PUBLIC HEALTH

Temperature extremes impact mortality and morbidity differently

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Increased temperature-related mortality is expected to significantly contribute to future economic damages from climate change, with declines in cold-related deaths outweighed by increases in heat-related deaths. While temperature-mortality relationships are well-documented, the effects of climate change on morbidity are less understood. Using data on emergency department (ED) visits, hospital admissions, mortality, and daily temperatures across California from 2006 to 2017, we find distinct differences in the temperature-response functions of these health outcomes, influenced by age distribution and underlying causes of morbidity and mortality. These differential responses fundamentally shape the burden of future climate change: We project that while future warming will increase ED visits, mortality will decrease due to fewer cold extremes. These results underscore the need to quantify temperature-morbidity responses to fully understand and anticipate the health impacts of climate change and suggest that local declines in mortality due to warming can mask economically meaningful increases in temperature-driven morbidity and health care utilization.

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*–*7*). The burden of human-induced warming on mortality is already detectable (*8*), and climate change is increasing the frequency and severity of health-damaging heat (*9*–*12*). Recent estimates find that temperature-related mortality is projected to be the leading economic cost of climate change (*5*, *13*–*17*).

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. Health care spending in the United States on chronic disease alone is estimated to exceed $3 trillion annually and accounts for nearly 18% of US gross domestic product (*18*). 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 these outcomes might be shaped by the environment.

There are a number of reasons why climate impacts on mortality—which for all-cause mortality fairly consistently show a characteristic U-shaped relationship with temperature—might not provide an accurate guide for morbidity impacts. First, deaths are disproportionately among older adults, who may have different underlying responses to environmental insults; 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 health care utilization such as emergency department (ED) visits or hospitalizations. These utilization measures can be shaped by a number of factors, including individual decisions about whether to seek care.

Existing work indicates that extreme temperatures can lead to subfatal, yet potentially still severe, health damages (*19*–*27*). However, this work remains mixed on whether morbidity responses to temperature differ from established U-shaped mortality responses and which populations and outcomes are most affected. To date, some studies using US data have not checked for nonlinear morbidity responses (*22*), found roughly linear responses (*20*), or found nonlinear responses depending on the lag structure (*24*). However, many of these studies only examined adults 65 years and older (*22*–*24*), 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 populations found that morbidity tended to show more muted increases, or even declines, in response to cold extremes than mortality, but that both increased substantially at hot extremes (*28*–*31*).

Here, we seek to advance our understanding of the effects of temperature on health by investigating the impact of daily temperature extremes on ED visits, hospitalizations, and mortalities using comprehensive, localized data from California, the most populous state in the United States. A substantial advantage of our setting is that we can observe the universe of mortalities and the near-universe of both ED visits and hospitalizations among the same population over the same time period and explore whether responses for 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.

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Specifically, we joined data on ED encounters and admissions to all non-federal hospitals in California, data on all deaths in California, and high-resolution temperature data from 2006 to 2017. To compare the effect of temperatures on ED visit rates, hospitalization rates, and mortality rates, we constructed parallel datasets and conducted nearly-identical analyses—the only distinction was that ED visits and hospitalizations were analyzed at the zip code level, whereas deaths were analyzed at the county level due to data availability. Daily records of individual ED visits and hospitalizations were first aggregated to the zip code level and then to the monthly level ($n = 222{,}229$ zip code months). We estimated all-cause and age- and cause-specific visit rates per 100,000 population using linearly interpolated American Community Survey (ACS) population estimates (Materials and Methods). 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 (ICD) 9 and 10 (Materials and Methods); it is worth noting directly that heat-related ICD codes are rare and do not capture the full range of outcomes influenced by heat (*32*), so we opt to analyze all outcome groups.

To address the multiple dimensions of temperature's impacts on health, we first estimated hourly population-averaged ambient temperature from the widely used gridded Parameter-elevation Relationships on Independent Slopes Model (PRISM) data (*33*) in each zip code (county), which were subsequently summed to the population-averaged fraction of time (i.e., days) experienced in nine equally spaced 4°C bins (i.e., temperature was <6°C, between [6 to 10), …, [30 to 34), >34°C) in a given month (Materials and Methods). Thus, we characterize the duration of population exposure to each temperature bin across the full range of temperatures, a common way of nonparametrically assessing temperature impacts on societal outcomes (*34*).

Figure 1 summarizes the data. Between 2006 and 2017, we observed a total of 123 million ED visits, 45 million hospitalizations, and 2.9 million deaths. Over this period, zip code ED visit rates increased from an average of 1936 to 2531 per 100,000 people per month and county death rates increased from 64.5 to 74.4 per 100,000 people per month. Hospitalization rates varied over the time period and year to year, from a minimum of 1025 to a maximum of 1766 per 100,000 people per month in 2015 and 2007, respectively. All three outcomes and daily temperatures displayed substantial spatial and temporal heterogeneity.

Using longitudinal data on >1500 zip codes (56 counties) over time, we isolate the effect of temperature on ED visit rates and hospitalization rates (mortality rates) from other time-trending or

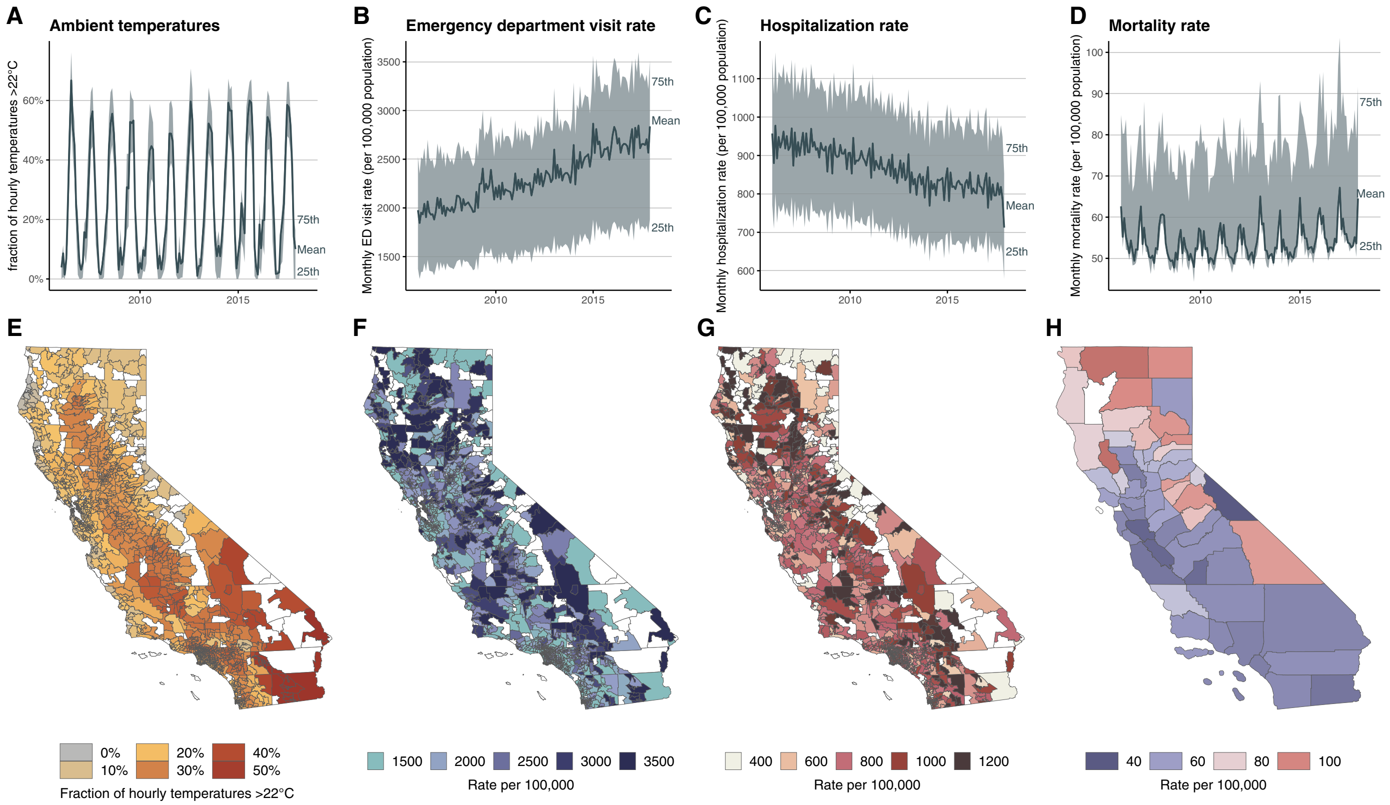

Fig. 1. Distribution of daily temperatures, all-cause ED visits, all-cause hospitalizations, and all-cause mortality rates in California, 2006–2017. (**A**) Population-weighted average, 25th percentile, and 75th percentile of the monthly zip code–level fraction of all hours where the population-weighted average temperature was greater than 22°C. (**B**) Population-weighted average, 25th percentile, and 75th percentiles of monthly zip code ED visit rates. (**C**) Population-weighted average, 25th percentile, and 75th percentiles of monthly zip code hospitalization rates. (**D**) Population-weighted average, 25th percentile, and 75th percentiles of monthly county mortality rates. (**E**) Average zipcode level hours where the population-weighted average temperature was greater than 22°C from 2006 to 2017. (**F**) Average monthly zip code ED visit rates from 2006 to 2017. (**G**) Average monthly zip code hospitalization rates from 2006 to 2017. (**H**) Average monthly county mortality rates from 2006–2017. Areas shown in white do not have data, in large part, because there are no zip codes in this area (not every piece of land in the United States is associated with a zip code).

