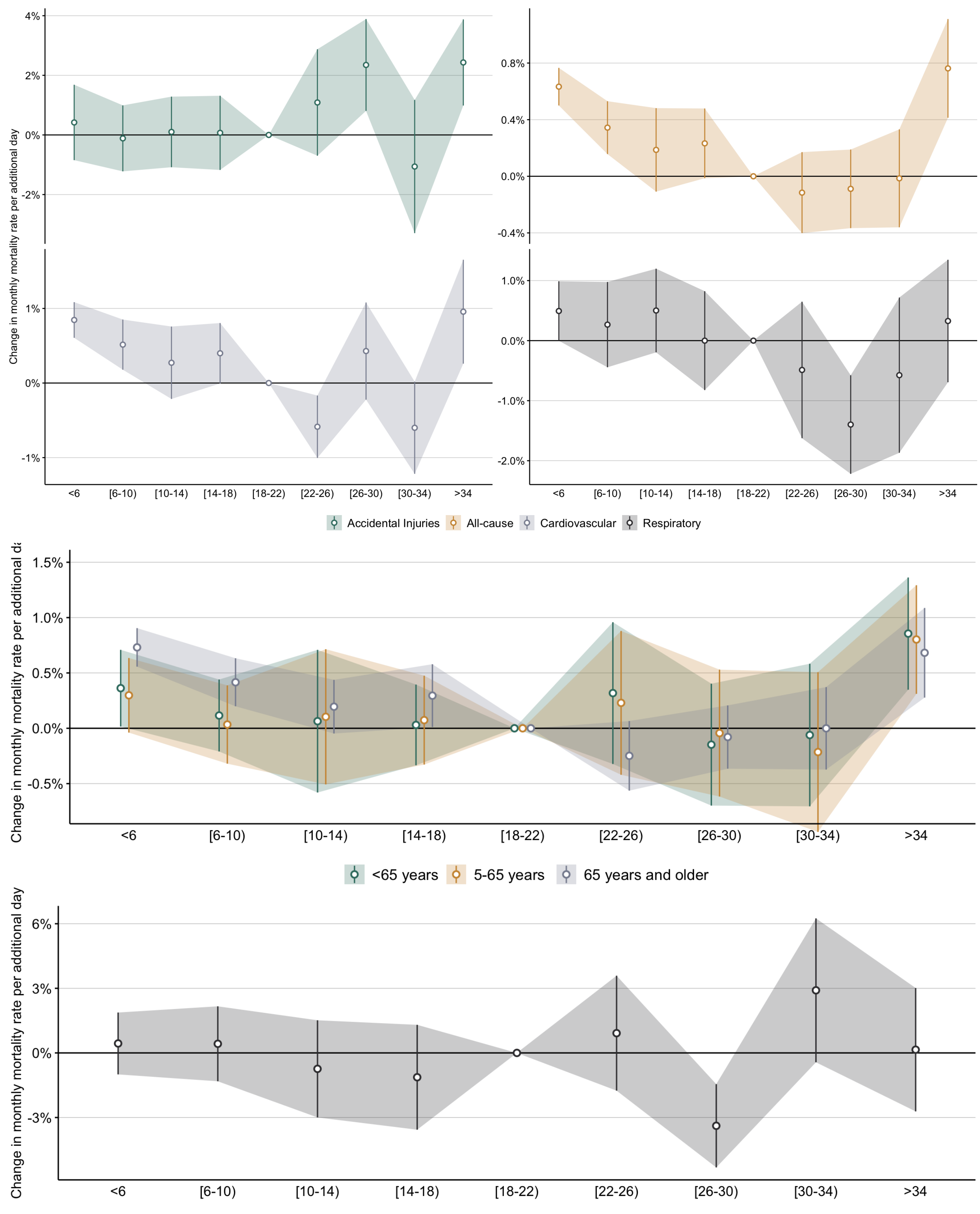


Figure S10: **Impacts of temperature on monthly ED visits and mortality rates in the same month and with a lagged response.** In addition to our main specification, which is not lagged, we also show impacts where we include the previous month's temperature bins and estimate the cumulative effects.

