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Understanding and addressing temperature impacts on mortality

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ABSTRACT

A large literature documents how ambient temperature affects human mortality. Using decades of detailed data from 30 countries, we revisit and synthesize key findings from this literature. We confirm that ambient temperature is among the largest external threats to human health, and is responsible for a remarkable 5-12% of total deaths across countries in our sample, or hundreds of thousands of deaths per year in both the US and EU. In all contexts we consider, cold kills more than heat, though the temperature of minimum risk rises with age, making younger individuals more vulnerable to heat and older individuals more vulnerable to cold. We find evidence for adaptation to the local climate, with hotter places experiencing the least risk at higher temperatures, but still more overall mortality from heat. Within countries, higher income is not associated with uniformly lower vulnerability to ambient temperature, and the overall burden of mortality from ambient temperature is not falling over time. Clinically, deaths from ambient temperature manifest in a wide variety of ways, are not often coded as temperature-related, and represent a large fraction of murders, suicides, accidents, and sudden or otherwise unexplained mortality, especially for those ages 5 to 44. Finally, we systematically summarize the limited set of studies that rigorously evaluate interventions that can reduce the impact of heat and cold on health. We find that many proposed and implemented policy interventions lack empirical support and do not target temperature exposures that generate the highest health burden, and that some of the most beneficial interventions for reducing the health impacts of cold or heat have little explicit to do with climate. We highlight remaining research gaps.

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1 Intro

Ambient temperature affects human mortality, a link established by large theoretical and empirical literatures spanning public health, medicine, sociology, and economics. Temperatures both below and above moderate ranges increase all-cause mortality, with the relationship between daily ambient temperature and mortality taking roughly a "U-shape" [1–7]. This empirical regularity is observed worldwide and withstands the inclusion or exclusion or humidity [8, 9], the use of alternative "feels like" metrics or different weather datasets [10–12], and the uses of alternate statistical models to relate temperature to mortality. Globally, mortality caused by heat and cold is estimated to represent a remarkable 7–9% of all deaths [4, 6]. Given the size of this present-day health burden and projections that this burden will grow with climate change [13–15]—representing about half of the projected social costs of warming [16]—there is considerable interest in designing and better targeting interventions and policies that can reduce these burdens.

To support these goals, research has sought to better understand who is most affected by deviations from suboptimal temperatures, the extent to which individuals or communities are able to successfully adapt on their own to repeated or expected exposures, and/or the whether additional interventions or policies can and should be deployed to further reduce burdens. Existing work has uncovered a number of sources of heterogeneity in the temperature–mortality relationship, including age and other sociodemographic characteristics, variation in access to healthcare resources or relevant technologies such as air conditioning, and acclimatization and adaptation to the local climate [17–23]. Well-identified causal research on which specific policies can further reduce the mortality impacts of temperature on a given population is more recent and more rare.

Here we harmonize decades of detailed subnational data on temperature and mortality across 30 countries in North America and Europe, analyze them in a unified empirical framework, and use derived insights to revisit, synthesize, and expand on the existing temperature–mortality literature. We organize insights into ten key findings on the magnitude of temperature impacts, how these impacts vary across observed population characteristics, and what they tell us about how societies are adapting to this changing threat.

We then organize and summarize current research on the efficacy of interventions or policies that might reduce temperature-related health impacts. Our work contrasts with most existing synthesis work in this area [24–27] in two major ways. First, our primary focus is on studies that can make plausibly causal claims about the effect of an intervention or policy on the temperature–mortality relationship—that is, studies with a research design that can isolate variation in the intervention of interest from other correlated factors that might also affect the temperature–mortality relationship. Because this remains an unfortunately small set of studies, precluding formal meta-analysis, a secondary focus is on studies that are able to make credible causal statements about interventions that result in favorable changes to an individuals' realized exposure to suboptimal temperatures, even if these changes are not observably linked to health outcomes in the same study. These include interventions that alter the ambient environment, change the indoor environment, or alter behavior in a way that could translate to health benefits. We view such changes as useful but not sufficient for understanding health impacts (see Supplement for a more formal treatment of this point). Unlike many other studies, our focus is not on whether a technology or approach can function in principle (e.g., can air conditioning [AC] cool a room) but whether programs or interventions that expand access to that technology reduce exposures or impacts (e.g., does a program that subsidizes AC units reduce indoor temperatures and health impacts).

Second, we take a purposefully broad view of interventions that could be helpful in mitigating the health impacts of extreme temperatures. A chief goal is to understand the extent to which reducing the impacts of moderate or extreme temperatures on health requires interventions or technologies explicitly designed to reduce heat or cold impacts (e.g., improved provision of information about heat exposure) and/or whether it can also substantially benefit from policies or interventions not specifically designed with temperature or even health impacts in mind (e.g., improved access to social safety nets). Our review thus draws from a very broad range of disciplines, including public health, epidemiology, economics, engineering, and atmospheric science.

2 Key impacts and vulnerabilities

We assemble weather, mortality, and sociodemographic data at a subannual scale for municipalities in over 30 countries for a period spanning 1968 to 2023. We analyze these data using a well-established empirical framework that relates location-specific variation over time in excess mortality to anomalous hot or cold temperatures in that location, controlling flexibly for a range of time-invariant and time varying confounds that could be correlated with both mortality and temperature exposure (Methods). We allow temperature-mortality response functions to vary non-linearly across the temperature distribution, and allow functions to vary as a function of location specific characteristics, including age, income, baseline average health, and average climate. We analyze cause-specific data to shed light on the diverse causes of temperature-related health impacts, and analyze high temporal resolution data to show stark differences in how extreme heat and cold events translate into mortality impacts. We relate key insights to the large existing temperature-mortality literature which has explored many of these issues in isolation. We organize results into ten key findings.

1. Ambient temperature is among the largest threats to human health As shown in Figure 1, mortality is minimized at around 20-25°C across the populations we study, and deviations in temperature above or below this mortality minimum cause substantial increases in death rates. We estimate that roughly 5% of all deaths in the United States and around 11-12% of all deaths in the EU and Mexico are attributable to exposure to sub-optimal temperatures. Put another way, replacing every day's temperature with the mortality minimizing temperature would save 5–12% of deaths in our data. Studies with a broader geographic focus estimate that temperature causes between 7 and 9% of deaths globally [4, 6].

We estimate that exposure to sub-optimal temperatures was responsible for more than 500,000 total deaths annually in the EU over the last decade, higher than all causes except heart disease and cancer [28]. In the U.S., we estimate that suboptimal temperatures have resulted in about 120,000 deaths annually over the last decade, and estimate that ambient temperature ranks as the eighth most common cause of death in the country, similar in magnitude to all neurodegenerative disease [29]. In Mexico, we estimate that suboptimal temperatures were responsible for about 75,000 deaths annually over the last decade.

2. Cold often kills more than heat In nearly all settings and time periods in our study countries, cold is responsible for substantially more overall mortality than heat (Figure 1 and Figure 2). Across the population as a whole, we estimate that cold deaths – or deaths attributable to exposure to temperatures below the mortality minimizing temperature – outnumber heat deaths by at least a factor of 5. These findings directly contradict common claims in the US that heat is the most deadly weather-related disaster in the US [30]. We emphasize that these results represent patterns in largely temperate countries with frequent cold exposure, and might not represent other contexts, particularly in tropical countries with large populations and very limited cold exposure; however, many tropical countries also experience substantial cold-related deaths [4].

These facts have important implication for the impacts of a warming climate, which will generally reduce the number of cold days and increase the number of hot days. Given the current importance of cold relative to heat in temperate latitudes, multiple studies suggest that near-term warming is likely to reduce annual temperature-related deaths among countries in our sample [22, 31]. Importantly, the opposite is likely true in most high-population tropical countries, meaning that the net global impact will still likely be an increase in mortality, particularly at higher levels of warming [15].

3. Moderate temperature days kill more than extreme temperature days A single extreme hot or cold day increases mortality rates more than a single moderately cold or hot day, but moderate days occur substantially more often. This means that moderate cold and hot days are responsible for a much larger overall mortality burden than extreme cold and heat days, a fact that holds across regions and age groups in our data (see Figure 3), consistent with [4]. In the US and EU, moderately cold days with average temperature between 5-10°C result in by far the largest number of total deaths, with a much smaller second peak on days with temperature between 25-30°C . Extreme temperature days - e.g. days above 30°C – which are often the focus of policies aimed at reducing temperature-related health burdens (see below), are responsible for a very small share of overall temperature-related mortality.

These facts perhaps challenge the common policy approach of focusing interventions on these extreme days. Data we compiled on official heat warnings in the US, which are typically used to trigger a range of official community responses (as discussed below), show that heat warnings are rarely issued on days with forecasted average temperature below 30°C , and aren't issued consistently until forecast averages are above 35°C (Figure S3), despite most heat-related mortality occurring below these temperatures. Work on heat-related hospitalizations in the US similarly suggests meaningful increases in risk below typical heat alert thresholds [32].

The importance of moderate temperatures in overall health burdens also suggests that other policies or interventions that are able to marginally improve health outcomes on moderate days – which likely include policies that have little explicit to do with temperature, such as general improvements in access to health services – could have larger benefits for overall temperature-attributable mortality than policies that target efforts at extreme days, even if these latter polices are very successful on those days. We find some evidence of this below.

4. The relative risk of death from heat decreases with age, and the risk of death from cold increases with age As shown in the top panels of Figure 4, which focuses on Mexico and the United States (where detailed age data are available), the temperature at which mortality risk is minimized rises with age. As a result, younger individuals are relatively more vulnerable to cold and older individuals are relatively more vulnerable to heat. Older individuals' smaller relative sensitivity to heat is counterweighted by their higher baseline mortality, as is clear in the first column of Figure 2; as a result, older individuals experience similar or greater overall mortality from heat than younger individuals, despite being relatively less sensitive.

In the U.S. especially, however, this is not true for those in middle ages: those aged 5 to 44 in aggregate exhibit a temperature-mortality relationship that is approximately linear in temperature rather than U-shaped. For individuals in this age group, deaths from temperature are the result of suicide, homicide, or accident at much higher rates; these causes tend to have roughly linear relationships with temperature [33–35] (see below). If we re-estimating age-specific relationships excluding these causes, empirical relationships for those in age groups spanning 5 to 44 are much more similarly U-shaped to those of other age groups (see Figure S4).

These patterns again have important implications for a warming climate [31]. A reduction in the number of cold days and an increase in the number of hot days will shift the relative burden of temperature away from the elderly and toward younger populations, at least in our sample of relatively temperate countries; absolute burdens will nevertheless likely remain highest among older populations.

5. Deaths from heat and cold manifest differently over time The temporal response of mortality to temperature exposure has attracted considerable research interest [36–38]. In general (Figure 4), we observe that cold exposure has an immediate, negative effect on mortality rates, though subsequent days demonstrate elevated mortality; as a result, the cumulative effect of cold exposure, which can take three to four weeks to fully manifest, is a substantial increase in mortality. By contrast, heat exposure generally leads to a large, immediate increase in mortality on the day of the heat event followed by a return to normal (in US data) or a short period of below-normal mortality (in Mexico data), consistent with harvesting or temporal displacement; as a result, the eventual cumulative effect of heat exposure can be much smaller than its short-term consequences, though short-term spikes can have important implications for health system management [39].

These results have at least two important implications. First, studies that wish to either attribute total mortality to temperature exposure, or to project changes in mortality under future changes in temperature, will substantially understate cold-related burdens, and possibly overstate heat-related burdens, if impact windows are too short. Second, and more speculatively, the immediacy of the impacts of heat, and the initial protective effects of cold and the substantially delayed impact of cold on mortality, could contribute to an under-appreciation of cold risks.

6. Deaths from temperature manifest in many ways Leveraging information on the cause of each death in the U.S. and Mexico, harmonized to broad ICD-10 classifications, we find that heat and cold increase most types of mortality (Figure 5). Consistent with related work [40], cardiovascular disease, the leading cause of death in the U.S. and Mexico, bears a clear, strong U-shaped relationship with daily temperature. This U-shaped relationship is also observed in both countries for deaths attributed to cancer, respiratory disease, poisonings, and otherwise sudden or unexplained deaths. One interpretation of these results is that temperature amplifies the mortality risk of a broad range of co-morbidities, an interpretation consistent with locations of lower baseline mortality risk having substantially reduced temperature-related mortality for both heat and cold (Fig 2, column 4).

In contrast to U-shaped temperature-mortality functions for all-cause and cardiovascular mortality, we find that violent deaths (suicides and homicides) as well as accidental deaths exhibit a nearly linear, positive relationship with temperature, consistent with published results [33–35]. Given existing population demographics, this implies that homicide, suicide, accidents, and sudden or otherwise unexplained mortality may account for as much as 50% of overall heat-related mortality in the U.S. and Mexico.

Finally, clinician coding of "temperature-related" deaths dramatically understates total temperature-attributable mortality. Over the period 1968 to 2019 in the U.S., we observe 68,200 deaths listing temperature exposure or a temperature-adjacent cause as any of the multiple causes of death. This is 0.058% of the observed 117 million deaths over the period, or nearly two orders of magnitude smaller than our estimate of the total burden of temperature-related mortality in the US.

7. Adaptation to local climate substantially shapes temperature-related mortality. The average climate of a location is one of the strongest sources of heterogeneity in temperature-mortality relationships. Consistent with a host of research [4, 22], we find that mortality in hotter places is less sensitive to a day of extreme heat and more sensitive to a day of extreme cold; the opposite is true for colder places. For instance, a 0°C day in the US, EU, or Mexico is many times more deadly in locations that experience these days infrequently than locations that experience them frequently (Fig 2, Fig 6). The temperature at which mortality risk is minimized in a location is also monotonically increasing in average temperature (Figure S5). These differences likely reflect a range of individual and community-level actions and investments – e.g. changes in behavior, alterations to the built environment, adoption of heating or cooling technology – undertaken in response to frequent exposure to certain temperatures.

Despite the availability of adaptation options, many locations – but hotter locations in particular – do not appear to have made mortality-minimizing adaptation investments, even in settings where those investments would appear affordable to them: we estimate that in the US, exposure–response relationships observed in colder places with otherwise similar levels of observable characteristics (income and baseline mortality rate) would result in lower overall temperature-related mortality than those that hot places are observed to have chosen (Figure S6). Put another way, many locations appear to be able to afford response functions that would lower overall temperature-related mortality in that location, but do not choose them. This is true over time as well: had the US "kept" the temperature-mortality response function from the 1970s in subsequent decades, the percent of deaths attributable to sub-optimal temperatures would have been meaningfully lower than what it actually experienced (Figure S7).