cross-sectional factors that are plausibly correlated with both temperature and health care utilization (death). To do so, we estimated the impacts of daily temperatures on monthly ED visit rates and hospitalization rates (mortality rates) in panel fixed effects Poisson models. Models included fixed effects for every combination of zipcode (county) and month of year and for every combination of zip code (county) and year to nonparametrically account for local seasonality in both ED visits and temperature, average (time-invariant) differences in baseline temperatures and public health, and long-term trends in both public health and temperature. By aggregating daily temperatures into monthly bins, our approach inherently captures the distributed (lagged) effects of daily temperatures within each monthly period. We included total precipitation levels and its square to control for weather conditions that may be correlated with both temperature and public health. Regressions were weighted by average zipcode (county) population to generate population-averaged effect estimates, and SEs were clustered at the zip code (county) level. Coefficients can be interpreted as the percent change in monthly health outcome rates per an additional day (24 hours) where the temperature was fully within a given temperature bin relative to a day (24 hours) fully between [18° and 22°C). We also estimated this model separately across age groups to better understand heterogeneity in age-stratified responses (Materials and Methods).

Last, we projected the impacts of future climate change on ED visits, hospital admissions, and mortality in California using the outputs from 33 global climate model simulations run under a "middle-of-the-road" emissions scenario (SSP2-4.5). We calculated baseline-corrected daily temperatures from 2018 to 2100 and, assuming that future ED visit, hospitalization, and mortality rates will respond to temperatures as they have in the past, estimated a distribution of changes and associated damages from temperature-related health outcomes by mid-century and end of century (Materials and Methods).

RESULTS

We found distinct differences between how all-cause ED visit, hospitalization, and mortality rates respond to daily temperatures. As expected, we recovered the typical U-shaped temperature-mortality relationship in which all-cause mortality rates increase under both anomalously hot and cold temperatures. A similar response was found for all-cause hospitalizations. In contrast, however, 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° and 22°C, monthly ED visit rates increased in response to both moderately warm days (i.e., 22° to 26°C and 26° to 30°C) and hot days (i.e., 30° to 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. 2C).

To understand why ED visits respond so differently to cold temperatures as compared to mortalities we explored three related potential mechanisms: (i) differences in the ages of the affected populations, (ii) differences in the causes of ED visits versus causes of death, and (iii) declines in ED visits at colder temperatures may in part be explained by shifting burdens from ED visits to hospitalizations or mortalities (more severe outcomes), i.e., ED visits are "displaced" to hospital admissions and deaths.

Age-stratified responses to temperatures

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. The age profile of hospitalizations lies between ED visits and mortalities (Fig. 3).

We found that mortality rates increase at high and low temperatures among those aged 65 years and older (Fig. 3). 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, these days had no impact on mortality rates among those under 65 years. Confidence intervals for estimates at each temperature range overlapped across these two age groups. Daily temperatures had no meaningful impacts on deaths among those under 5 years of age, although the small number of observations made confidence intervals wide (fig. S1). Hospitalization rates increased among those older than 65 years of age the most due to extreme temperatures, in comparison to those under 5 years and between 5 and 65 years, whose all-cause rates responded similarly to extreme temperatures.

The shape of age-stratified ED visit rates' responses to temperatures was in large part similar, with some exceptions (Fig. 3). Changes in ED visits were disproportionately driven by variations in ED visit rates among children under the age of 5 years (fig. S2), in large part because this group uses the ED much more than other groups on a rate basis. Despite children under 5 years accounting for only 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 5 years accounted for 40% of excess visits on the hottest days and 35% of the fewer visits on the coldest days (fig. S3). We observed an isolated increase in ED visits among children under 5 years at mild cool temperatures (10° to 14°C) despite decreases at cooler temperatures. We tested alternative binning strategies (fig. S4, stratified by age) and found this anomaly to persist. This may reflect a methodological artifact of the binning approach rather than a meaningful causal relationship. 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.

Do differences in affected ages explain the differences we see in the response functions? To evaluate this hypothesis, we reweighted 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, then would the temperature-ED response function look more similar to the temperature-mortality response? For instance, instead of those over 65 years accounting for 5% of ED visits, we now weight their temperature response at 73%, reflecting the group's share of mortality. We then did the reverse process for mortality, reweighting the age-stratified mortality responses to reflect the younger age distribution observed for ED visits. The resulting response functions are shown in Fig. 3 (G to I). 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

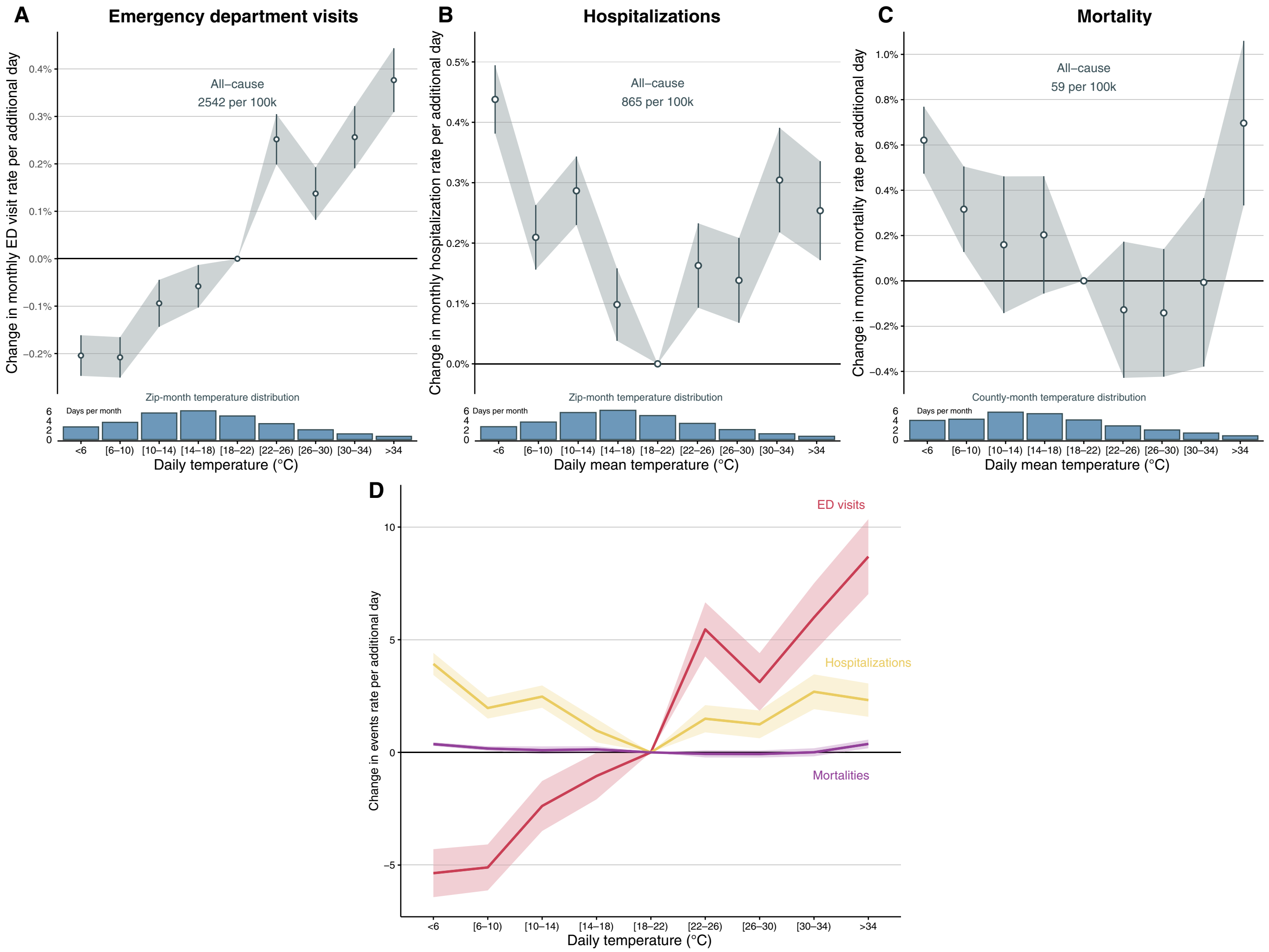

Fig. 2. Effects of daily temperatures on all-cause ED visit rates, hospitalization rates, and mortality rates in California, 2006–2017. Point-range responses indicate coefficient estimates and 95% CIs for an additional day fully in each temperature bin relative to an additional day fully between [18° and 22°C) for ED visits (**A**), hospitalizations (**B**), and mortalities (**C**). Bottom panels show the average days per month in each daily temperature bin. Panels are labeled with the average rates across the full study period. (**D**) Responses for ED visits, hospitalizations, and mortalities in rate terms (per 100,000 population), where outcomes were modeled as Gaussian (normal) instead of Poisson but regression models were otherwise identical.

response is due to differences in the age composition. The mortality response is relatively unchanged by reweighting, although the increase in cold temperature–related mortality risks is somewhat attenuated. Reweighting hospitalization rates by ED visit ages attenuated results, whereas reweighting them by mortalities led to higher effect estimates at all temperatures—leading them to more closely resemble the estimated mortality response.