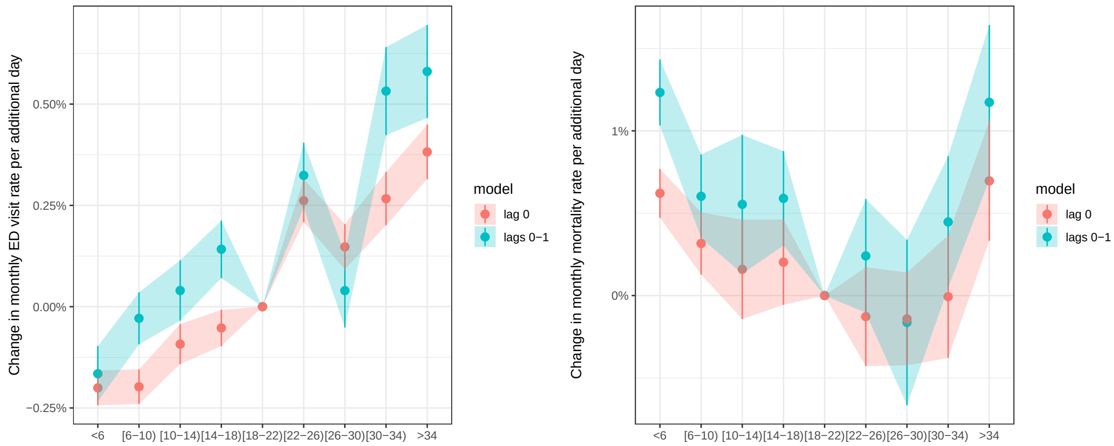


Figure S11: **Assessing the impacts of daily temperatures on daily emergency department visit rates at various lags.**

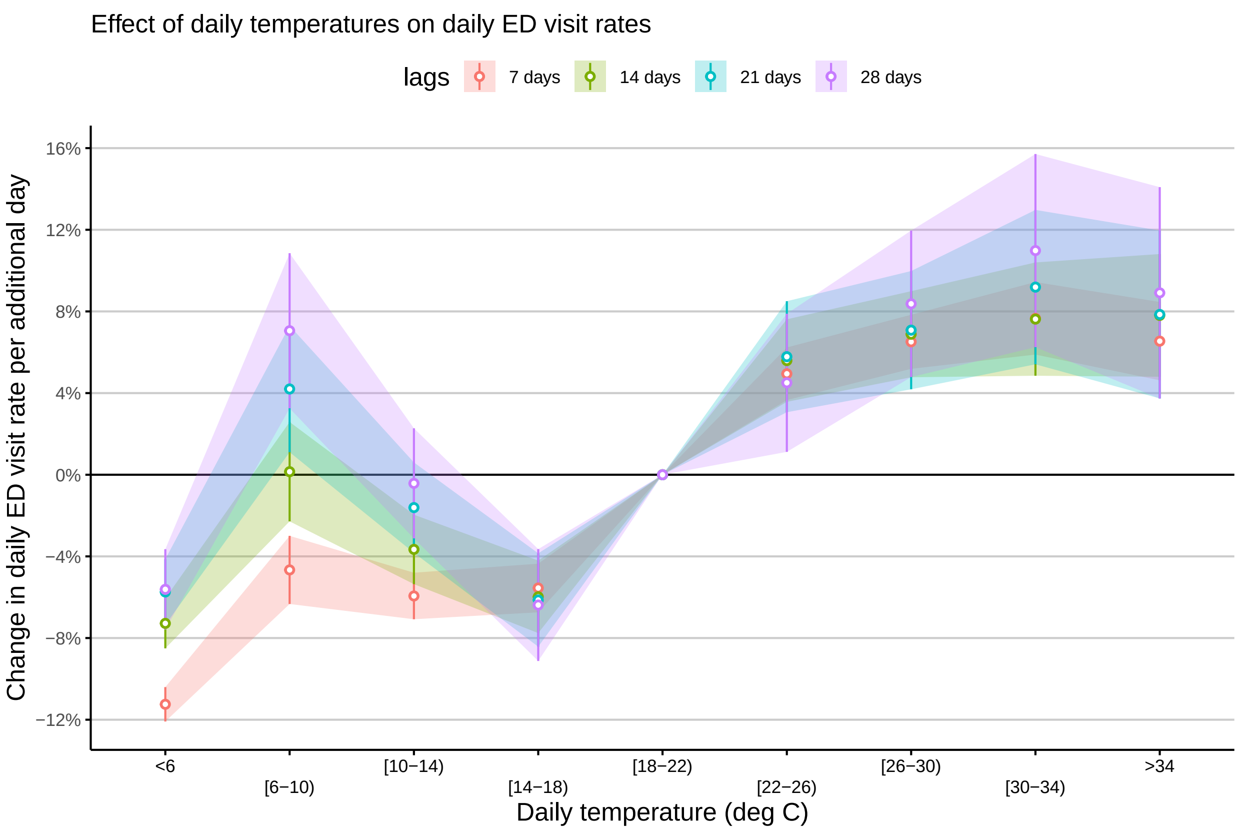


Figure S12: **Systematically omitting months and years from assessment of effect of daily temperatures on monthly ED visit rates.** Top panel shows the temperature-ED visits relationship, labeled according to which year is omitted from the analysis. Bottom panel does the same, but for month of year omitted from the analysis. We choose this approach because we are able to retain our preferred time controls (i.e., month of year and year fixed effects). Responses indicate that the results are consistent across months and year.