There are multiple possible non-exclusive explanations for these apparently puzzling choices.

These include a relatively higher value being placed on heat-related deaths, for instance because such deaths are relatively more common among younger populations; a lack of recognition that cold can be quite deadly in warmer places, perhaps due to the delayed nature the impact of a cold event; a large unobserved disutility of heat exposure, leading people living in hotter places to make heat-specific adaptation investments that increase their sensitivity to cold (for instance, by exhausting a fixed adaptation budget on heat-related rather than cold-related investments); or similarly, relatively high unobserved costs of cold-related adaptations that make their adoption net beneficial in places with frequent cold but less beneficial in places with infrequent cold. Under the assumption that individuals are well informed about risks and are optimally trading off costs and benefits of adaptive actions, recent work shows how the costs of these adaptive actions can be inferred and suggests that their magnitude is often very large [15]. Better evaluation of whether individuals are actually well informed and/or whether they face other constraints to adaptive action (e.g. difficulty in financing investments) is critical for further interpreting observed patterns of adaptation [41]. Some interventions test these and other constraints, as described below.

8. Income is not consistently protective Across all settings explored in this paper, average income in a given location is not associated with systematically lower temperature-related mortality in that location. In both the U.S. and the EU, moving from the lowest to the highest tercile of location-specific income is associated with an increase in overall temperature-related mortality; in Mexico, it is not associated with a meaningful change in overall temperature-related mortality (see Figure 2). Comparison across countries also suggests an unclear role of income: average (purchasing power corrected) per capita incomes in the EU are more than twice as high as in Mexico, yet the mortality burden of heat and cold is similar between the two regions (Fig 1).

These findings do not preclude the possibility that income is protective at very low baseline levels, as these are not well represented in our data or in other global analyses [15]. Nor do they preclude the possibility that income of the person, rather than income of the place, could explain additional heterogeneity in temperature-mortality relationships. Indeed, finer-scale data in the US do suggest larger income-based heterogeneity in temperature-mortality relationships [42], especially for heat, but suggest that these differences reflect variation in the built environment that generates higher realized temperature extremes (for a given ambient exposure) for low income populations. These findings highlight a broader difficulty in using income-based heterogeneity estimates to infer how temperature-mortality responses will change as incomes change, as income is correlated with many other potential sources of heterogeneity in temperature-mortality relationships: for instance, income is negatively correlated with both average temperature and baseline mortality rates in all sample countries (Figure S8). As discussed below, quasi-experimental studies that can isolate program- or policy-driven changes in income from other factors find somewhat mixed evidence on the benefits of these programs in reducing temperature-related health impacts.

9. The mortality burden of sub-optimal temperatures is not uniformly falling In the last two decades, the overall burden of temperature-related mortality has fallen modestly in Mexico, but has risen modestly in the EU. In the U.S., cold-related mortality rose dramatically from the 1970s to the 1990s, as sensitivity to cold increased across the exposure distribution; since the 1990s, cold-related mortality has fallen somewhat, though remains at an elevated level relative to that observed in 1968—1979 (see Figure 2). The overall mortality burden from heat and cold in the US was the same in percentage terms in the 2010s as it was in the 1980s.

At least part of this lack of change over time is a result of populations becoming older: age-adjusted estimates in both the US and Mexico suggest that temperature-attributable burdens have declined over time (more limited data on age structure in the EU make comparisons difficult) (Fig S2).

10. The EU remains substantially more sensitive to both heat and cold than the US Temperature-attributable deaths in the EU, as a percent of total deaths, are over twice as high than in the US and roughly equivalent to Mexico, where per capita incomes are many times lower (Fig 1). This difference is unchanged even when carefully accounting for differences in age, income, average mortality rate, and average climate: for the over-65 population in a location with average temperature of 15°C and average income of $22k (in 2015 USD) and the same baseline mortality rate, the predicted temperature-mortality response is many times more sensitive on both a cold and hot day in Europe as compared to the US, and roughly the same as in Mexico (Figure S9). These sensitivities remain high even in the most recent years, despite apparent adaptation in some EU countries after the incredibly deadly Aug 2003 heat wave [43–45].

High relative sensitivities in the EU relative to the US have at least two implications. First, these differences help generate and refine hypotheses on the sources of temperature-related mortality, many of which are amenable to direct intervention (as discussed below). In this setting, possible explanations include remaining differences in demographic structure and resulting temperature sensitivity, differences in competing risks due to differing comorbidities and causes of death, higher energy costs in the EU, and possible non-economic barriers to the adoption of protective technologies such as AC [46].

Second, these differences suggest that temperature-mortality response functions designed to capture globally-representative relationships by pooling data across many countries might not accurately describe region-specific impacts, even when response functions are allowed to vary by a parsimonious set of covariates. This is because there are likely many additional sources of heterogeneity in temperature-health relationships across countries, many of which hard to model. This in turn implies that if there are ample data in a region, then the most accurate estimate of temperature impacts in that region will likely be based on data from that region.

3 What interventions work to limit the negative health effects of heat and cold?

Here we synthesize existing research on interventions and strategies to reduce the substantial ongoing health burden of both cold and hot temperatures. We organize our review topically, grouping existing research into broad classes of interventions, and assess the strength of the causal evidence for reducing heat or cold temperatures, exposures, behaviors, and health outcomes. We judge evidence to be "strong" if there is repeated causal evidence from real-world applications of the impact of a given approach on objectively-measured health outcomes (see Methods). We emphasize that the absence of evidence is not evidence of absence, and highlight a number of critical research needs. We summarize the following narrative results visually in Figure 7; more detail on the reasoning behind specific judgments is provided in the Supplement.

Temperature alerts and temperature action plans Many countries, regions, and localities now operate systems for temperature alerts or "action plans", which are typically some combination of risk communication to vulnerable populations (for instance, heat alerts) and emergency responses (for instance, opening of dedicated cooling centers) triggered by the onset of extreme weather. These appear to be much more common for heat than for cold, and heat action plans (HAPs) are much better characterized in the literature that comparable responses to cold. Responses during heat events are sometimes combined with longer-term strategies to reduce extreme heat exposure and vulnerability, such as planting trees in certain neighborhoods.

Despite increased take-up of these plans globally, causal evaluation of their impact on health outcomes remains limited. Many existing studies measure whether temperature-mortality relationships differ before versus after the introduction of a HAP or a system of heat alerts in a region, including studies in India, Spain, and a set of European cities [25, 44]; overall, these studies find somewhat mixed evidence whether temperature-mortality relationships changed after HAP adoption [47], or note the lack of causal evidence on whether heat warning systems have systematic benefits [48]. However, a key challenge in interpreting this work is in confidently ruling out any other changes that could have occurred at a similar time as HAP or heat warning system adoption and also affected the heat-mortality relationship. For instance, adoption of HAPs increased substantially in the immediate aftermath of the deadly summer 2003 European heat wave, but many other things also likely changed—such as investments in home cooling by individual households in response to the same event.

A smaller set of studies have taken perhaps more promising approaches to understanding causal impacts of HAPs, heat alert systems, and provision of temperature-related information. One approach has been to randomly vary information on heat risks. A randomized controlled trial (RCT) in Pakistan that trained community health workers to deliver information to households on heat-related health risks and preventative behaviors found that the intervention reduced unscheduled hospital visitation by 38%, but had no discernible effect on mortality during hot summer months[49]. RCTs in Australia and Japan with older adults found that provision of information on heat risks and protective behaviors led to increased self-reported adoption of some behaviors and lower self-reported heat stress, but neither study measured health outcomes directly [50, 51].

A second approach to evaluate the effects of HAP adoption has been to use difference-in-differences approaches, either comparing health outcomes over time in regions that adopted a program versus those that didn't, or comparing health outcomes on days in which a program was triggered versus not, before and after program adoption in a given location. Studies of this type have found substantial (>50%) reductions in heat related morbidity in New York City after the city lowered the temperature threshold at which its HAP was triggered [52], and 5–10% reductions in all-cause mortality on hot days after HAP adoption in Montreal [53]. A study of the sequential rollout of a HAP across a set of Italian cities found that HAPs reduced the effect of extreme heat days on mortality by over half, an effect driven substantially by a heat alert component which successfully induced people to stay at home during heat events [54].

A third approach has been to use quasi-experimental variation in when heat alerts and/or action plans are triggered, resulting from forecasting errors or local discretion that generated variation in alert status across days that ended up having equivalent temperatures, or from careful approaches to match alert days to non-alert days. Studies in the U.S. following these strategies have found limited or uncertain effects of heat alerts on mortality [55–57], and, sometimes, increases in hospitalizations. Similar work in Japan found no effect of alerts on mortality but again an increase in hospitalizations and ambulance requests on days in which alerts were issued, an effect in this setting perhaps explained by people leaving their homes in order to save on home energy costs [58]. Evidence from Korea found small increases in all-cause, all-age mortality resulting from triggered heat alerts and associated action plans [59], although possible reductions in mortality among some subgroups were also observed.

A key challenge in using forecast errors to generate variation in heat alerts is that the errors themselves can be consequential if individuals are already making decisions based on widely available weather forecasts. Indeed, work in the U.S. shows that next-day forecast errors (forecasts that were too cold on hot days, or too hot on cold days) can lead to increases in mortality because people do not undertake protective behaviors they otherwise would have [60]. Conversely, improvements in forecasts reduce mortality, although the effects appear modest: $<1\%$ change in excess mortality on hot or cold days if forecast errors are eliminated [60]. Related work demonstrates that longer lead-time forecasts of hazardous winter weather reduces car accidents [61], with a 1-day increase in lead time reducing accidents on wintry days by 18%.

In addition to information provision, another key component of many heat action plans is the activation of various forms of community support. A leading strategy is the use of cooling centers, or dedicated public locations such as libraries or community centers where individuals can enjoy cool indoor temperatures on hot days [62]. We know of no randomized or quasi-experimental evaluation of the impact of cooling centers on health outcomes, nor even any systematic data collected on the how much these centers are used and by whom; pilot data in one US county reported highly-varying utilization [63]. One lab-based study simulated the impacts of cooling center access by randomizing older adults to either a sustained 9-hr heat exposure, or the same exposure but with a 2-hr midway break in a cool environment; core temperatures fell among those accessing the cool environment but quickly climbed again when individuals re-entered the hot environment [64]. It therefore remains unclear whether a brief reduction in heat exposure protects against negative health impacts of heat waves, whether those who can most benefit from reduced heat exposure can or are willing to access cooling centers, and whether travel to centers can actually increase heat exposure relative to staying at home [65, 66].

Together, this work suggests that having accurate and available information about extreme temperatures can be important for reducing temperature-related mortality and morbidity, but that, in most settings, public provision of additional heat alerts or warnings beyond existing forecast information is alone unlikely to substantially protect health during extreme heat. We find no evidence on the impact of cooling centers. Key research priorities include substantially expanded causal evaluation of broader heat action plans, which often include information provision as a component, as well as a better understanding of which (if any) of the included components of HAPs are most effective. Currently, comparison in effect sizes across existing HAP studies is challenging, given that HAPs differ substantially in their content and the extent to which they are actually implemented [67]. Achieving both research priorities appears possible, given large variation in the timing and nature of HAPs that have now been adopted [62], and strong guidance from the causal inference community on how best to take advantage of the staggered adoption of a given program to estimate causal impacts. However, evaluation of these plans may be hampered by inconsistently available information on plan features, implementation timing, and how closely implementation adhered to the original plan.

Examples of analogous action plans for cold weather appear to be much less common, and have received much more limited characterization and evaluation in existing literature. A difference-in-difference analysis of the introduction of Toronto's Cold Weather Plan, which combined a system of alerts with access to shelters and other services, found no discernible effect of the program on morbidity or mortality [68]. One before-after evaluation of the UK's Cold Weather Plan found that mortality declined among some groups but increased among others after the plan was introduced, but the study could not isolate whether these changes were due to the Plan itself [69]. Identifying and evaluating ongoing programs to issue cold alerts and related services, as occurs in the US, EU, and likely other settings, is a research priority.

Green infrastructure and urban design Urban greening, or the deliberate planting of trees or other plant species in populated areas, is a very commonly-applied strategy to reduce urban heat, among other goals. Evidence from various spatial scales and a very broad range of study locations suggests that urban greening can reduce surface temperatures and the potential population exposure to heat. Detailed high-resolution in-situ and satellite measurements have revealed lower surface temperature under tree canopy, yet the cooling magnitude depends on a variety of factors, including the vegetation species, tree canopy configuration (e.g., connectedness, fragmentation, size, and shape), the interaction between tree canopy and impervious surfaces, and day-night differences [70–72]. Most existing evidence is derived from cross-sectional studies comparing temperature in areas with different canopy cover. A few studies have evaluated likely exogenous changes in urban greening, through tree-protection programs or changes in natural conditions (e.g., outbreak of insect species) and found similar results [73–75]. Meta-analyses of studies using various approaches to studying the cooling benefits of trees suggest that the presence of urban trees can reduce pedestrian daily maximum temperatures by on average 2-3°C relative to no trees, with limited effect on daily minimum temperatures; effects appear more pronounced in hot and dry environments [76]. Multiple observational studies suggest that temperature benefits are non-linear in canopy cover, with limited benefits to greening at low levels of initial tree cover [70, 75].

Causal evidence on the impact of tree planting or urban greening on temperature-related mortality or morbidity remains very limited. Based on derived relationships between urban greening and surface temperature, many studies use established heat-mortality relationships to project large potential of urban greening to mitigate heat-related health impacts and mortality (e.g. [77]). A separate groups of studies from cities and countries around the world compare heat-mortality risk for populations living in greener versus less green environments, typically finding that the relative risk of heat-mortality is higher for the population living in less green environments or further from green spaces [42, 78–84]. A meta-analysis of heat-related mortality and urban microclimates, driven by trees or impervious surfaces, suggests a 5% reduction in risk of mortality on hot days in cooler urban microclimates [85].