Cause-specific responses to 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 and 50% of all ED visits in the US are nonurgent conditions (*35*, *36*), 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 and 50% of all deaths in the United States, but only 3% of ED visits (Fig. 4). Similar to how the distribution of ages among those hospitalized fell between ED visits and mortalities, the causes of hospitalizations overlapped with both ED visits and mortalities.

However, unlike our age-stratified analysis, the large differences in causes that lead to death and those that lead to ED visits (or hospitalizations) renders a reweighting procedure impracticable. For example, 28% of deaths in the United States are from cancer, but less than 1% of ED visits are related to cancer; reweighting ED cancer visits by their share in mortality would require markedly upweighting a response with very few observed outcomes. Nevertheless, visual inspection reveals several key insights. Figure 4 shows the responses of ED visit, hospitalization, and death rates for circulatory causes, respiratory causes, and accidental injuries. We see relatively strong agreement in the response of circulatory and respiratory ED visits, hospitalizations, and deaths to daily temperatures, suggesting

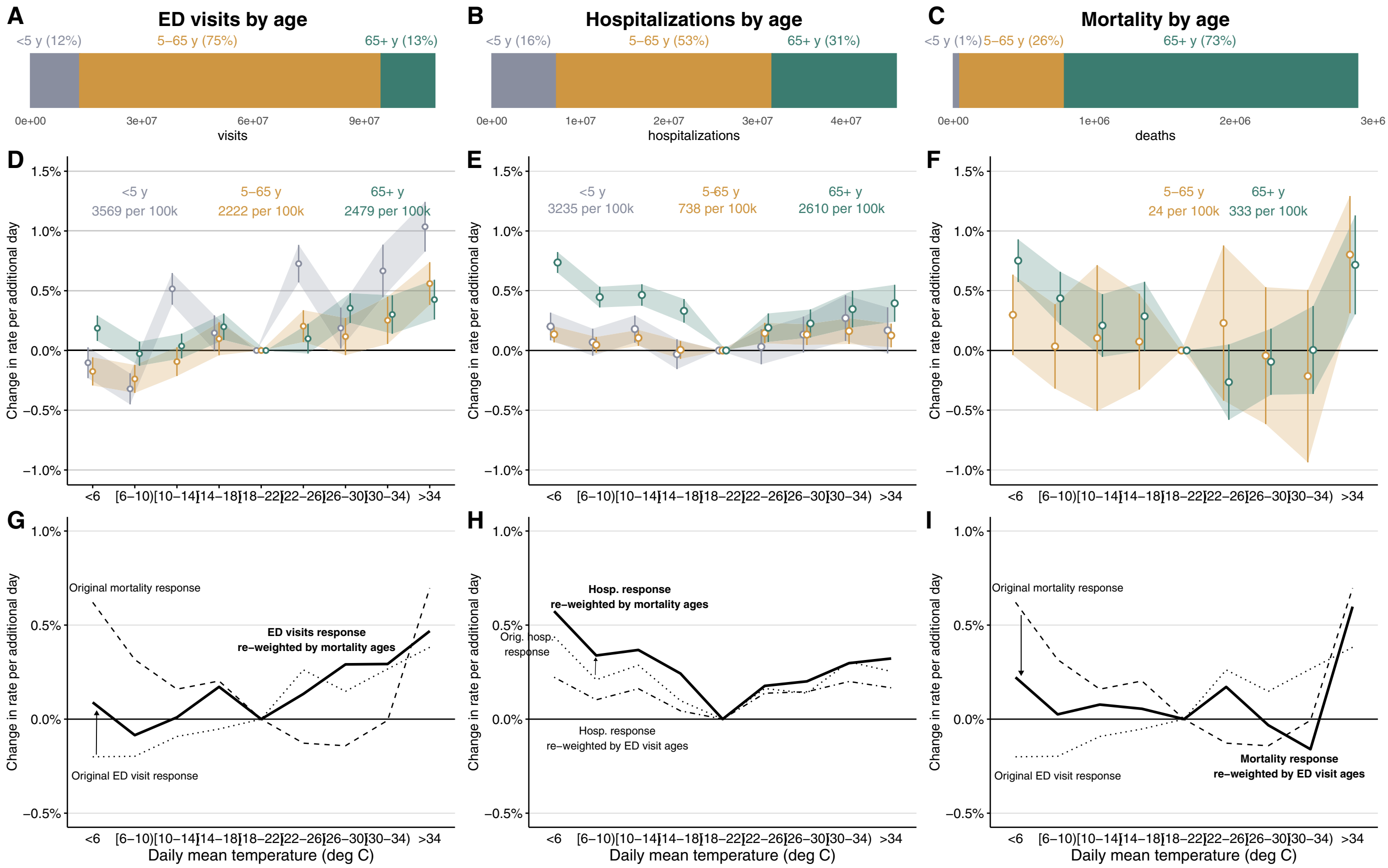

Fig. 3. Heterogeneity of associations between daily temperatures and all-cause ED visit rates, all-cause hospitalization rates, and all-cause mortality rates by age. (**A** to **C**) Number and proportion of events (e.g., ED visits) by age group (<5 years, 5 to 65 years, and 65+ years). (**D** to **F**) Age-stratified responses of each outcome to temperatures, mirroring the main regression models. Each plot is annotated with average rates across the full study period. Point-range responses indicate coefficient estimates and Bonferroni-corrected 95% CIs for an additional day fully in each temperature bin relative to an additional day fully between [18° and 22°C). All-cause age-stratified ED visit 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). (**G** to **I**) Results from our reweighting exercise where we redistribute the importance of age-stratified responses for one outcome (e.g., ED visits) according to their contribution to the importance of another outcome (e.g., mortalities). Arrows indicate the impact of weighting, i.e., show movement from the unweighted original responses to the weighted responses.

that the harms of temperature on both fatal and subfatal 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 (relative to California averages, <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° to 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 net increase in circulatory visits at higher temperatures is driven by an increase in visits for dysrhythmias that is partly offset by a decline in hypertension-related visits (fig. S5) and that respiratory-related visits during hot periods are composed of fewer visits for acute respiratory infections and chronic obstructive pulmonary disorders but more visits for asthma (fig. S6).

Together, these results reveal substantial heterogeneity in temperature responses across different health outcomes, reflecting distinct physiological and behavioral mechanisms. For circulatory conditions, heat-related increases in dysrhythmias could result from fluid loss, electrolyte imbalance, and cardiac stress, whereas decreased hypertension-related visits could reflect beneficial short-term effects of heat-induced vasodilation and fluid depletion. While prior studies typically find increased respiratory-related healthcare utilization on colder days (*37*, *38*)—attributed to greater indoor crowding, viral transmission, and cold-related stress—we observed the opposite pattern. In California, where winters are relatively mild, cooler days may still support some outdoor activity and reduce indoor mixing (at least comparatively), potentially limiting respiratory infection exposure. Increases in general symptoms, genitourinary, and mental health-related ED visits at higher temperatures may reflect systemic physiological