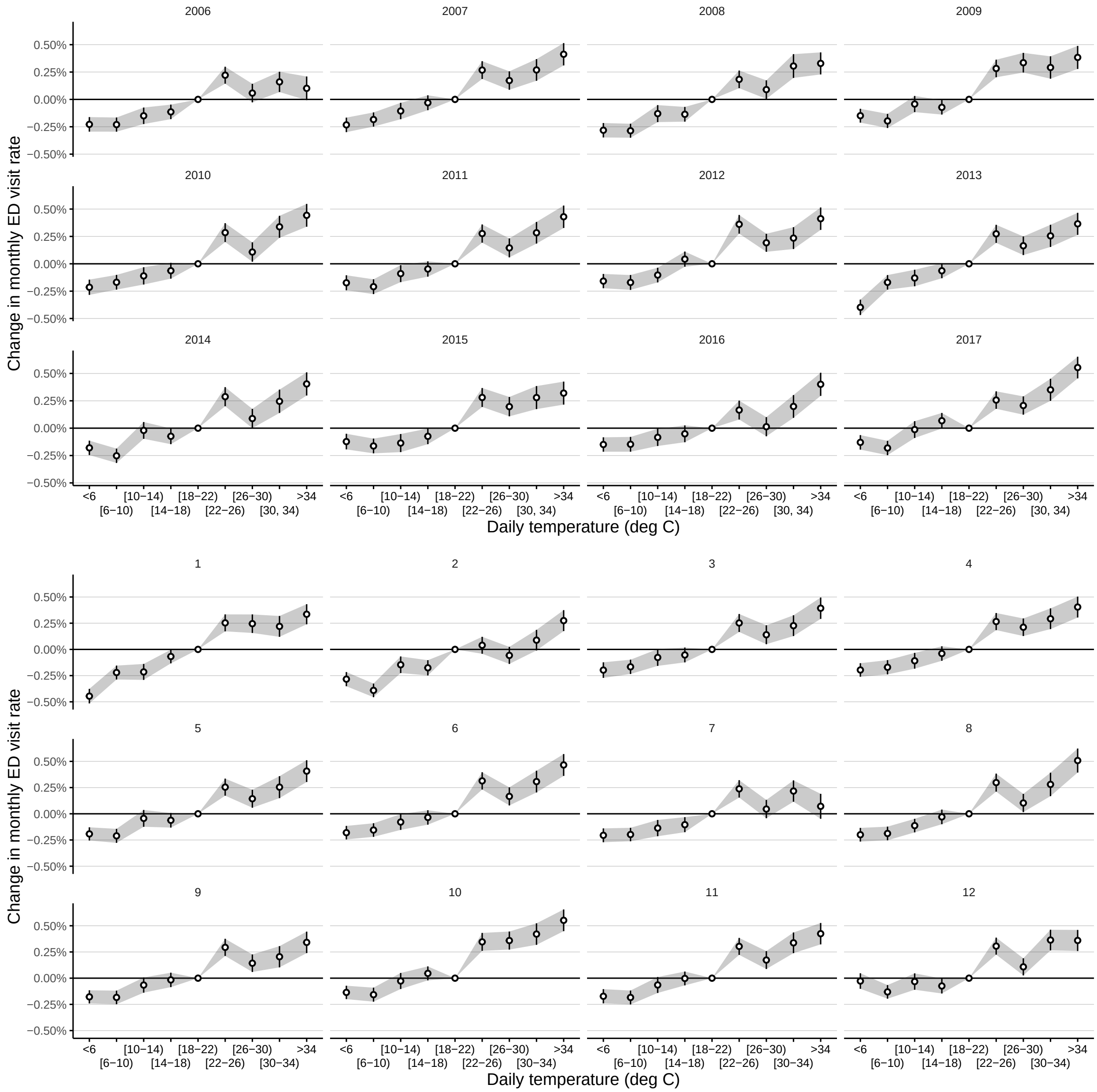


Figure S13: **Systematically omitting months and years from assessment of effect of daily temperatures on monthly mortality rates.** Top panel shows the temperature-mortality relationship, labeled according to which year is omitted from the analysis. Bottom panel does the same, but for month of year omitted from the analysis. We choose this approach because we are able to retain our preferred time controls (i.e., month of year and year fixed effects). Responses indicate that the results are consistent across months and year.