Four specific challenges make drawing causal conclusions from this work difficult. First, proximity to greenness is likely correlated with a range of other individual or community-level covariates that could also moderate temperature-related mortality; many of these covariates are likely hard to enumerate, observe, and adjust for. Strong evidence that greening interventions (or their absence) affect temperature-mortality only at parts of the temperature distribution expected to be affected by the intervention (e.g. on hot versus cold days) can help rule out, if perhaps not eliminate, such "selection" stories [42]. Second, tree planting almost surely brings other environmental changes that can independently affect mortality, as is now demonstrated by multiple causal papers. Studies have found declines in mortality after tree planting programs (or increase in mortality rate after tree deaths due to outbreaks of insects such as emerald ash borer) in Beijing [86], Oregon [87], New York [88], and Northeast US [89]. Many studies attribute the health impacts to changes in particulate matter concentrations [75, 86, 88, 89], but do not explicitly report results related to heat-induced mortality changes. Conversely, increased urban vegetation can also increase pollen and ozone pollution, which may negative impact human health [86, 90]. Third, urban greening might alter individual behavior, or change the composition of individuals who can afford to live near green space by altering home prices [75, 91], in a way that either enhances or erodes health outcomes, making temperature attribution of any measured health effects difficult. Finally, studying the impact of extant urban greenspace on temperature-mortality is not the same as evaluating interventions designed to enhance urban greening, as the latter could face a range of implementation challenges (e.g. lower tree survival [92]) not present in the former. Causal studies that better elucidate whether tree planting or related interventions affect temperature-related mortality and morbidity are a key research priority, and would help contextualize the increasing number of studies providing strong evidence that trees can improve overall health [74, 86–89].

A related literature assesses the impact of various other components of urban geometry and design on ambient temperatures and thermal comfort, including the ratio of building heights to street widths, the proportion of sky visible from a given location, and street orientation relative to prevailing wind direction. Both modeling and observational studies find that each of these factors can meaningfully affect temperatures, but often in complex ways that depend on location-specific characteristics (e.g., latitude, aridity, season) [93]. As with urban greening, identification of the causal effect of these factors on health outcomes is very limited, and faces similar challenges: variation in these factors can affect other environmental variables that also affect health (e.g., orientation of streets to the prevailing wind can cool nighttime temperatures but also ventilate air pollutants), and many larger-scale urban design features might not be easily amenable to intervention in existing cities (e.g., changing street orientation). However, large-scale choices over urban design remain quite relevant in rapidly-urbanizing locations in the developing world, and understanding the impact of these choices of temperature-related health outcomes is another key priority. That certain urban design factors affect different parts of the temperature distribution differentially, with predictable effects by season and latitude, offers exciting empirical opportunities to isolate the effects of these choices on health.

Built environment The design and construction of individual buildings, and the use of specific technologies or behaviors to manage indoor temperatures in those buildings, are another set of common strategies for managing thermal comfort and temperature-related health risks. We first discuss passive approaches to heating and cooling, and then below discuss active approaches (e.g., AC).

A vast literature assesses the impact of a range of passive heating and cooling strategies on energy use and temperatures, including insulation, changes to thermal mass, solar shading, increased albedo, and changes to ventilation. Some of these technologies, in particular green or ”cool” roofs that could alter evapotranspiration or reflectivity at larger scale in an urban environment, could alter both indoor temperatures as well as ambient temperatures. A large number of physical-model-based or small-scale experimental studies suggest that some version of each of these technologies could reduce indoor air temperatures in both residential and commercial settings by 1-3°C and meaningfully reduce energy use [93–95], although particular technologies aimed at cooling (e.g. cool roofs) could increase heating-related energy demand during cold periods [96, 97]. Modeling studies also suggest such green or cool roofs, if adopted at scale, could reduce urban ambient temperatures [97]; a study of large-scale expansion of reflective greenhouses in Spain [98] confirms this finding, although we know of no large-scale observational evaluation in urban environments. Finally, we know of no published quasi-experimental or experimental studies on the health impacts of the expanded use of passive cooling strategies, although multiple evaluations are currently ongoing (e.g., [99, 100]). As with green infrastructure interventions, improvements to the built environment could affect health in other ways beyond temperature, including through changes to indoor air quality, dampness, or noise [101–103]. They could also improve temperature-related health outcomes through an income channel, if adoption led to substantial savings on energy.

A central programmatic approach to expanding the use of largely passive home heating and cooling strategies has been large-scale weatherization and home retrofit programs run in many higher-income countries. Randomized or quasi-experimental evaluations of such programs, which are typically aimed at improving home energy efficiency and thus lowering energy costs among lower-income households by subsidizing improvements in insulation, air sealing, window quality, or appliance efficiency, consistently find that these programs deliver much lower energy savings than anticipated – a result of both over-optimistic engineering models of energy savings and variation in installation quality [104, 105]. However, this does not rule out program benefits for temperature-related health outcomes. Such benefits could arise via two channels: by altering temperature exposures, for instance by allowing households to alter indoor air temperatures toward a desired ”set point” that was difficult to previously achieve, or by making it cheaper for households to heat or cool to an unchanged set point, thereby freeing resources to be spent on other health-protective investments. Existing analyses of these programs in the US, UK, and New Zealand – which did not causally measure impacts on objective measures of health – indicate that households appear to slightly alter their indoor temperature upon receipt of these programs [104–108], with estimated increases in cold-season indoor temperature ranging from ~0.15-1^{0}C.

Quasi-experimental evaluation of weatherization of lower-income multi-family dwellings in the US found that weatherization improved self-reported thermal comfort, sleep, and some self-reported morbidity outcomes [109]. An RCT and quasi-experimental evaluation of a New Zealand program to insulate homes found that the program increased cold-season indoor temperatures, improved self-reported health, and reduced all-cause and respiratory hospitalizations [110, 111]. Finally, a quasi-experimental evaluation of a program that provided subsidized loans to East German homes for retrofits following German reunification in 1990 found that improvements in home insulation and heating led to fewer cardiovascular hospitalizations among people over 45, with largest effects on the coldest and hottest days [112]. No known studies identified effects of weatherization or related programs on all-cause or temperature-related mortality.

Active heating or cooling technologies Adoption of technologies designed to actively heat or cool indoor air—with air conditioning being the most salient example—is an obvious strategy to limit the health impacts of extreme temperatures. However, understanding the impacts of adoption of a specific technology on health is challenging given that adoption can be correlated with many other factors or behaviors that also reduce the mortality effects of heat.

A large number of studies examine whether locations or households with higher adoption of air conditioning (AC) experience lower mortality during extreme temperatures. An early meta-analysis showed that households with working AC were much less likely to experience heat related mortality during heat waves [113]. Studies in the U.S. and Japan find that AC adoption is correlated with lower mortality and morbidity under extreme heat but not extreme cold [22, 114–116], a study in U.S. prisons found that heat related mortality was substantially lower in prisons with AC as compared to prisons without AC [117], and studies of 300 cities across multiple developed countries find that AC adoption is correlated with lower summertime heat mortality [118] but that variation in adoption can only explain a modest proportion of variation in heat mortality. A study in Portugal found that hospitals with and without AC had similar mortality prior to the extreme August 2003 heat wave, but hospitals with AC had a remarkable 40% lower mortality rate during the heat wave [119]. A study in India showed that adoption of both evaporative cooling technologies and AC was associated with lower heat mortality, but that the association was three times higher for AC [120]. Somewhat in contrast, data from Vietnam suggest that AC adoption is correlated with lower mortality under extreme cold but not extreme heat [121], again highlighting the difficulty in making causal claims regarding the role of AC adoption given its correlation with other mortality-relevant factors (e.g., income). Furthermore, as discussed below, owning an AC or related technology is not the same as being able to afford to run it: low income households who own an air conditioner run it substantially less than higher income households on hot days [122]. For both reasons, a cross-sectional or time-series correlation between AC penetration and heat-related mortality, as now documented in many studies, does not indicate the extent to which a policy to increase adoption of AC or related technologies would reduce temperature-related mortality.

Unfortunately, few examples exist of evaluations of programs that promote use of AC or related technologies. For heating, an RCT in low income communities in New Zealand found that improved home heating increased indoor temperatures and reduced doctor visits for children with asthma [123], in part because improved heating emitted less indoor air pollutants. A non-randomized evaluation of a program that distributed free AC units to low-income households in New York City found that households who accessed the program were more likely to stay at home on hot days and report improved health relative to those who did not access the program, but the latter population was different among multiple dimensions [124]. Quasi-experimental evidence from Mexico suggests that lessening cash or credit constraints can boost AC adoption [125], and this channel could help explain links between income transfers and reduced heat impacts observed in some studies (see below). While it stands to reason that cooling technologies such as air conditioning should provide health benefits during extreme heat, additional understanding of the cost and efficacy of programs that can help households overcome frictions in accessing these technologies remains a central research priority. Access to these technologies remains low, and will likely continue to remain low, in many lower-income populations of the world absent intervention [126].

A large literature also studies the efficacy of active strategies designed to add or remove heat directly from the body. Modeling and experimental lab studies of electric fans show that they can be useful in reducing core body temperatures during moderate or extreme heat, but that benefits depend on age, hydration status, and humidity, and there is ongoing disagreement over the temperature beyond which fan usage is no longer beneficial or even harmful [127, 128]. Experiments suggest that fans might have no benefit for elderly populations, whose sweat rate is lower [129], and could be harmful at very hot temperatures [130]. Modeling and lab experiments suggest that combining fans with skin wetting to enhance evaporative cooling can reduce cardiac strain and lower core temperatures [127, 130]. Relatedly, wearable personal cooling garments (e.g., air-ventilated "fan" jackets, cooling-pack vests) could reduce heat strain by increasing convective and evaporative heat transfer, thereby lowering skin and core temperatures and easing cardiovascular load. Controlled studies of individuals exercising or performing physical work generally find that these garments enhance evaporative heat loss and reduce physiological strain [131–133], though effects depend on humidity, workload, compatibility with job tasks, and specific patterns of use [134, 135]. We know of no causal, program-level evidence from real-world settings evaluating these technologies.

Experiments also show that cool or cold-water immersion of extremities is an effective way to lower core temperatures and heart rate [136], and partial- or whole-body immersion remains the primary clinical treatment for hyperthermia and heat stroke [137]. While evaporative cooling, personal cooling garments, and simple immersion strategies are likely to be cost-effective strategies for reducing health impacts during heat waves, we know of no causal evaluation of programs to measures or influence the adoption of these strategies on health-related outcomes in non-laboratory settings. Finally, along with evaporative cooling, adequate hydration is a cornerstone of public health messaging during extreme heat events, and has been shown in lab experiments to substantially reduce core temperatures during heat stress [128]. We again know of no causal evaluation of programs to promote adequate hydration during heat waves.

Energy use, affordability, and reliability While the above literature focuses on whether the ownership of specific technologies can reduce temperature-mortality relationships, a related set of studies focuses on the affordable use of these technologies, and whether affordability, or lack thereof, can alter health outcomes during extreme heat or cold. A substantial descriptive literature highlights the financial difficulty that many low-income households around the world face in heating and cooling their homes, and the adverse effects that strategies for coping with these high costs can have on a range of outcomes. These include forgoing food and medical expenses, increasing debt, or reducing electricity consumption [122, 138–140], all of which could affect subsequent economic and health outcomes [141].

Multiple papers provide strong causal evidence that changes in energy prices affect energy use, including home heating and cooling. Experimental or quasi-experimental studies estimate household price elasticities of demand for electricity or natural gas of between -0.1 and -0.35 in the US, with lower-income consumers exhibiting higher elasticities [142, 143], and a quasi-experimental evaluation of time-of-use electricity pricing in California showed that a doubling of prices during peak hours reduced energy use for cooling by 15% and increased indoor temperatures by 1^oF [144]. Lower income households also appear more sensitive to the energy costs of home heating or cooling incurred during periods of extreme hot or cold temperatures, with low-income energy expenditures half as responsive to temperature extremes than expenditures of higher-income households in the US [122].

A small set of papers find that changes in energy prices and energy use can affect temperature-related mortality, presumably in part because they affect home heating and cooling, although this is not shown directly. A quasi-experimental study in the US using variation in natural gas prices found that a doubling of home heating prices increases all cause mortality by 4% in winter months [145], and a study in Japan using variation in energy prices generated by the Fukushima nuclear accident showed that increases in residential energy prices increased mortality on days with temperatures below 0°C, but not on other days [146]. A separate study in Japan found that government encouragement to conserve energy following the Fukushima accident increased mortality substantially on hot days, with the average energy savings target proposed by the government roughly doubling the mortality impact of a 30°C day [147].

Other papers suggest that utility disconnections due to non-payment, during which households lose access to energy, are more common during extreme heat events [148] and are most common among racial minorities and other vulnerable groups [149, 150]. Policies that seek to limit disconnections, such as moratoria during extreme temperatures, pandemics, or certain times of the year, appear successful in doing so [151], but we could find no direct causal assessment of whether such programs alter temperature exposures or affect temperature-related health outcomes.

There are a large number of existing local, state, and federal programs that seek to directly improve energy affordability (e.g. energy bill discounts or refunds for low income households) or maintain energy access during extreme temperature events. Prior work has suggested that these types of programs may reduce self-reported energy insecurity [152], and correlate with declines in excess winter mortality [153]. However, a regression-discontinuity evaluation of the UK's Winter Fuel Payment, a direct income transfer to households with at least one elderly inhabitant, found no effect of the program on indoor temperatures or on a range of health outcomes [154]. We found no additional work that effectively isolates the causal impact of related programs on a specific health outcome. Such evaluation is a clear future research opportunity and a critical research need.

A related set of programs seek to address energy affordability by improving the energy efficiency of homes, e.g. by subsidizing improvements to home insulation, furnaces, or windows as in the "weatherization assistance" programs common in the US. As reviewed above, careful ex post evaluation of these programs has shown that they tend to deliver at most half of the expected energy savings in the US, but do not measure health impacts. One quasi-experimental evaluation in Germany suggests that a large-scale weatherization program reduced cardiovascular morbidity on very hot or cold days [112].

A final set of studies focus on the reliability of energy supply, and specifically on the impacts of power outages on health outcomes. Among many possible sources of energy supply interruption, high energy demand during periods of extreme temperatures can worsen the health impact of those periods by leading to supply interruptions which in turn undermine communities' abilities to use health-protective energy technologies, which include heating/cooling devices and also electricity-reliant medical devices or health services. A large number of studies show that power outages can worsen health outcomes including mortality [155, 156], but few specifically examine whether outages exacerbate temperature-health relationships. A study in the US found in recent data that power outages meaningfully increase heat related mortality, with one additional hour of lost power increasing monthly heat-related mortality by 3‰ [157]; no clear effect was found for cold-related mortality. A study in Australia found that power outages doubled the effect of extreme heat on ambulance attendances, but similarly saw no effects during cold weather [158].