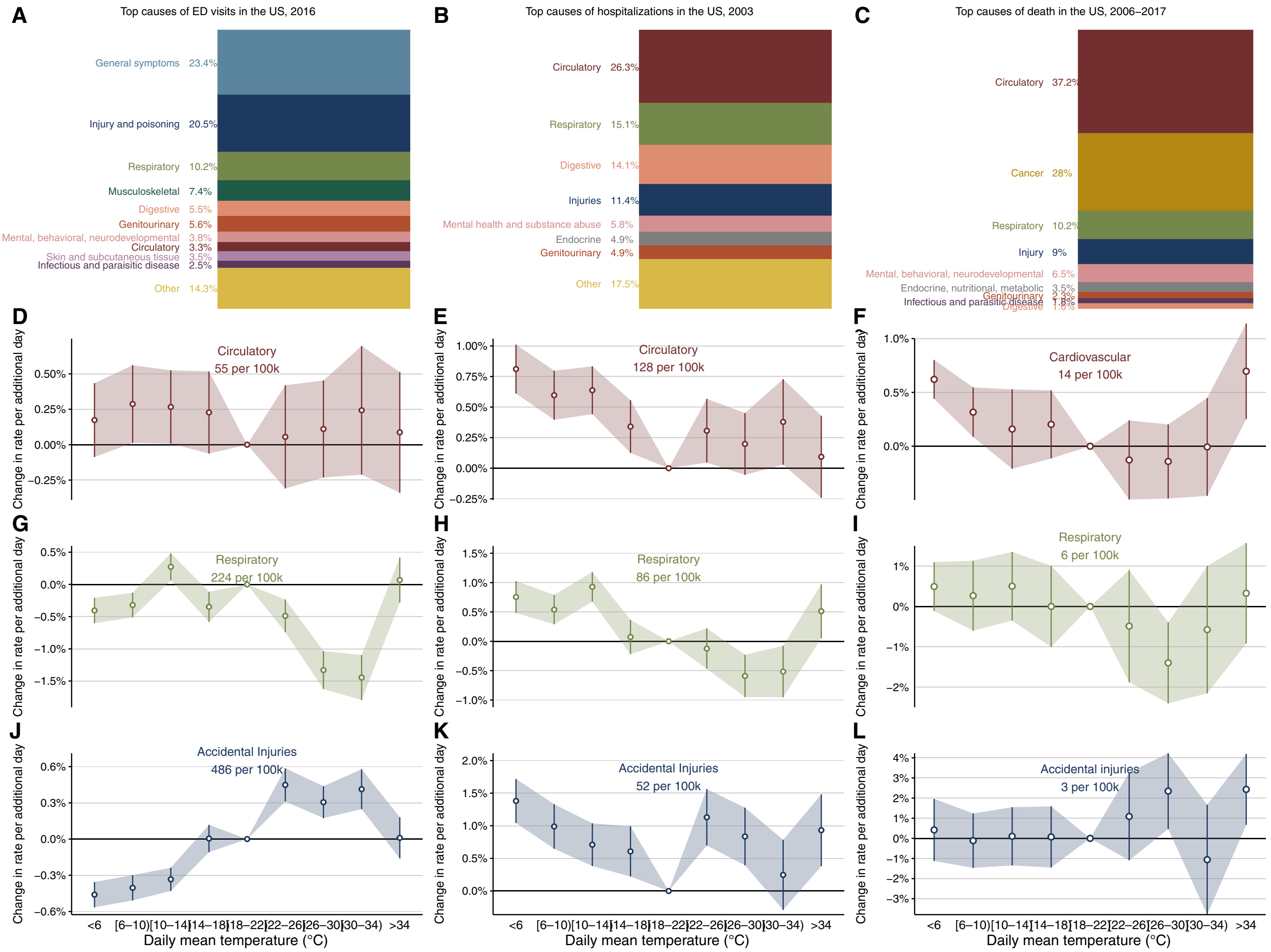

Fig. 4. Impact of daily temperatures on ED visit, hospitalization, and mortality rates, for selected causes. (**A** to **C**) Proportion of causes for ED visits, hospitalizations, and deaths in the United States, illustrating that the distribution of the causes of these events varies. (**D** to **F**) Responses of ED visits, hospitalizations, and mortalities from circulatory related causes to temperatures mirroring main specifications. Point estimates and 95% CIs for an additional day spent fully in a given temperature bin relative to an additional day fully in the 18° to 22°C bin. Labels show the average group-specific monthly rates per 100,000 population. Panels (**G** to **I**) show the same for respiratory related causes, and panels (**J** to **L**) show the same for events caused by accidental injuries.

stress or exacerbation of chronic conditions. These diverse responses underscore the complexity of temperature impacts across distinct pathways.

Exploring explanations for reductions in ED visits on cold days

Displacement of ED visits to hospital admissions

One potential explanation for why we see ED visits decline at cooler temperatures is if patients are being admitted directly to the hospital for more intensive care. In this case, the observed reduction in ED visits may obscure an actual increase in acute health impacts. There are two features of the data structure and hospital admissions that facilitate this potential narrative. First, ED visits that result in hospitalization are omitted from the ED visits records to avoid double counting. Second, in 2017, 35% of hospitalizations were directly admitted from the same hospital ED ($n = 1.4$ million), so 25 ED visits per 100,000 population are "displaced" and admitted directly to the hospital each month.

In aggregate, we find that declines in ED visits at colder temperatures may in part be explained by shifting burdens from ED visits to hospitalizations or mortalities (more severe outcomes). A day where the temperature is below 6°C reduces average ED by 5.4 visits per 100,000 population in that same month [95% confidence interval (CI), 4.3 to 6.4]; at the same time, average hospitalizations are increased by 3.9 visits per 100,000 population (95% CI, 3.4 to 4.4). Hot days increase both ED visits and hospitalization rates. Because we do not see any evidence of substitution between ED and hospital visits at hot temperatures, we focus the remainder of this section on responses at cold temperatures.

If displacement was to be the primary mechanism through which ED visits decline at cooler temperatures, then we would expect offsetting declines in ED visits and increases in hospital

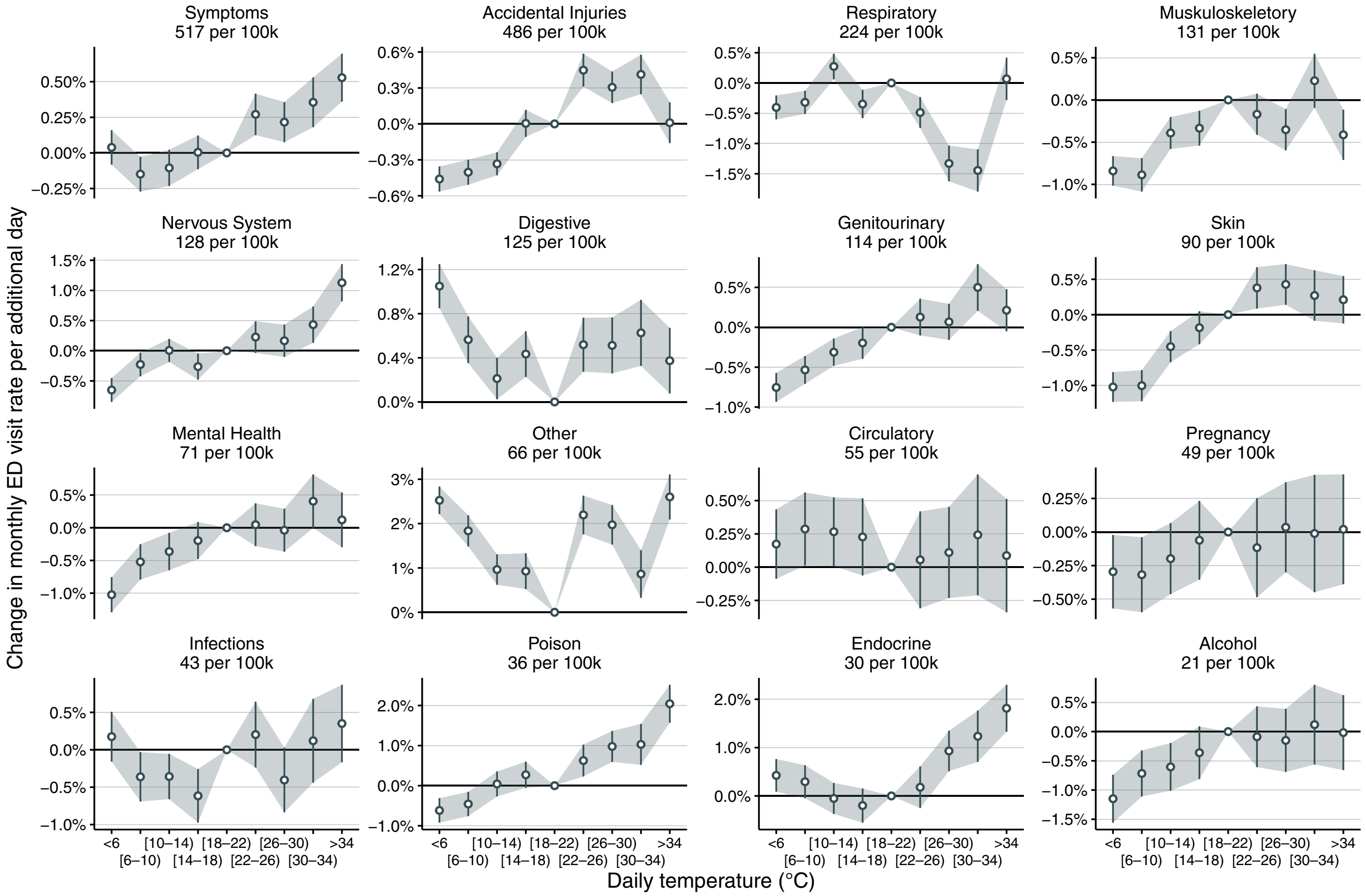

Fig. 5. Effects of daily temperatures on cause-specific ED visit rates. Point-range responses indicate coefficient estimates and Bonferroni-corrected 95% CIs for an additional day fully in each temperature bin relative to an additional day fully between [18° and 22°C). Below each outcome category is the sample-wide monthly ED visit rate for that cause per 100,000 population.