Income and financial support The likely importance of energy affordability in responding to temperature extremes suggests a broader role for higher incomes, and the related availability of financial services, to mitigate health impacts of extreme temperatures. Conventional wisdom and some evidence suggests that income is climate protective, with higher income locations less harmed by a given climate exposure in global data [15]. This protective benefit is less obvious using within-country variation (Figure 2 and Figure S2), but at both local and global scales, the correlation between income and other covariates relevant to temperature-mortality relationships can complicate understanding of the particular role of income (see Figure S8. Households with higher income could be better able to afford protective technologies or relevant healthcare, or they could be better educated on climate threats or work in occupations that are less climate exposed. Thus, as with heating and cooling technologies, a cross-sectional or time-series correlation between income and temperature-related mortality does not indicate the extent to which a policy that increases incomes would reduce temperature-related mortality.

To isolate the role of changes in income on temperature-related health outcomes, studies have examined the rapidly growing set of contexts in which a range of government programs—including cash transfer, cash-for work, and minimum wage programs—have bolstered incomes for some populations and not others. These studies present a mixed picture of the role of income increases in reducing temperature-related mortality. Evidence from Mexico suggests that the implementation of a cash transfer program to low-income households reduced the impact of extreme temperatures on homicide, although rates returned to pre-program levels within five years after program initiation [159]. Separate evidence from Mexico found that an increase in the minimum wage in certain districts reduced mortality from both extreme heat and cold relative to nearby untreated districts, especially among workers in climate-exposed sectors [160]. A study in Ghana found that a cash transfer program reduced the effect of *in utero* extreme heat exposure on incidence of low-birth-weight [161], and a study in Kenya found that a large village-level cash transfer reduced infant and child mortality especially during drought [162]. A study in India found no evidence that a workfare program which provided guaranteed minimum-wage work reduced the effect of hot temperatures on infant mortality, perhaps because the work required eligible individuals (e.g., mothers) to conduct physical labor [163]. A separate study in India found that the expansion of bank branches into rural India, which enabled new access to both credit and savings in those regions, reduced the effect of extreme heat on mortality by three-quarters [164].

A growing body of experimental and quasi-experimental evidence on the broader income-health relationship also finds mixed results on the impacts of income increases on mortality and other health outcomes, with substantial benefits in some settings [162, 165, 166] but no measurable protective effects in many other recent studies [167, 168]. These studies do not measure temperature-related health impacts. Evidence from energy affordability studies suggests that key temperature-related health inputs such as home heating and cooling are income- and price-sensitive, perhaps suggesting that temperature-related health outcomes could be more income-responsive than other causes of poor health, although one study in the UK found that labeled cash transfers aimed at wintertime home heating had no discernible health benefits [154]. The growing body of high-quality causal research on income-health relationships, alongside an ongoing expansion of income-transfer and social safety net programs in many low and middle income countries [169], offer important future opportunities to better understand the role of these programs in moderating climate-health relationships.

Health services Given the diverse set of health outcomes affected by heat and cold, the impact of these exposures could be plausibly mediated by access to and affordability of healthcare. Multiple studies have used the rollout of various community health or healthcare access programs to understand how better access to healthcare affects temperature-mortality relationships. These studies have demonstrated how programs that seek to improve healthcare access, affordability, or insurance can yield large health benefits under extreme temperatures for some groups.

Studies in both Mexico [170] and Colombia [171] show that the rollout of universal or subsidized health insurance for low-income households reduced the effect of moderate cold on mortality by at least half, with less clear benefits for moderate or extreme heat. Hospital desegregation in the Southern U.S. during the 1960s and 1970s, which substantially increased access to acute care for Black populations, nearly eliminated the effect of cold temperatures on infant mortality among those populations [172]. The expansion of community health centers in the U.S. during the same period, which provided inexpensive primary care services to low-income patients, reduced heat-related mortality by 14%, but had no effect on cold-related mortality [172]. In India, the rollout of a community health worker program reduced the impact of hot temperatures on infant mortality by about 10% [163]. In Uganda, the strengthening of an existing community health worker program led to a remarkable 46% reduction in under-5 mortality during drought [173]. For non-mortality outcomes, the staggered rollout of community mental health services reduced the impact of heat and humidity on adverse mental health outcomes in India [174], and access to prenatal care reduced the impact of heat on low birth weights in sub-Saharan Africa [175].

In addition to improved overall access to and operation of healthcare systems, better operation of existing health systems during extreme events could also improve related health outcomes. Indeed, evidence from Mexico suggests that surges in demand for health services during extreme heat events leads to congestion at hospitals, which substantially exacerbates the health impacts of these events as access suffers even for those not directly affected by heat [39]. While data from Italy suggest that hospitals with higher number of beds or more efficient operations are not more effective in reducing the effects of extreme temperatures on health [54], this work was not able to identify whether interventions to promote surge capacity during extreme temperature events were beneficial. A modeling study of improvements to hospital preparedness during the unprecedented 2021 Pacific Northwest heat wave suggest that the implementation hospital upstaffing and mass casualty procedures could substantially reduce emergency department wait times during such an event [176]. Real-world evaluation of such programs, which are a component of some heat action plans, is a clear research need.

There is suggestive evidence that educational programs targeted at health care providers can improve heat-related health outcomes. An intervention in Pakistan that trained emergency department physicians to identify and treat heat-related illness led to more heat-related diagnoses and more heat-relevant treatments [177]. A separate RCT in Pakistan that trained community health workers to deliver information to households led to a 38% reduction in unscheduled hospital visitation but had no measurable effect on mortality during hot summer months [49]. An RCT in China that included training on heat-related illness for providers reduced the prevalence of self-reported discomfort due to heat after implementation, though it is unclear whether these benefits extended to mortality or other severe health outcomes [178].

Other policies and interventions A final set of studies identify additional policy and regulatory interventions that meaningfully affect, but do not explicitly target, temperature-related health outcomes. In the US, laws that limit residents' ability to carry concealed firearms reduced the effect of temperature on homicides by 3% [179]; a relaxing of restrictions on carrying guns in Texas increased the relationship between temperature and gun crimes by 40% [180]. Also in the US, a reformulation of a commonly abused opioid that made it harder to abuse essentially eliminated the impact of temperature on intimate partner violence [181].

Finally, in California, the impact of extreme heat on workplace injuries fell in targeted industries by 75%-90% following implementation of a law requiring worker protections – including heat illness training and access to shade, water, and cooling breaks – for outdoor workers during extreme heat events [182], with the decline concentrated at hot temperatures and among firms more exposed to the policy, suggesting it was the policy adoption that was the cause of the decline. Difference-in-difference evaluation of a mandated 10-min rest break every 4 hours among construction workers in Dallas, Texas found that these breaks modestly reduced worker's compensation claims for injury [183]. A study in Guangzhou, China similarly found that workplace injuries on hot days fell by 13% after the implementation of workplace heat standards [184], but could not rule out the possibility that other things might have changed as well. A number of additional studies on workplace safety programs used before-after designs and also suggested benefits of these programs for a range of health-relevant outcomes (e.g. [185]), but also did not have designs that could clearly attributed changes in outcomes to the program. Such studies highlight the broader need and opportunity to adopt research designs that can construct plausible (untreated) counterfactuals for groups that are treated by a program or intervention.

4 Discussion

Data from our sample of countries and from countries around the world suggest that exposure to sub-optimal temperatures is a substantial contributor to excess mortality. These data also indicate that for the population as a whole, moderately cold temperatures are by far the largest contributor to temperature-related mortality, a fact that appears to hold true in both temperate and many tropical countries [4]. This is not because moderately cold days are more individually deadly but because they are much more common. Extreme heat days (days in the top percentile of a locations daily temperature distribution) are individually deadly but by definition rare, and thus contribute little to overall temperature-related mortality.

Despite these facts, policy and community efforts explicitly aimed at reducing health effects of sub-optimal temperatures tend to largely focus on extreme heat days. Even with this focus, we find little existing causal evidence that such policies, which include heat alerts, action plans, urban greening investments, and other efforts, substantially reduce the health impacts of extreme heat. The absence of strong causal evidence does not necessarily imply that such interventions are ineffective or that they should not be pursued as part of a plan to reduce the health impacts of extreme temperatures. Instead, it suggests that we currently do not have the evidence base to be able to prioritize what interventions are most effective (and most cost effective) in reducing health impacts of extreme heat.

Given the importance of moderate cold and (to a lesser extent) moderate heat in worsening health outcomes, policies or interventions that perhaps inadvertently affect health-relevant variables on a large number of moderately cold or hot days might be more effective in reducing overall health burdens of suboptimal temperatures. Indeed, we find somewhat more consistent causal evidence that access to affordable health care, affordable home energy, and/or social insurance programs help reduce temperature-related health burdens. This again does not imply that policies or interventions that seek to protect health on extreme days are not worthwhile, but that these approaches would need to be combined with complementary efforts to improve health on moderate days if overall health burdens from temperature are to be meaningfully reduced.

Our findings, and the literature as a whole, have perhaps subtle implications for the regional impacts of future warming on mortality. The importance of cold temperatures for current mortality suggest that a warming world will experience fewer cold-related deaths. However, because mortality minimizing temperatures rise with average temperature, both in cross section and in time series, locations actually appear to become more sensitive to the same (cold) temperature exposure with warming, while at the same time becoming somewhat less sensitive to the same heat exposure. The net effect of these forces on overall mortality will depend on how these sensitivities change and the relative distribution of hot and cold days in a location. Multiple analyses suggest that for the US, the net effect of these changes is likely no aggregate change in temperature-related mortality under future warming [15, 22]. Given high existing burdens of sub-optimal temperatures, the implication is that temperature-related health burdens will likely remain high under future warming as well, and thus that better understanding what policies, interventions, and actions can reduce these burdens remains an important research priority.

5 Data

5.1 Mortality

5.1.1 U.S.

Data on all deaths in the United States during the period 1968–2023 are collected from [186]. The data contain information on cause of death, the decedent's age and county of residence, and the weekday, month, and year of death. The data are aggregated to the county–month–year level, with subgrouping by primary cause of death or age as required for different analyses. Causes of death are harmonized according to Appendix Table 1 of [187] with limited modifications.

5.1.2 EU

Counts of deaths by week in the EU during the period 2000–2019 are collected from [188]. The data contain information the decedent's age in 5-year age bins and their NUTS3 of residence, as well as the week and year of death occurrence (date of registration in the case of the UK). The data are aggregated to the county–month–year level, with subgrouping by age as in the analyses.

5.1.3 Mexico

Data on the universe of recorded deaths in Mexico during the period 1990–2023 are collected from [189]. The data contain information the decedent's age, cause of death, municipality of residence, and date of death. The data are aggregated to the municipality–month–year level, with subgrouping by age or cause as in the analyses.

5.2 Weather

Data on temperature and precipitation in harmonized geographies are constructed from ERA5 [190]. Consistent with [191] and [15], we construct polynomials of temperature up to order 4 and polynomials of precipitation up to order 2, then aggregate these features to the administrative unit–day level using population weights from the Global Human Settlement Layer [192].

5.3 Sociodemographic information

5.3.1 U.S.

County-level personal income data is taken from the U.S. Bureau of Economic Analysis (BEA) [193]. Incomes are deflated using the BEA's personal consumption expenditure price index. County-level, age-specific population is taken from the Surveillance, Epidemiology, and End Results Program (SEER) of the National Cancer Institute [194].

5.3.2 EU

NUTS3-level PPP-adjusted GDP per capita and NUTS3-level age-specific population are taken from Eurostat [195, 196]. GDP per capita for the UK is taken from the UK Office of National

Statistics [197], with corresponding amounts in British pounds sterling converted to euros using a Eurostat echange rate product [198]. All GDP per capita values are deflated using a GDP deflator from Eurostat [199].

5.3.3 Mexico

6 Methods

To the extent possible, we attempt to unify our empirical approach across impact regions, though our exact specification varies according to the datasets' respective limitations. In general, we estimate a model of the form

$$D_{it} = f_c(\mathbf{T}_{it}, \mathbf{X}_{it}) + g_c(\mathbf{R}_{it}) + \gamma_{im} + \delta_{iy} + \epsilon_{it} \quad (1)$$

where D_{it} is the death rate per 100,000 in unit i during period t. In Mexico and the U.S., t represents one month; in the EU, it represents one week. In Figure 1, $f_c(\cdot)$ is solely a function of population-average nonlinear vectors of temperature, $\mathbf{T}_{it}$; in Figure 2, $\mathbf{X}_{it}$ is a vector of 20-year average temperature, the log of average per capita income, the baseline mortality rate, or a factor indicating age (in three groups: under 15, 15 to 65, and 65-plus) or decade (roughly 10-year periods), each interacted linearly with $\mathbf{T}_{it}$. In Figure 6, linear interactions between $\mathbf{T}_{it}$ and members of $\mathbf{X}_{it}$ are included simultaneously. $\mathbf{R}_{it}$ is a quadratic in population-average precipitation. γ_{im} represent fixed effects by administrative unit–month and δ_{iy} represents fixed effects by administrative unit-year. We cluster idiosyncratic errors, ϵ_{it}, at the next-highest administrative unit (e.g., states in the U.S.).

The temperature–mortality response functions resulting from this estimation are centered such that the predicted change in mortality is zero at a post-estimation-derived minimum mortality temperature. We constrain this minimum mortality temperature to lie between 0 and 30°, a constraint that is only binding in a very small number of cases where the recovered polynomial turns sharply negative at an extreme end of the temperature distribution. This recentering is arbitrary: the inclusion of fixed effects means that the level of the response function is not recoverable; only slopes are causally identified. As a result, the attribution of total temperature-related deaths is relative to a counterfactual where each location is treated with its mortality minimizing temperature on each day.

Assessment of evidence on adaptation interventions To identify relevant literature on adaptation interventions for inclusion in our review, the author team divided into groups focused on specific topics and searched academic databases. Given that we were looking both for studies evaluating interventions explicitly labeled as climate adaptation interventions by study authors, as well as studies that identified climate-impact-reducing interventions but which were not cast as adaptation interventions by the study authors, research teams used a very large variety of keywords to identify candidate studies in Google Scholar as well as through simple web search. Relevant papers were screened by at least two researchers, and narrowed to studies that met our main criteria of (1) evaluating a specific intervention relevant to climate exposure or impacts, and (2) using statistical approaches or research designs that plausibly isolate the causal impact of the intervention from other confounding factors. Searches were run through July 2025.

To ensure that we had identified the full set of relevant studies in a topic area, after the above manual search, we made additional use of research tools in multiple large language models (LLMs). Specifically, we asked ChatGPT o3 Deep Research, Gemini Deep Research, and Elicit to identify studies that met our search criteria in each topic area. Although these tools often returned topically-relevant studies that did not meet our rather strict causal criteria, they almost always found at least one study in a topic area that met our criteria and which we had not found through manual search. We view these models (as of August 2025) as a useful complement to, but certainly not a substitute for, more traditional database-driven literature search.