admissions within similar age groups and groups of causes, with declines balanced by increases. Figure 6A indicates that these dynamics do not hold true for age-specific responses. ED visit rates among those less than 65 years of age decline in large magnitudes, whereas hospitalization rates increase only marginally for this age group. For those older than 65, both ED visit and hospitalization rates increase at cold temperatures. Thus, the observed decline in ED visits and increase in hospitalizations at cold temperatures is driven by differing responses across age groups rather than substitution: Cold temperatures lead to large declines in ED visits among those under 65 and large increases in hospitalizations among those over 65 years of age.

Similar to ED visits, we found that a broad range of cause-specific hospitalization rates were influenced by temperature extremes (fig. S7). For some outcomes (i.e., general symptoms, accidental injuries, respiratory related conditions, genitourinary illnesses, infections, and poisonings), ED visits declines and hospitalizations increased, although for the most part, declines in ED visits were larger than increased hospitalization rates. For other outcomes (i.e., digestive illnesses, skin-related conditions, mental health, and circulatory related causes), ED visits and hospitalizations either both increased or both declined from colder temperatures.

Beyond cause of the admission, there are two additional features of hospitalizations that we can leverage to better understand morbidity responses to extreme temperatures: whether the hospitalized patient was admitted to an acute care center and whether the hospitalization was scheduled or not. In the first analysis, we stratify our data to examine hospitalization admissions to acute care centers versus hospitalization admissions to nonacute care centers (i.e., skilled nursing facilities, psychiatric care, chemical dependency recovery centers, and physical rehabilitation centers). We find that only hospitalizations in acute care centers (97% of all hospitalizations) respond to daily extreme temperatures and that the response mirrors our previously established U-shaped response seen across the pooled group of all hospital types (fig. S8A). In the second analysis, we subset our data to whether or not the hospitalization was scheduled at least 24 hours in advance and find that both scheduled and unscheduled hospitalizations are responsive to extreme temperatures (fig. S8B).

Potential for alteration of activity patterns to shape health care utilization responses

Colder temperatures could reduce injuries by depressing economic activities, lowering exposure to hazards, or by changing health care–seeking behaviors. Previous research in California, for example,

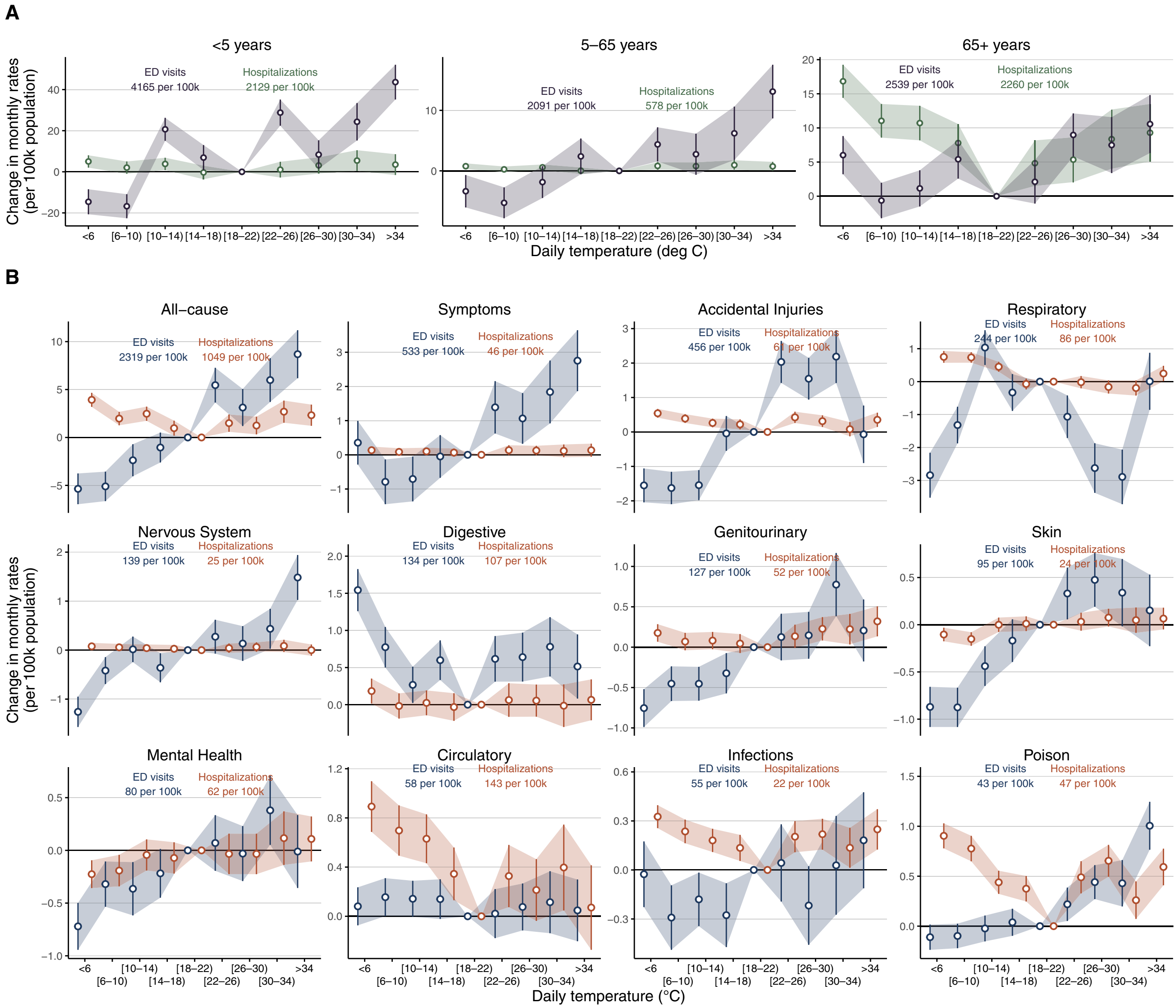

Fig. 6. Displacement of visits from ED visits to hospital admissions does not fully explain declines of ED visits from cold temperatures. (**A**) Age-stratified ED visit and hospitalization rate responses to temperatures. (**B**) Cause-specific ED visit and hospitalization rate responses to temperatures. Point-range responses indicate coefficient estimates and Bonferroni-corrected 95% CIs for an additional day fully in each temperature bin relative to an additional day fully between [18° and 22°C). Below each outcome category are the sample-wide monthly ED visit and hospitalization rate for that group per 100,000 population.

found fewer work-related injury claims on colder days (*39*). To explore this hypothesis, we estimate changes in daily ED visit rates due to temperatures on weekends versus weekdays, accounting for 7 days of lags (Materials and Methods).

If work-related injuries were the primary explanation for our observed declines, then we would expect clear differences between weekdays (when occupational exposures are greater) and weekends. Instead, we observe similar declines in both ED visit rates for all causes and rates for injury-related causes across weekends and weekdays for all age groups (fig. S9), including for the 18 to 34 group most likely exposed to occupational hazards. This pattern suggests mechanisms beyond strictly occupational injury reduction. One possibility is that colder days lead to overall reductions in risky activities, benefiting health broadly but possibly signaling welfare losses due to foregone activities. Alternatively, these declines could reflect altered health care–seeking behavior, such as reduced willingness or ability to seek care during colder weather, implying the true burden of injuries might remain unchanged. Unfortunately, without detailed data on daily economic activities and health care–seeking motivations, we cannot conclusively differentiate between these explanations.

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 on whether adaptation has been taking place in response to temperatures rising in recent decades (*40*). While some studies have modeled future temperature-related health burdens using response functions specific to baseline temperatures or incomes (*5*), we observe relatively little heterogeneity in these stratified responses (figs. S10 and S18). However, we do observe meaningful differences in age-stratified responses; furthermore, population aging means that the responses of older adults will become increasingly important to aggregate outcomes, as has been illustrated elsewhere (*41*–*43*). Thus, we investigate future health burdens under conditions where future age-stratified ED visits, hospitalizations, and mortalities respond to changes in daily temperatures as they have in the recent past while accounting for predicted demographic shifts (Materials and Methods).

We calculated an increase in ED visits in California due to changes in temperatures by 2050, representing an additional 0.46% visits (95% CI, 0.19 to 0.62%) or 1.50 million cumulative excess visits between now and 2050 (Fig. 7, B and E). In contrast, both hospitalizations and mortalities due to changes in temperatures are projected to decline by 0.18% (95% CI, −0.33 to −0.01%) and 0.43% (95% CI, −0.89 to 0.12%), respectively, over the same period in the state, totaling 244,000 fewer hospital admissions and 53,500 fewer deaths. By 2100, we predict a 0.76% increase in ED visits (95% CI, 0.13 to 2.26%), a 0.38% decline in hospital admissions (95% CI, −0.63 to −0.08%), and a 0.77% decline in deaths (−1.53 to 0.08%) due to excess outcomes from changes in temperatures. Allowing health impacts of temperature to accumulate over a 1-month lag does not meaningfully change our projections (see Materials and Methods and table S1).

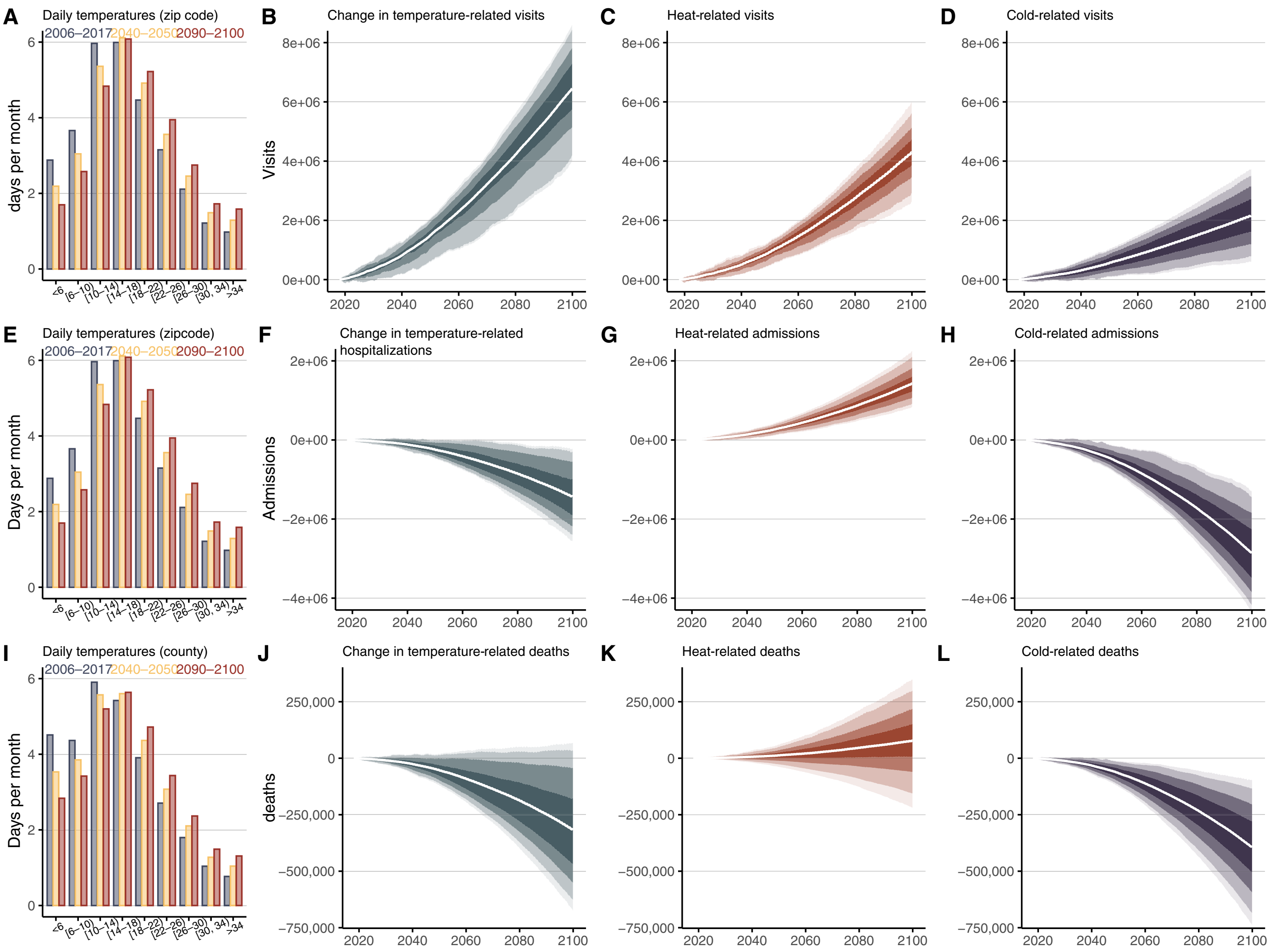

Fig. 7. Projections of changes in temperature-related ED visits, hospital admissions, and mortality, 2020–2100. Panels (**A**), (**E**), and (**I**) Compares the population-averaged baseline-corrected days per day in each temperature bin across the 33 climate models in zip codes [for (A) and (E)] and counties [for (I)], respectively, in 2006–2017 (study period) to 2040–2050 and 2090–2100. Panels (**B**) to (**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) estimated from zip code data. The white line shows the average estimate in every month-year between January 2018 and December 2100 (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**) to (**H**) indicate the same but for hospitalizations, and panels (**I**) to (**L**) for mortalities at the county level.

These estimates are the aggregates of both heat- and cold-related changes and age-stratified changes. For both hospital admissions and mortalities, we estimate that declines in cold-related deaths will outweigh increases in heat-related deaths in the coming decades (Fig. 7, C and D). The largest contributions to these changes come from those over 65 years of age, whose predicted declines outweigh small predicted increases in temperature-related hospital admissions and deaths among those 5 to 65 years old (fig. S12). For ED visits, we found that warming temperatures would increase ED visits for every age group in California in the coming decades (Fig. 7, C and D). While for those under 5 years and between 5 and 65 years, we predict increased ED visits due to warmer future temperatures on both the relatively colder and warmer end of the spectrum, for those over 65 years of age, we predict declines in cold-related ED visits that are outweighed by predicted increases in heat-related ED visits (fig. S12).

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 value of a statistical life (VSL) or increase in health care costs, we estimate that (nondiscounted) annual mortality damages by 2050 would decline by $30 billion, and hospitalization costs would decline by $53 million, while ED visit costs would increase by $52 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 United States; 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 United States (fig. S13). In other words, California appears to have larger mortality increases at extreme temperatures. 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 that at least our excess mortality estimates are not driven substantially by idiosyncracies in the CA data or sample (fig. S13). However, because the CA-specific response function is meaningfully different from the rest of the United States, we would urge some caution in any extrapolation of our response functions to the remainder of the country.

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. The remarkably different aggregate responses of mortality and hospitalizations as compared to ED visits 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*, *44*–*46*) and cause-specific [especially for cardiovascular (*3*, *44*, *46*) and respiratory (*44*)] mortality and a growing body of literature studying the effects of daily temperatures on all-cause and cause-specific health care utilization (*20*–*22*, *47*–*52*). We contribute specifically to the much smaller set of studies that analyze mortality and morbidity in overlapping populations and expand on this existing work by examining multiple causes of disease, unlike many studies that focus on single causes (*28*–*31*, *53*–*56*).

We observe both differences and similarities in how ED visits, hospitalizations, and mortalities respond to temperature variations. We show that differences in the shape of overall dose-response relationships is driven, at least in part, by the age distributions of those affected and the underlying causes of the events. These differences are particularly stark for the comparison of ED visits and mortalities. In comparison, the aggregate response of hospitalizations to extreme temperatures is more similar to that of mortalities than ED visits. This may be partly explained by similar age distributions of individuals hospitalized and those who die. In addition, hospitalizations are often driven by more severe health outcomes than ED visits, necessitating unavoidable care, thus aligning them more closely with mortalities. For research and for policy, our results emphasize the importance of considering the underlying patient population (age distribution and common causes of disease) of interest when interpreting the effects of a climate or environmental hazard on a health outcome. Further, these results caution the extrapolation of one health response function to another population with meaningfully different age structure or underlying health burdens, and the application of a temperature-mortality to temperature-morbidity response function and vice versa.

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 health care utilization than for mortality (*28*, *54*). As in (*29*), we identify no such minimum risk temperature for our ED visits response and identify a somewhat lower minimum risk temperature for hospitalizations than deaths. In our work, this lack of a minimum risk temperature for ED visits 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 (fig. S14), suggesting further work is needed to assess response functions in regions more frequently exposed to extreme cold. One other possible explanation for the difference between ED response and mortality response is that, at colder temperatures, more people visiting ED are being admitted because their conditions are severe enough to warrant overnight care. We do see some evidence of this with the hospitalization response, but the magnitude of the ED visit response is not canceled out by increased hospitalizations at these cooler temperatures.