We translate the narrative evidence presented in the main text into judgments of the strength and direction of evidence of different interventions. Judgments are unavoidably somewhat subjective. Factors contributing to each judgment include:

- *Whether a given study had a research approach designed to isolate the causal impact of an intervention on a temperature exposure or health impact*. There is no agreed-upon threshold above which a paper can be interpreted as "causal" and below which not. Randomized controlled trials are considered the goal standard of causal designs and are included. We also include a range of "quasi-experimental" designs or "natural experiments" that combine observational data with a range of techniques designed to isolate variation in an intervention of interested from a range of other potentially correlated variables. The majority of studies of this type measure impacts using difference-in-difference type variation in intervention or program rollout over time, for instance by studying differences in exposure-outcome relationships between earlier-treated and later- or never-treated units, or by studying spatial units (e.g. a city or state) and comparing differences between groups more or less exposed to an intervention. In either case, temperature-health relationships are compared for treated and untreated groups over time. We included related designs that use discontinuities in treatment generated by policy rules (so called regression discontinuity designs). We put less confidence in studies that do not contain data on untreated and treated groups during the same period, as temperature-health relationships can evolve strongly over time for many reasons; these include before-after studies as well as some interrupted time series studies.
- *Whether the program or intervention being studied was carried out in a "real world" context* that would account for a range of outcome-relevant factors, including behavioral responses that could moderate exposures (e.g. leaving windows open), financial constraints that could moderate technology use (e.g. not running an AC due to energy costs), or implementation challenges from enacting a program at scale (e.g. tree mortality after a tree planting program). Thus, a study evaluating a scaled intervention in the real world (e.g. the effects on indoor temperature of a program to paint roofs white across a neighborhood) was given higher weight than a study evaluating an approach in an idealized setting (the effects on indoor temperature before and after the roof of an uninhabited structure was painted white).

- *The number of studies and/or the population size covered by a study.* For instance, a study using mortality data from every county in the US over many years would get higher weight than a study using data from a handful of cities.

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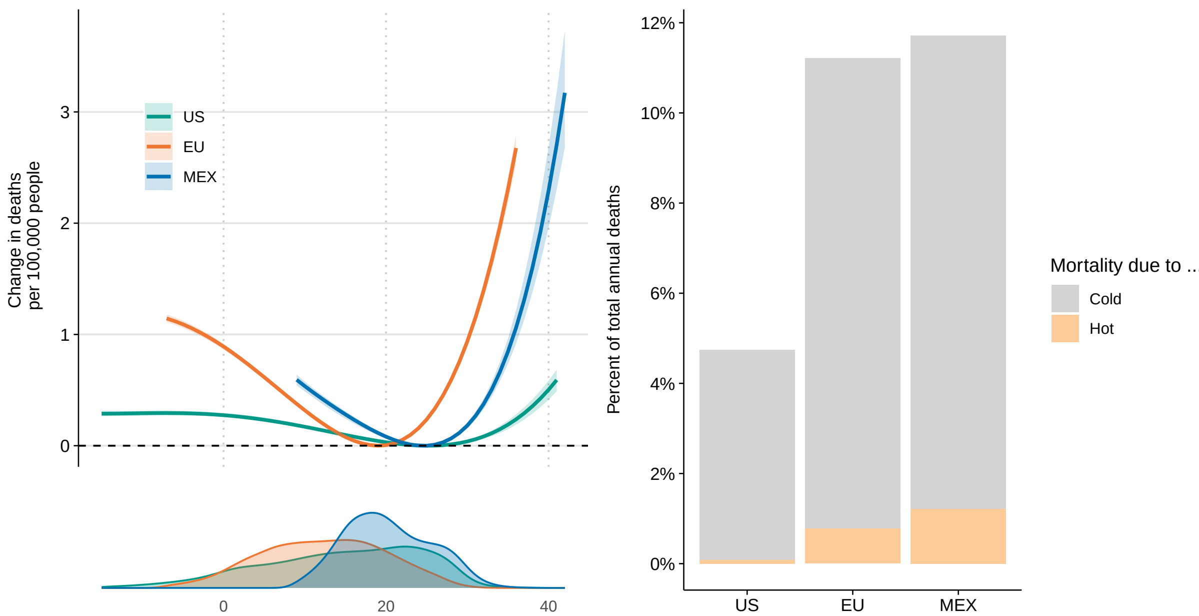

Figure 1: **Temperature-mortality relationships, and attributed total deaths from sub-optimal temperatures**. Left panel shows relationships between temperature and monthly mortality rates in the US, EU countries, and Mexico. Right panel shows the percent of overall deaths in each country currently attributable to sub-optimal hot and cold temperatures over the entire study period – i.e. deviations in the hot or cold direction from the country-specific mortality-minimizing temperature. Cold temperatures are currently responsible for 3-10x the number of attributable deaths.

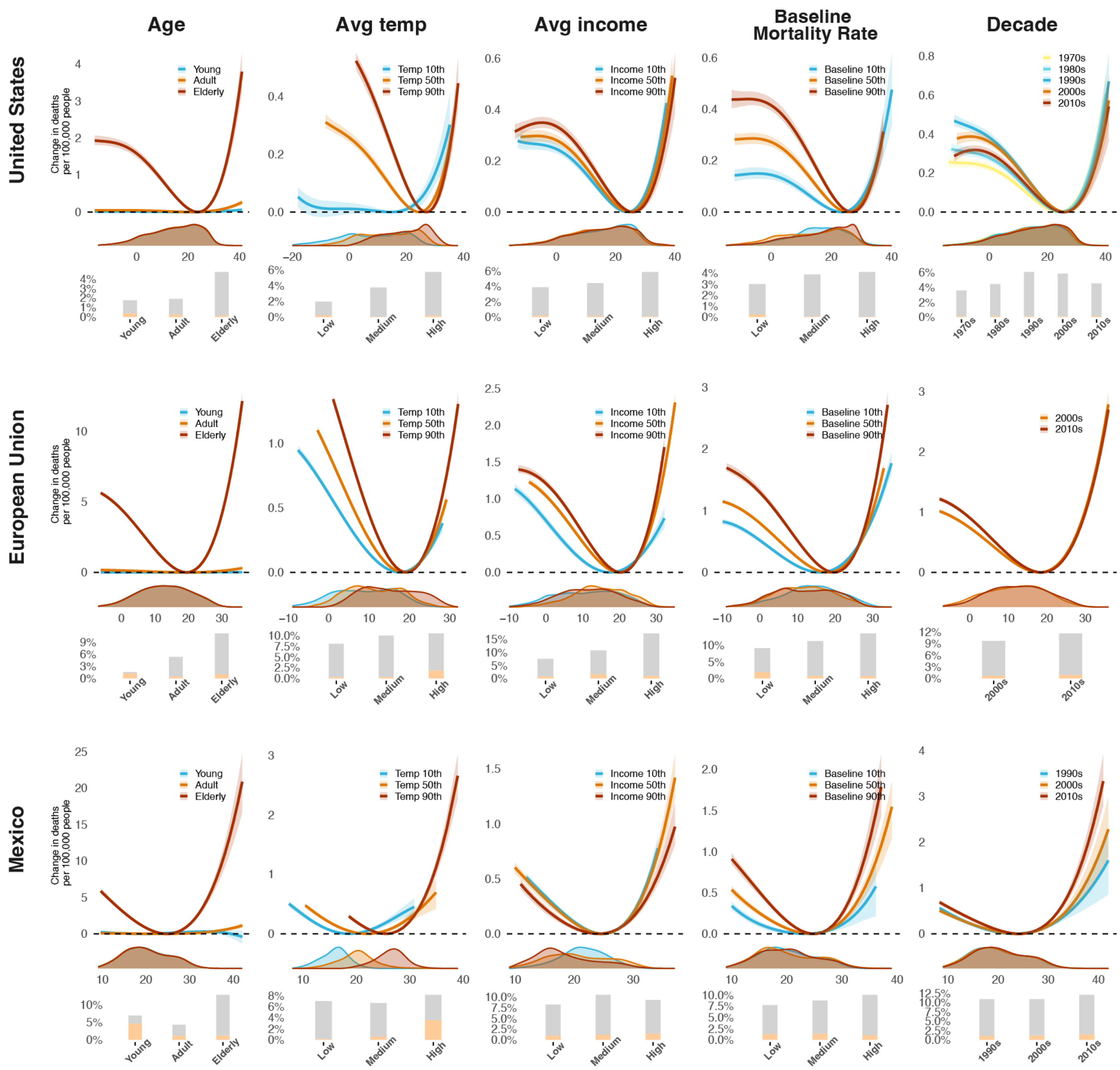

Figure 2: **Heterogeneity in the impacts of temperature on mortality.** Columns show heterogeneity by age group, location average temperature, location average per capita income, location average mortality rate, or by decade; rows are impact regions. Density plots below each set of response functions show the distribution of temperature exposure for each sub-group. Bar plots show attributable total mortality in each sub-group, with orange representing heat deaths and grey representing cold deaths. Estimates are not age-adjusted; comparable age-adjusted estimates are shown in Fig S2.

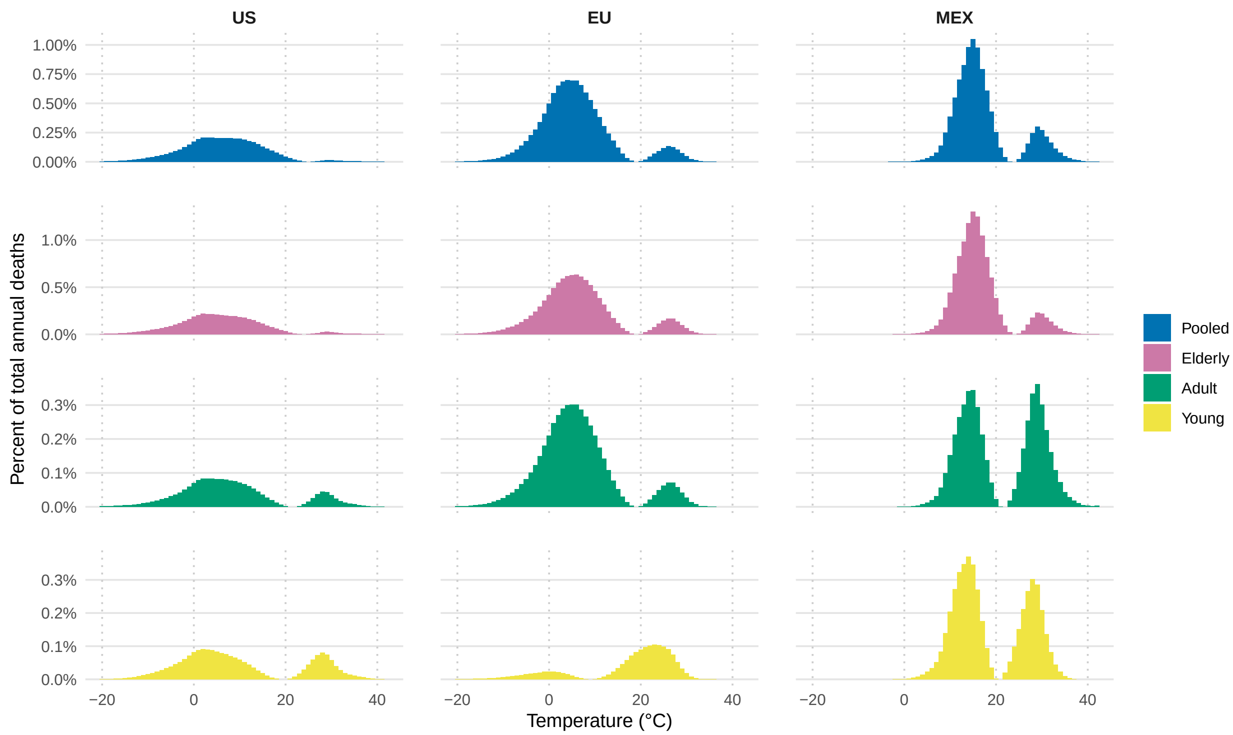

Figure 3: **Moderately hot or cold days account for a much higher proportion of totals deaths than extreme temperature days.** Each panel shows the percent of overall annual deaths in a country-age-group attributable to days in each 1C temperature bin. Columns are countries, rows are age groups: 65+ (elderly), 15-64 (adult), and <15 (young). For instance, days with an average temperature of 2C, 6C, and 15C are responsible for the most number of elderly deaths in the US, EU, and Mexico, respectively. Only among youth populations in the EU and Mexico are moderately hot days more deadly than moderately cold days. Extreme hot and cold days, while individually more deadly, are relatively rare and so account for very small proportions of overall mortality.