We also identify noteworthy similarities across all three outcomes. We find similar dose-response relationships across some cause-specific outcomes, such as respiratory and circulatory related events; responses of hospitalizations and ED visits for genitourinary and skin-related disorders were also qualitatively similar. In addition, for older adults, the rates of all three outcomes all increase under both extreme heat and cold, underscoring the vulnerability of this age group to environmental hazards. We also find that all three health outcomes increase with extreme heat, which implies substantial morbidity and mortality burdens from ever-increasing anomalously hot days.

Our work on the response of ED visits to extreme temperatures is most similar to White (*27*), who also use the near-universe of ED visits in California (their data range from 2005 to 2014) to examine associations between daily temperatures and health care utilization. White (*27*) find that short-term responses to daily temperature variations are linearly increasing, as we do: a day below 4.4°C is associated with 6% fewer total ED visits, and a day above 26.66°C is associated with 4% more total ED visits on that same day, relative to a day between 15.55° and 18.33°C. However, when accounting for 30 days of lags, White (*27*) observes that declines in ED visits under cold temperatures are reversed, and an 11% increase in total ED visits is observed following a single day where the temperature is below 4.4°C, relative to a day with temperatures between 15.55° and 18.33°C. This reversal is in large part attributable to observed delayed increases in respiratory-related ED visits and is observed across all age groups. This work is consistent with evidence that cold-related health impacts have longer lags than heat-related health impacts (*57*, *58*). When we attempt a replication using our own data, we find that ED visits still decline from daily temperatures <6°C even when including 28 days of lags, although temperatures between 6 and 10°C are reversed from causing net declines in ED visits to causing net increases in ED visits (fig. S15). Further work is needed to understand the drivers of these morbidity responses to low temperatures.

Cause-specific investigations into the different responses of ED visits, hospitalizations, and mortality to temperatures in parallel analyses remain rare; most studies have focused on all-cause, cardiovascular, and respiratory related causes. 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- and end-of-century decline in temperature-related mortality in California is consistent with a few recent US-wide and global analyses (*5*, *59*), but in contrast to others (*14*). Direct comparison is challenging given differences in age groups studied and warming scenarios assumed. Some previous studies have used end-of-century projections from RCP8.5, a more extreme—and potentially less realistic—scenario than the SSP2-4.5 scenario we use. Some studies have only included adults 65 years and older, which we show can lead to meaningfully different responses than our approach that includes all ages and conducts age-stratified responses and projections or only modeled heat-related deaths (*60*). Here, we estimate an average of 560 and 703 additional heat-related deaths each year across California due to future warming in 2050 and 2100, respectively; however, these are outweighed by expected declines due to fewer cold-related deaths roughly four times as large. Differences may also arise from different empirical specifications whereby some other studies model country-wide or global responses, incorporating heterogeneity as a function of climate or income. By contrast, we use California-specific data and do not rely on smooth models of heterogeneity across the country or globe. This approach reflects a tradeoff between internal and external validity. 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, most of the studies projecting the health damages from climate change focus exclusively on mortality (*19*, *40*, *61*). This focus on mortality comes in part from data availability as we have been recording and studying deaths for far longer than systematic documentation of health care utilization 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 attention, and we encourage further joint study that compare and contrast projections of future warming on mortality and morbidity.

Our study has limitations worth discussing to contextualize our results. 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 (*62*, *63*). In addition, our presentation of the projections' results 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 zip codes whose residents typically spend substantial time outside of their home zip code, although we note that temperatures tend to be very highly correlated across nearby zip codes. In addition, given our rich set of area and time controls, our analysis relies on variations in daily temperatures and ED visit rates (mortality) within zip codes (counties) within the same month of year; however, the possibility of residual confounders that covary with our outcomes and daily temperatures on the monthly timescale remains, for example, humidity, fine particulate matter concentrations, and ozone, which are imperfectly correlated with temperature. Including a rich set of daily fine particulate matter concentrations does not substantively change our observed response of ED visits to extreme temperatures (fig. S16). 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 (*64*), heat waves (*65*), nighttime temperatures (*66*), and temperature variability (*67*), which future work should continue to evaluate.

We contend that future studies of the health effects of environmental hazards could 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 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 (*5*, *68*)—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.

MATERIALS AND METHODS

Exposures

Daily minimum and maximum ambient temperatures were obtained from the PRISM climate mapping system. PRISM estimates daily maximum and minimum temperature and precipitation levels in a 4 km–by–4 km grid across the United States and has been widely used in epidemiological analyses evaluating the effects of temperature on health (*33*). Specifically, we used a modified version of PRISM that maintains a consistent set of contributing weather stations over time developed and made publicly available by Wolfram Schlenker (https://zenodo.org/records/10625288). 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 as follows

$$\text{byhour}_i c(h) = \frac{t\text{Max}_{ic} + t\text{Min}_{ic}}{2} + \left(\frac{t\text{Max}_{ic} - t\text{Min}_{ic}}{2}\right) \cdot \sin\left[\frac{\pi \cdot (h-6)}{12}\right], \quad (1)$$
$$\text{for } h \in \{1, 2, \ldots, 24\}$$

where i is a day of the year in grid cell c. We defined a range of temperature bins from −10° to 40°C. These hourly temperature values were then grouped into our preferred nine equally spaced bins: <6°C, [6 to 10), [10 to 14), [14 to 18), [18 to 22), [22 to 26), [26 to 30), [30 to 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 (*69*) to calculate the population-weighted average proportion of each day where the ambient temperature was in each bin at the zip code 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 (which is itself the number of hours divided by 24) in a zip code month (county month) where the ambient temperature was within a given temperature bin. We selected 18° to 22°C as the reference bin.

Outcomes

ED visits

Data on ED visit by cause, age, sex, and zip code 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 1 January 2006 and 31 December 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 (zip code of residence, age at time of service, self-reported race, and sex), primary diagnosis, up to 20 secondary diagnoses, and hospital identifier. Annual population counts were obtained from the ACS.

Zip code–day ED 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 Department of HCAI (symptoms, accidental injuries, respiratory system, nervous system, musculoskeletal system, digestive system, genitourinary system, skin, mental health, pregnancy, infections, circulatory system, poison, endocrine system, and 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 (*70*). Monthly ED visit rates were standardized per 100,000 population.

Hospitalizations

Data on admissions to all non-federal hospitals in California by cause, hospital type, age, sex, and zip code of residence came from California's Department of HCAI. Our data included both scheduled (arranged at least 24 hours beforehand) and unscheduled admissions to hospitals of all types of licensures including acute care, skilled nursing facilities, psychiatric care, chemical dependency recovery care, and physical rehabilitation care. The vast majority of visits in our data were to acute care. The data included all admissions with discharges between 1 January 2006 and 31 December 2017. Each record consisted of a single inpatient visit, which typically means that the patient was admitted to the hospital and stayed overnight. For each hospitalization, we observed the date of admission, date of discharge, type of hospitalization, patient characteristics (zip code of residence, age at time of service, self-reported race, and sex), primary diagnosis, up to 20 secondary diagnoses, and hospital identifier.

Zip code–day hospitalization rates were constructed for total (all-cause) visits, for 15 mutually exclusive principal diagnosis groups mirroring the ED visit groupings (see above), admissions by hospital licensure type, and admissions by whether the hospitalization was scheduled or not. Monthly hospitalization rates were standardized per 100,000 population.

Mortality

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 to 4, 5 to 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.

Population

We used 5-year average populations from the ACS, matching each analysis year to the 5-year ACS estimate centered on that year (e.g., populations for 2012 were averages from 2010 to 2014). Zip codes without residential populations (e.g., P.O. Boxes) were excluded. To calculate age-specific ED visit rates, we divided the number of ED visits per age group in each zip code on a given day by the corresponding age-specific annual zip code population estimates. Our approach implicitly assumes that short-term temperature fluctuations do not induce substantial age-specific shifts in zip code populations beyond those accounted for by zip code–month and zip code–year fixed effects.