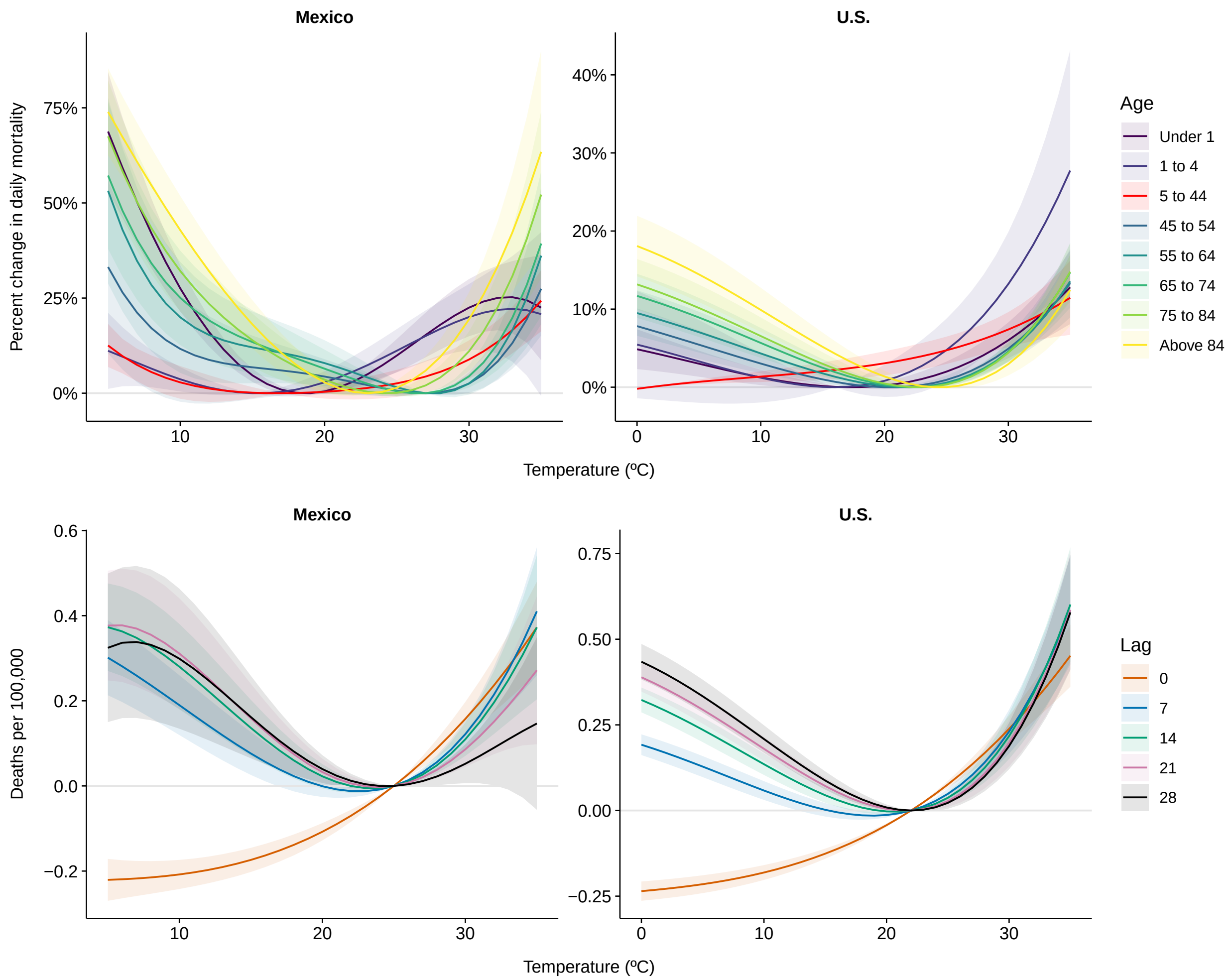

Figure 4: **Temperature-mortality relationships by age group and by lag length, US and Mexico.** Top row shows temperature-mortality relationships by age group for Mexico and the US, measured as the percent change in mortality for that age group above group-specific baseline rates. Older age groups are nearly uniformly more sensitive to cold, with a mortality-minimizing temperature (MMT) that is much warmer. Mortality in middle age groups have a more linear relationship with mortality, reflecting the role of differential cause-specific mortality across groups – in particular, the importance of accidents, suicide, homicide, and poisonings among this group, which have more linear relationships with temperature. Bottom row: Effect of daily temperature on daily mortality, by number of included daily lags. For instance, the dark black line relates mortality on a given day to temperature on that and the previous 28 days. US data are from 1972-88 sample when daily data are available.

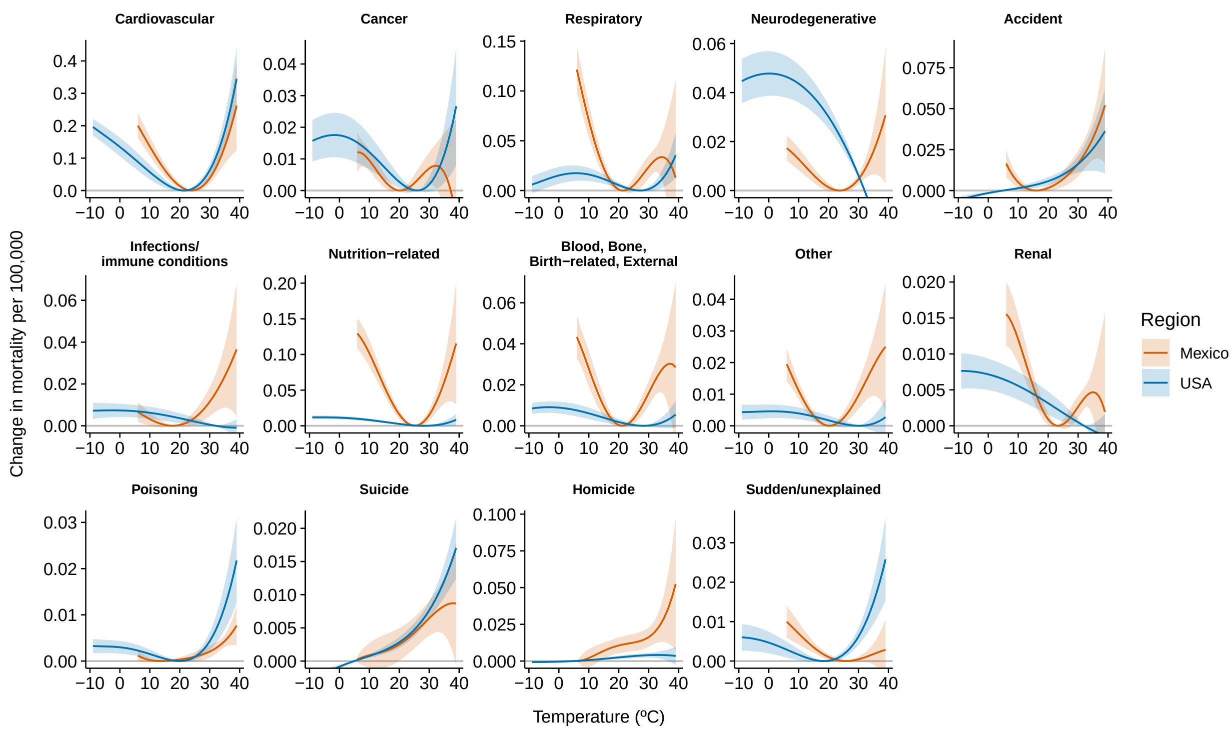

Figure 5: **Cause specific data indicate the diverse channels through which hot and cold temperatures affect mortality**. Each panel shows the relationship between temperature and cause-specific mortality in the U.S. and Mexico. Panels are ordered according to the prevalence of each cause in U.S. death records over the period 1968–2023 (i.e., cardiovascular mortality is the leading cause of death in the U.S., whereas sudden/unexplained deaths account for the smallest overall number of deaths). Note that y-axes differ in scale across outcomes.

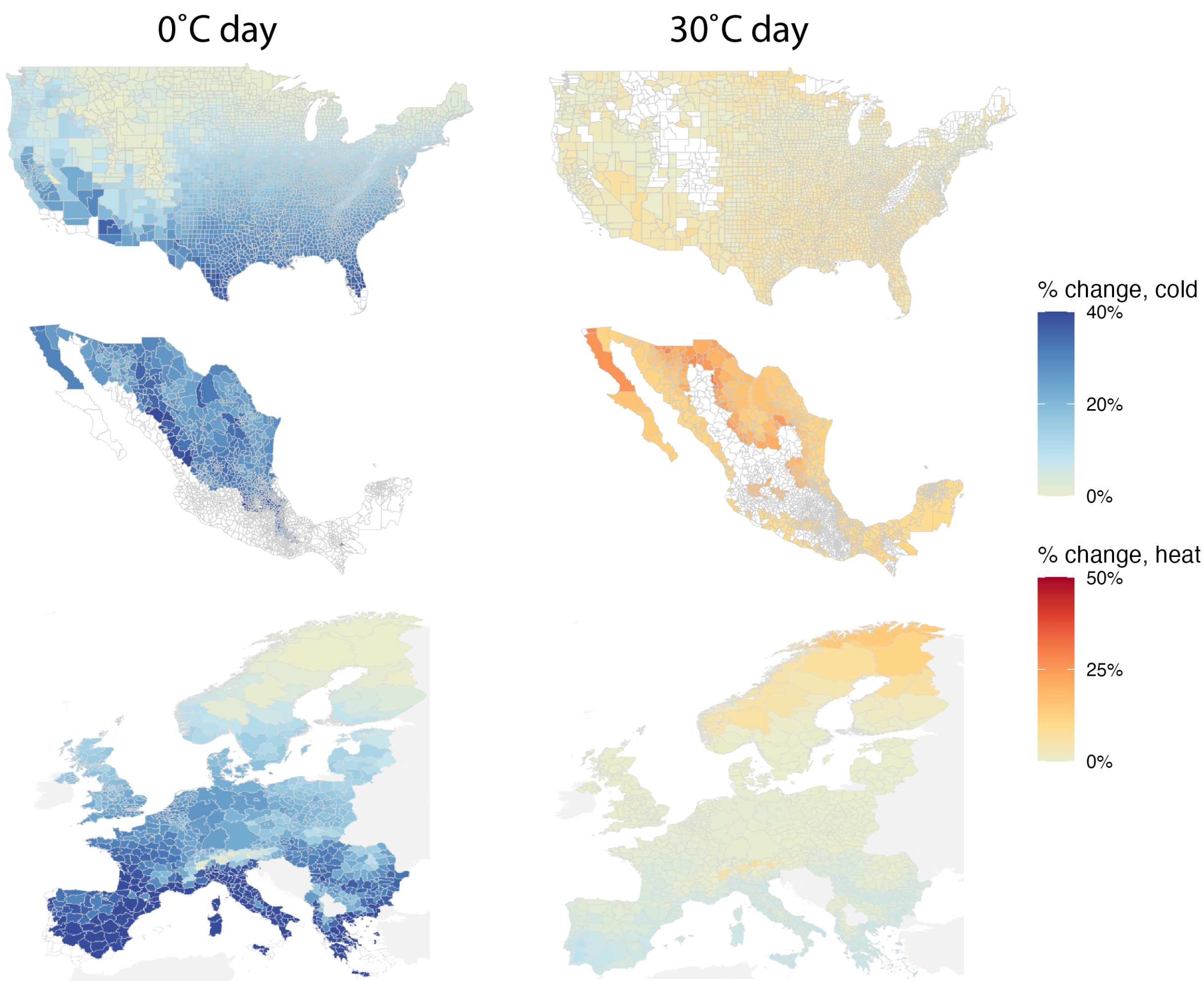

Figure 6: **Change in daily all-cause mortality due to one day at 0°C or 30°C** . Estimates account for heterogeneity in average temperature, income, and baseline mortality. Locations with no estimate do not experience that temperature.

Figure 7: **Matrix summarizing the state of the literature on various interventions to reduce the effects of ambient temperatures on mortality**

Supplemental Information

Assessment of evidence

We provide additional information how we translated available evidence into judgements of the direction and strength of evidence on each intervention.

6.1 Information provision

Weather forecasts One well-executed quasi-experimental study in the US provides clear evidence that better weather forecasts reduce both heat- and cold-related mortality. The study uses all deaths in the US over many years. Thus although the study only represents outcomes in one country, we judge that there is strong evidence that improved weather forecasts can improve both heat- and cold-related outcomes. This paper provides some evidence that health benefits are a result of individual changes in behavior, including using more energy on hot days and working from home, and so we judge that there is moderate evidence of changes in heat and cold exposure.

Temperature alerts and warnings Existing evidence on heat alerts is very mixed regarding health impacts. A quasi-experimental study in Italy suggested the rollout of a heat alert system substantially reduced heat-related mortality, but studies in the US, Japan, and Korea found heat warnings to have mixed benefits (or even harms) for health outcomes. Some of these studies use variation in forecast accuracy to study impacts, which could be problematic if forecast accuracy itself is important in health outcomes. We thus judge that there is moderate evidence of mixed benefits from heat alerts. Studies of cold-weather programs in Toronto and the UK, which included cold alerts alongside other interventions, found either no or mixed impacts on health outcomes. We thus judge that there is moderate evidence of mixed benefits of cold alerts.

Targeted information campaigns Experimental or quasi-experimental studies on programs which targeted temperature-related information to vulnerable groups have found that this information appears to change behavior in a way consistent with risk reduction, but either did not measure objective health outcome data or found mixed results. We know of no systematic research on efforts to target information about cold. We thus judge that there is moderate evidence that targeted information about heat can change exposures in a way beneficial for health, but no clear evidence that such information can meaningfully affect heat-related health outcomes.

6.2 Community interventions

Extreme temperature action plans Three quasi-experimental studies using the adoption of heat action plans in New York, Montreal, and Italy suggest reductions in either morbidity or mortality after adoption of these plans. Multiple other before-after evaluations, which did not have strategies to isolate the impact of heat action plan adoption from other trending variables which also could have shaped temperature-health relationships, also suggested benefits – but these papers do not have a clear causal interpretation.

Heat action plans typically contain multiple components, and studies differed to some degree in which if any specific plan component was most beneficial. In Italy, a study suggested it was the heat warning component of the plan that was most useful. This contrasts with findings in the US, Japan, and Korea that found heat warnings to have mixed benefits (or even harms) for health outcomes. Given the lack of empirical clarity on how best to design these programs to maximize health benefits, but clear reduced form evidence that plan adoption brings benefits for health, we judge that the existing literature provides moderate evidence that the adoption of a heat action plan can improve temperature-related health outcomes.

Studies of cold weather plans in Toronto and the UK, which combined alerts with other services, found no consistent evidence that the implementation of these plans altered cold-related morbidity or mortality. We judge there is moderate evidence that implementation of these plans has mixed results.

Cooling centers We know of no randomized or quasi-experimental evaluation of the impact of cooling centers on health outcomes, nor even any systematic data collected on the how much these centers are used and by whom. One lab-based study found that brief exposures to cool temperatures led to short-term reduction in core temperature among older adults, but it remained unknown whether this brief reduction would guard against negative health impacts, especially given real-world challenges in accessing centers during heat waves. We thus judge that there is no causal evidence that cooling centers can reduce heat exposures or heat-related health outcomes. We know of no equivalent evidence on warming centers.

6.3 Energy use and affordability

Energy savings encouragements One causal study found that government encouragements to conserve energy substantially increased heat-related mortality, with people spending more time outdoors. Because this is only one study, and because government encouragement might have very differential effects in different countries, we judge that there is moderate evidence that such encouragements worsen heat related exposures and outcomes.

Energy price and affordability interventions There is strong causal evidence that increases in energy prices affect energy use and worsen temperature-related mortality. However, there is very little existing evaluation of interventions that seek to alter energy prices or affordability. One study in the UK found that income transfers aimed at improving wintertime energy affordability had no effect on indoor temperatures or health. We thus judge that there is weak evidence that energy price or affordability interventions improve extreme temperature exposures, and moderate evidence that those interventions improve cold-related mortality. We do not know of evidence regarding impacts on heat-related health outcomes.

Energy efficiency programs There is strong causal evidence that weatherization assistance programs and other retrofit programs can generate energy savings (albeit at a higher cost than ex ante assessments would indicate). Effects on temperature exposure, through effects on indoor temperature, appear to be small. Causal evidence on health impacts suggests improvements in temperature-related morbidity in multiple countries, but no known studies assess mortality impacts. Nearly all benefits are measured for cold temperatures and not for heat. We thus judge that there is moderate evidence for changes in cold exposure, but moderate to strong evidence for changes in cold-related health outcomes, despite the lack of information on mortality impacts.

Programs that limit disconnections We could find no literature that evaluated the effect of programs that limited utility disconnections on either realized climate exposures or health outcomes.

Programs to improve energy reliability A paper in the US showed that even very short term power outages meaningfully increased heat-related mortality. This finding suggests that limiting outages would thus reduce these impacts, although we could find no literature that directly assessed efforts to improve energy reliability on exposures or outcomes. We thus judge that there is moderate evidence that improved reliability could improved heat-related outcomes, but no evidence on exposures or cold.

6.4 Housing and urban design

Tree planting and urban greening There is strong evidence that variation in tree cover can affect maximum surface temperatures, but impacts vary as a function of a large range of potential factors. Nevertheless, we rate the evidence as strong that higher tree cover reduces surface maximum temperature. Evidence is more mixed on the impact on summertime minimum temperatures or on cold temperatures.

We know of no quasi-experimental studies that are able to identify the effect of changes in tree cover on temperature-related mortality. Existing studies either use variation in tree cover that could be correlated with other factors also affecting mortality, or are unable to isolate the temperature-specific impacts from the large range of other environmental impacts (e.g. air pollution) that trees can cause. We thus judge that there is limited causal evidence on heat and cold-related health outcomes.

Green and cool roofs This class of intervention includes the use of vegetation or reflective paints or other materials on roofs in order to moderate indoor temperatures. There is strong evidence that these approaches can be successful in reducing indoor temperatures on hot days. There is some evidence that widespread adoption can reduce ambient temperatures as well. There is some evidence that, especially cool roofs, can reduce indoor temperatures on cold days (or raise energy expenditures) because they reflect solar heat. We know of no quasi-experimental or experimental studies on the health impacts of these and other passive cooling approaches.

Other passive cooling or heating approaches These include trombe walls, solar chimneys, solar shading and various other strategies. There is a large amount of evidence showing how these approaches can moderate temperatures, particular reducing heat extremes. The existing literature typically evaluates specific application of these technologies, often in controlled settings, and does not evaluate the impact on exposure or health outcomes of interventions designed to expand access to these technologies and approaches. Nevertheless, we judge the evidence as strong that these approaches can moderate indoor temperatures on hot days.

We know of no published quasi-experimental or experimental studies on the health impacts of the expanded use of passive cooling strategies. Weatherization assistance programs and home retrofit programs, which are largely designed around passive approaches to home heating, have been shown in quasi-experimental studies to have possibly substantial health benefits, at least for morbidity. We thus judge that there is moderate evidence for changes in cold exposure, moderate to strong evidence for changes in cold-related health outcomes, despite the lack of information on mortality impacts.

Active cooling or heating approaches These include approaches that use energy to heat or cool (AC, evaporative coolers, gas or electric heaters), as well as strategies to directly add, remove, or manage body heat, such as electric fans, skin wetting, immersion, and hydration. A large number of studies, but not all, find that ownership of energy-based technologies like AC is associated with lower temperature-related mortality. However, most of these studies cannot convincingly isolate the impact of the technology from a range of health-relevant factors associated with the technology, and typically do not evaluate programs or interventions designed to increase access to these programs. Existing causal evidence of the impact of programs seeking to expand access to active heating or cooling approaches is quite limited for temperature exposures, and non-existent for health outcomes. We thus judge that there is strong evidence that expanded access to these technologies would reduce temperature exposures, but only weak or moderate evidence on actual real-world programs that would expand access, and and moderate (for cold) or weak (for heat) evidence that such programs improve health outcomes. We emphasize again that the claim is not that these technologies or approaches do not affect temperature exposures, but that we do not have strong evidence on the impacts of programs seeking to expand access to these technologies.

6.5 Health Services

Universal or subsidized health insurance Quasi-experimental evidence from the US, Mexico, and Colombia finds that expansion of health insurance and access to healthcare led to very large reductions in cold-related mortality or morbidity. These studies showed limited evidence of health benefits under extreme heat. All studies assessed changes in health outcomes and did not assess changes in exposures.

Community health centers or workers Quasi-experimental evidence from the US, India, and Uganda showed that the expansion of community health centers or community health workers substantially reduced the health impacts of extreme heat or drought, but did not find evidence of benefits under extreme cold. All studies assessed changes in health outcome and did not assess changes in exposures.

Health systems disaster preparedness A quasi experimental study in Mexico showed that hospital congestion during heat waves was responsible for a substantial proportion of heat related morbidity and mortality. A study in Italy, however, suggested that hospitals with higher number of beds or more efficient operations are not more effective in reducing the effects of extreme temperatures on health. Neither study evaluated impacts of cold temperatures. We thus judge the evidence as moderate and mixed as to whether efforts to expand hospital capacity would improve health outcomes during extreme heat events.

Medical education for providers Evidence from two experimental studies in Pakistan suggest that educational programs targeted at health care providers can improve health outcomes under extreme heat. One study found changes in diagnosis and treatment, and the other found benefits for unplanned hospitalizations but not mortality. We thus judge that there is moderate evidence that these programs could have benefits under extreme heat, but no evidence for changes in heat or cold exposure or for changes in cold-related health outcomes.

6.6 Other policies

More restrictive gun laws Two quasi-experimental studies in the US find that more restrictive gun laws reduce the effect of hot temperatures on gun crimes and on gun-related mortality. No effects are studied for cold, perhaps in part because violence appears to decline at cold temperatures. We judge that there is strong evidence that more restrictive gun laws reduce heat-related health impacts.

Workplace protections for extreme temperatures One study in California found that the introduction of protections for outdoor workers during heat events reduced the effect of heat on workplace injuries. Multiple other studies from around the world used before-after designs and found that a range of health-relevant outcomes improved after adoption of a workplace heat safety program, but absent any plausible counterfactual could not definitively attributed changes in outcomes to program adoption. None of these studies measure directly measure changes in heat exposure in the workplace as a consequence of the policy changes. We thus judge that there is moderate evidence that worker protection laws for extreme heat can improve health outcomes under extreme heat, but no evidence for changes in exposure or for cold benefits.

Income support programs A quasi-experimental study in Mexico found that a cash transfer program reduced temperature-related homicide, but that the effect was short-lived. Another quasi-experimental study in Mexico found that an increase in the minimum wage in some districts reduced both heat and cold-related mortality. A quasi-experimental study in Ghana found that a cash transfer program reduced the effect of extreme heat exposure on low birth weight. In contrast, a study in India found no evidence that a guaranteed-work program altered the effect of hot temperatures on infant mortality, possibly because eligible individuals would have to conduct physical labor in the heat. We thus judge that there is moderate evidence that income support programs can reduce cold-related health impacts, and strong evidence that these programs can reduce heat-related health impacts. No studies evaluated changes in temperature exposure.

Changes in exposure versus changes in outcomes

In seeking to understand whether a given interventions reduces the impact of temperature on mortality or some other health outcome, we make the claim that strong causal evidence that an intervention changes temperature *exposure* is not sufficient for understanding whether that intervention improves temperature-related health *outcomes*. Here we attempt to make that claim slightly more formal. The claim is based on two related sub-claims: (1) variation in temperature exposure generated by an intervention rarely resembles the variation in temperature exposure used to estimate temperature-mortality relationships, and (2) interventions can alter individual choices and behaviors in ways that also alters temperature/health relationships.

Our understanding of how variation in temperature shapes mortality outcomes, based on this paper and many others, derives from relating mortality to variation in ambient outdoor temperature, conditional on temporal and spatial controls (as in Equation 1). The "reduced form" relationships that come out of this analysis are the result of a likely vast array of interacting variables (physical exposure, baseline health, changes in behavior, etc) that determine health outcomes on a hot or cold day; these variables are typically unobserved or only partially observed by the analyst.

For simplicity, assume that changes in ambient temperature T affect mortality risk y through two channels: a set of behaviors b that change based on ambient temperature (I stay inside on a hot day, I turn on the heat on a cold day) and a set of realized temperature exposures T_e that capture how the physical environment translates changes in ambient temperature to integrated personal temperature exposure throughout the day (ceiling insulation in my house means that indoor temperatures are 3°C lower than ambient temperatures). For simplicity, assume b is scalar. We can write $y = f(b(T), T_e(T))$, and the effect of changes in ambient temperature on health can then be decomposed into the effects through behavioral change and the effects through changes in physical exposure:

$$\frac{\partial y}{\partial T} = \frac{\partial y}{\partial b}\frac{\partial b}{\partial T} + \frac{\partial y}{\partial T_e}\frac{\partial T_e}{\partial T} \tag{2}$$

We are then interested in how some change brought about by an intervention Z affects the temperature-mortality relationship. The intervention could work through either the physical exposure channel (planting trees makes sidewalk temperatures cooler on a hot day) or the behavioral channel (now that there are trees I am more likely to exercise outside on a hot day), or both. Taking the derivative of both sides of equation 2 with respect to Z, we have:

$$\frac{\partial^2 y}{\partial T \partial Z} = \underbrace{\frac{\partial y}{\partial b}\frac{\partial^2 b}{\partial T \partial Z}}_{a} + \underbrace{\frac{\partial^2 y}{\partial b \partial Z}\frac{\partial b}{\partial T}}_{b} + \underbrace{\frac{\partial y}{\partial T_e}\frac{\partial^2 T_e}{\partial T \partial Z}}_{c} + \underbrace{\frac{\partial^2 y}{\partial T_e \partial Z}\frac{\partial T_e}{\partial T}}_{d} \tag{3}$$

Imagine a cool roof intervention where a carefully conducted randomized trial says that installation of a cool roof reduced indoor temperature by 3°C on a hot day. Under the quite strong assumption that this tells us everything about a person's realized exposure, then this RCT has identified the second part of the term in (c), $\frac{\partial^2 T_e}{\partial T \partial Z}$. Clearly this is not sufficient to tell us how the intervention affected health. Even if we're willing to make some simplifying assumptions – e.g. the intervention does not affect how changes in indoor temperature affect health (i.e. ($\frac{\partial^2 y}{\partial T_e \partial Z} = 0$) and does not affect how any changes in behavior affect health (i.e. $\frac{\partial^2 y}{\partial b \partial Z} = 0$), many terms remain unidentified. In particular, we need to know how the intervention alters behavior on a hot day ($\frac{\partial^2 b}{\partial T \partial Z}$) and how these changes in behavior affect health ($\frac{\partial y}{\partial b}$), and we also need to know how changes in indoor temperature affect health $\frac{\partial y}{\partial T_e}$. None of these terms are identified by either the RCT or the reduced form (equation 1).

However, a randomized trial or quasi-experiment that assigns some locations or households to receive cool roofs and others not, and which is able to track both ambient temperatures and health outcomes for treated and untreated locations, could directly estimate the outcome in Equation 3, $\frac{\partial^2 y}{\partial T \partial Z}$ even without estimating all the components on the right-hand side of the equation. Our focus in this paper is on identifying intervention evaluations of this sort.

Figure S1: **Heterogeneity in the impacts of temperature on mortality, using percentage change in mortality rates**. Results are as in Figure 2, except modeling the outcome as the log of the mortality rate.

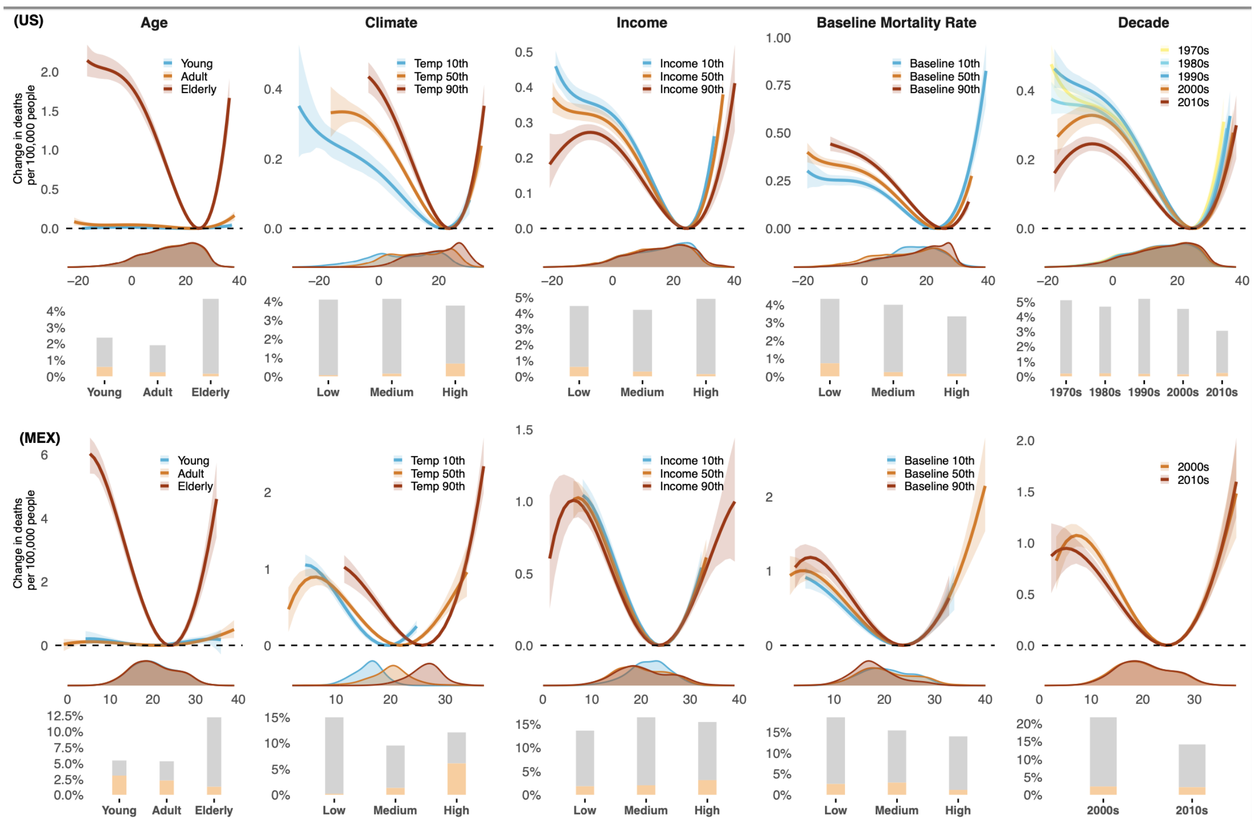

Figure S2: **Heterogeneity in the impacts of temperature on mortality, adjusting for age.** Results are shown for US and Mexico, two study regions with detailed data on age in the vital statistics data.