Statistical analysis

Given the level of aggregation of the outcomes data, we specified distinct but parallel models that in both cases estimate the effect of time spent in different temperature bins on outcome rates and nonparametrically control for a range of area and time-trending unobservables in panel fixed effects regressions. Specifically, we estimated the following regression

$$y_{\text{amy}} = \beta_1 \text{Tbin}^b_{\text{amy}} + \alpha \text{ppt}_{\text{amy}} + \omega \text{ppt}_{\text{amy}} * \text{ppt}_{\text{amy}} + \delta_{\text{am}} + \theta_{\text{ay}} + \varepsilon_{\text{amy}} \quad (2)$$

where y_{amy} is the ED visit rate per 100,000 population (or hospitalization rate or mortality rate per 100,000 population) in zip code (in the case of mortality rates, 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 (*71*). $\text{Tbin}^b_{\text{amy}}$ 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° to 10°C), [10° to 14°C), [14° to 18°C), [22° to 26°C), [26° to 30°C), [30° to 34°C), or >34°C. We included zipcode (county) monthly precipitation levels ($\alpha\text{ppt}_{\text{amy}}$) and its square ($\omega\text{ppt}_{\text{amy}} * \text{ppt}_{\text{amy}}$) and fixed effects for zip code month (county-month) and zip code year (county-year) to flexibly control for area-level short- and long-term trends in temperature and health outcomes. SEs were clustered at the area level.

Because we modeled the outcomes as a Poisson, coefficients can be interpreted as the percent change in monthly ED visit (hospitalizations and mortality) rates per additional day (24 hours) in that same month where the temperature was in a given temperature bin relative to additional day where the temperature was between [18° to 22°C).

Sensitivity analyses and alternative approaches

We tested the sensitivity of our results to alternative temperature bin specifications, omitting population weights, lagging our exposures by 1 month, and modeling outcomes in an ordinary least squares (OLS) regression and dividing by average rates to generate percent change estimates. Figure S14 shows these alternative specifications for ED visits, and fig. S17 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 fig. S18. We test 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 CIs 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 preferred 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. S19). As an additional check, we also systematically omitted years and months of years from our analyses to examine for consistency in our observed relationships over the study period and across the calendar year. We did not observe meaningful differences across these alternative specifications (figs. S20 and S21).

Daily ED visit data

In addition to these alternative model specifications, we also leveraged the availability of ED visit data at the daily level to model the impacts of daily temperatures on daily ED visit rates. While our primary specification facilitates the closest comparison between the effects of temperature on ED visit rates and mortality rates given data constraints dictated by mortality data only being available at the county-month level, there may be additional information gained by modeling ED visits at the daily level. To do, we applied the same outcome and exposure generating procedures but did not aggregate beyond the daily level and estimated the following regression

$$\begin{aligned} y_{zwdy} = {} & l\left(\beta_1 \text{Tbin}^b_{zwdy}, 0{:}7\right) + l\left(\alpha \text{ppt}_{zwdy}, 0{:}7\right) \\ & + l\left(\omega \text{ppt}_{zwdy} * \text{ppt}_{zwdy}, 0{:}7\right) + \delta_{zw} + \theta_d + \tau_y + \varepsilon_{zwdy} \end{aligned} \quad (3)$$

where y_{zwdy} is the ED visit rate per 100,000 population zipcode *z* in week of year *w*, day of week *d*, and year *y* modeled as a Poisson. Tbin^b_{zwdy} is the proportion of the day (i.e., number of hours divided by 24) where the temperature was in bin *b*, i.e., one of either <6°C, [6° to 10°C), [10° to 14°C), [14° to 18°C), [22° to 26°C), [26° to 30°C), [30° to 34°C), or >34°C in zip code week of year *zw*, day of week *d*, and year *y*. In addition to Tbin^b_{zwdy} on the day of the outcome, we included lags from 0 to 7 days. We included zipcode daily precipitation levels (αppt_{zwdy}) and its square ($\omega\text{ppt}_{zwdy} * \text{ppt}_{zwdy}$) and fixed effects for zip code week of year, day of week, and year to flexibly control for area-level short- and long-term trends in temperature and health outcomes. We estimated the cumulative effect of an additional day in each temperature bin summed across all lags and computed clustered standard errors at the zip code level. Beyond 1 week of lags, we also modeled 14, 21, and 28 days of lags.

Results for these daily models are shown in fig. S22 and largely agree with the monthly models. One exception is the [6° to 10°C) bin, which at longer lags appears to have a positive effect on ED visit rates but at shorter lags is estimated to have a negative effect. At all lags, however, the [14° to 18°C) bin and the coldest bin (<6°C) reduced ED visit rates. At all lags, all days above the reference increased ED visit rates.

Next, to explore the potential for cold days to decrease changes in workplace-related risks or alter availability to seek health care, we examined whether the relationship between daily temperatures and ED visit rates differed by weekends and weekdays. To do so, we modified our primary daily model specification (Eq. 3) to include interactions between temperature bins and an indicator for weekend versus weekday. Specifically, we estimated the following regression

$$\begin{aligned} y_{zwdy} = {} & l\left(\beta_1 \text{Tbin}^b_{zwdy}, 0{:}7\right) + l\left(\gamma_1 \text{Tbin}^b_{zwdy} \times \text{weekend}_{zwdy}, 0{:}7\right) \\ & + l\left(\alpha \text{ppt}_{zwdy}, 0{:}7\right) + l\left(\omega \text{ppt}^2_{zwdy}, 0{:}7\right) + \delta_{zw} + \theta_d + \tau_y + \varepsilon_{zwdy} \end{aligned} \quad (4)$$

where weekend_{zwdy} is a binary indicator equal to 1 if day *d* is a weekend and 0 otherwise. We modeled this separately for all-cause ED visits, injury-specific ED visits, and injury-specific visits stratified by age group. To quantify and compare temperature responses, we calculated cumulative lagged responses for weekdays (main effects) and weekends (interaction terms plus main effects) across 7 days of lags for each temperature bin. SEs were clustered at the zip code level, and estimates were weighted by zip code average population. Results from these interactions are presented separately for weekends and weekdays (fig. S9).

Missingness, statistical software, and multiple hypothesis testing

There was some missing data in the stratified analyses due to missing age (9%). R software version 4.3.1 (*72*) was used for analyses; regressions were conducted using the "fixest" package (*73*). Two-sided $P < 0.05$ was considered statistically significant. Where relevant, 95% CIs were Bonferroni corrected to account for multiple hypothesis testing (all-age all-cause $\alpha = 0.05$; all-age cause-specific ED visits $\alpha = 0.05/16$; all-age, cause-specific mortality $\alpha = 0.05/3$; age-specific all-cause $\alpha = 0.05/3$; and age-specific cause-specific $\alpha = 0.05/80$).

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 (*74*). 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 intermodel differences and internal variability as represented by initial-condition uncertainty.

Climate models are spatially coarse relative to zip code and county boundaries. Here, we calculated zip code– and county-level values from the model by assigning each zipcode (or county) the value from the model grid cell in which the zip code's centroid falls. For each zip code and county in each simulation, we conducted the same sinusoidal interpolation as described in the "Exposures" section 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 and 2017 for each zipcode (county). For each month between 2018 and 2100, 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.

Age specific, county-level population estimates from 2020 to 2070 were obtained from the California Department of Finance (available at https://dof.ca.gov/forecasting/demographics/projections/). 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 zip code–level population-weighted averages of intersecting counties. Future populations were then estimated by multiplying 2017 zip code populations by these ratios. To project populations between 2070 and 2100, we linearly extended projections based on area-level age-stratified rates of change between 2050 and 2070.

To estimate the effect of future warming on ED visits, hospital admissions, and mortalities, 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 zip code (county).

To calculate excess visits (or deaths), we averaged historical rates—drawing from the most recent 3 years in our data 2015–2017—to the area-month of year level and joined them to the projected percentage changes in future outcomes. Multiplying these two estimates together, along with estimates of future population, calculates excess ED visits (or hospital admissions 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 3300 estimates of future changes in ED visits, hospital admissions, and mortalities, 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 model projections.

Incorporating lag 0–1 models into our projections, alongside age-specific dose-response functions and demographic changes, yielded conclusions consistent with the main model: Future warming in California is projected to increase temperature-related ED visits and reduce hospital admissions and mortality (table S1).

Valuation of changes in mortality, hospitalizations, and ED visits

To value deaths, we used the US Environmental Protection Agency central estimate of the VSL in 2024 of $11.11 million. Economically valuing nonfatal health impacts is less straightforward because they can include a variety of difficult-to-monetize factors, including discomfort from illness, medical costs related to health care, loss of wages, and costs related to mitigating adverse health effects. In the absence of comprehensive estimates of willingness to pay data to avoid ED visits, we used public data on the average cost of an ED visit. According to the Healthcare Cost and Utilization Project (HCUP), based on data from the National Emergency Department Sample, the average cost of an ED visit in the United States in 2017 was $530 (*75*). 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, and 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 on the basis of charges ("the amount a hospital billed for the case") using HCUP hospital-specific cost-to-charge ratios. On average, hospital admissions cost more than ED visits because they require extended care, greater use of resources, and more complex medical services: We estimated the cost of an acute care hospital admission in California as $4400 per day [(*76*) as cited in (*77*)] and an average length of stay of 3 days (*78*).

Supplementary Materials

This PDF file includes:
Supplementary Text
Figs. S1 to S23
Table S1

REFERENCES AND NOTES

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