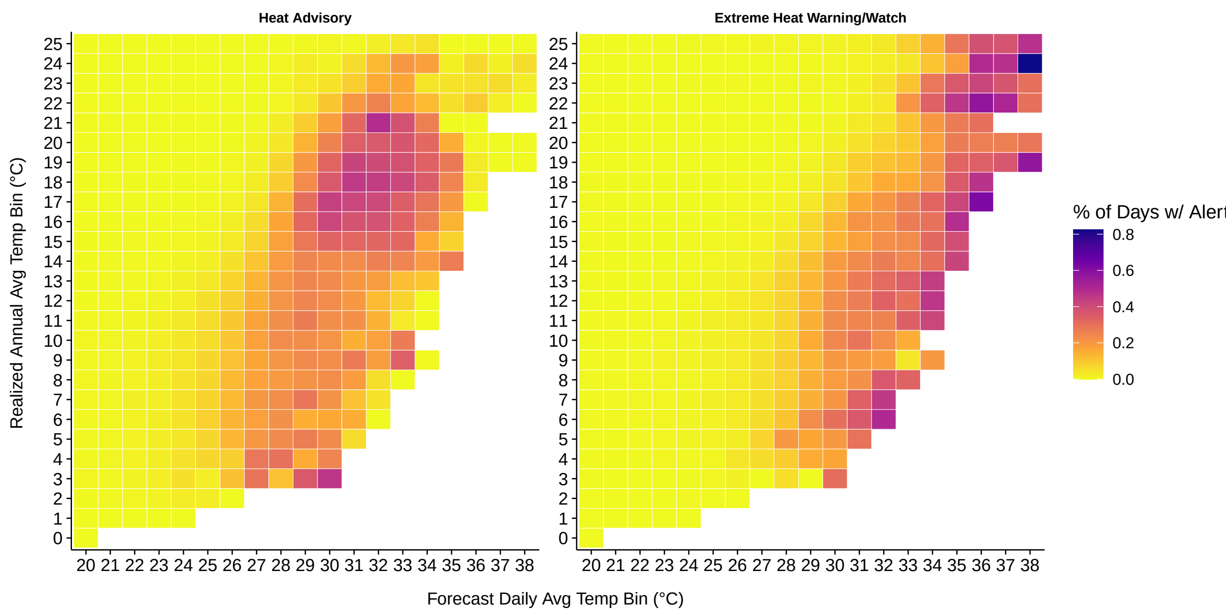

Figure S3: **The proportion of days in which heat alerts are issued across the US, by forecast daily temperature and location average temperature**. Left: heat advisories. Right: extreme heat warnings. Forecast temperatures are day-ahead forecasts. Both heat advisories and heat alerts are more likely to be issued on days where the forecast average daily temperature is above 30-35°C , but are issued at lower daily temperatures in colder locations (as denoted on the y-axis). For instance, a location with an average temperature of 20°C in the US rarely issues extreme heat warnings on a 30°C day, but a location with an average temperature of 10°C will issue alerts on most 30°C days. Data cover all days over the years 2006-2023.

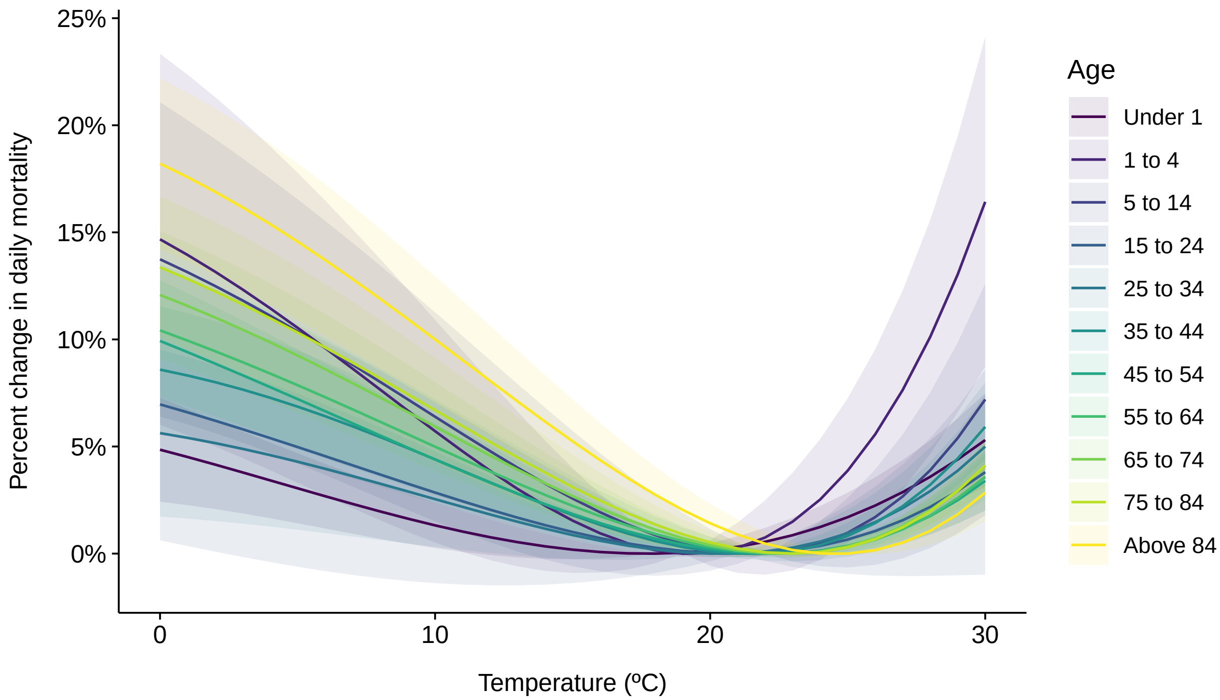

Figure S4: **Age-specific temperature-mortality relationships in the US, excluding violence (suicides and homicides) and accidents.**

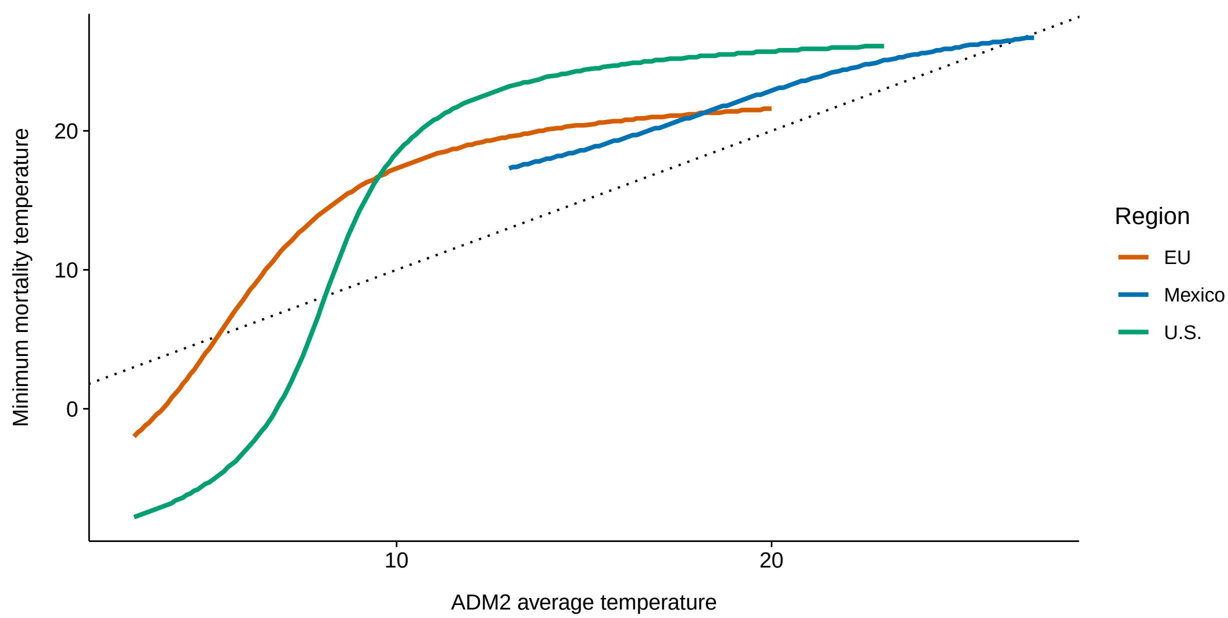

Figure S5: **Mortality minimizing temperature versus administrative unit average temperature.** Mortality-minimizing temperatures are derived from empirically observed exposure–response relationships.

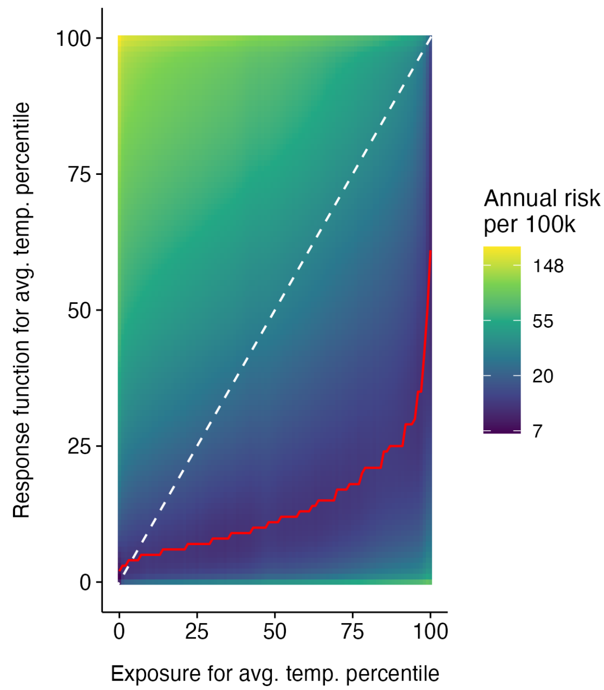

Figure S6: **Temperature-related mortality risk for combinations of observed exposure–response functions and temperature distributions.** Each pixel represents the overall temperature-related mortality risk for a combination of observed exposure–response function and temperature exposure distribution, holding income and baseline mortality rate at their mean values. For each exposure distribution percentile (x-axis), raster values indicate the overall temperature-related mortality that would result from choosing among exposure–response functions attainable at a fixed income and baseline mortality rate. Locations are observed to choose those that lie alone the 45° white dashed line. Overall mortality is minimized along the solid red line.

Figure S7: **Temperature-attributable deaths in the US would have been lower had the US kept its 1970's temperature-mortality response function in subsequent decades.** "Observed" bars are the estimated temperature-attributable deaths in each decade, using decade-specific response functions and temperature exposures shown in the last column of Fig 2. "Counterfactual" bars are the estimated temperature-attributable deaths had the US kept its 1970s response function in subsequent decades, but experienced its same population growth and observed temperature exposure in each decade.

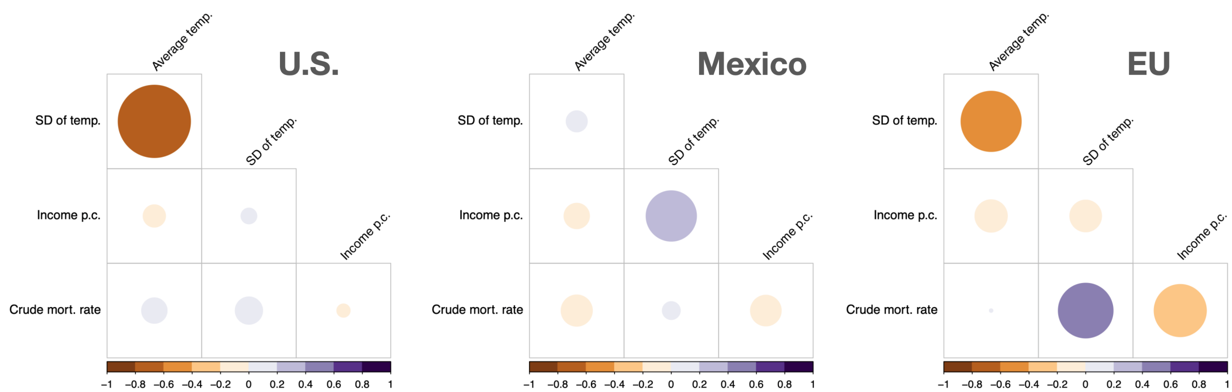

Figure S8: **Correlations between temperature-mortality relationship-relevant covariates across subnational units in the U.S., Mexico, and the EU**. Colors indicate sign of correlation, bubble size indicates correlation strength.

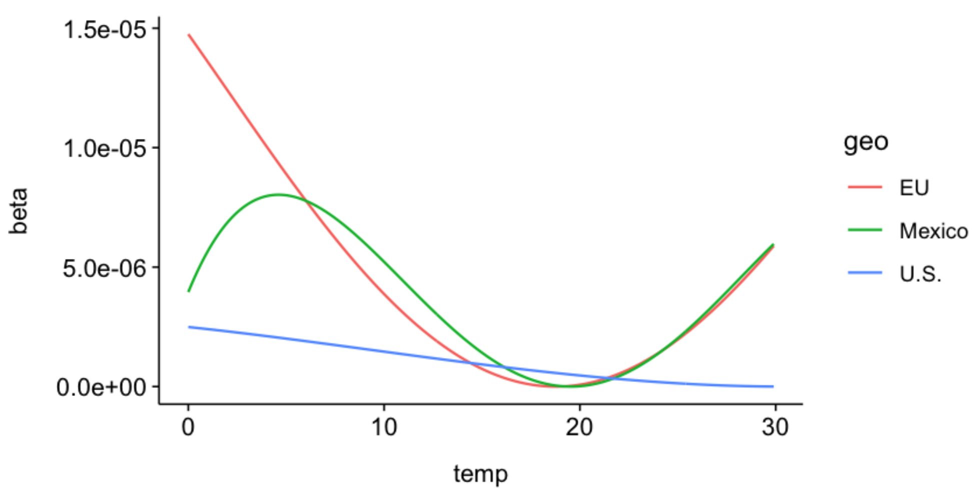

Figure S9: **Cross-country comparisons of temperature-mortality relationships for individuals over 65, holding fixed average temperature, income, and baseline mortality**.